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Vienna, 24.–26.11.2015

GELMON 2015

3rd International Workshop on Geoelectric Monitoring

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Geological Survey of Austria

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GELMON 2015

3rd International Workshop on Geoelectrical Monitoring

Collection of Abstracts

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November 24th – November 26th, 2015, Vienna

Scientific Program Committee:

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Contents

Preface 5

General Workshop Program Overview 7

Conference Program 8

Oral Presentations 14

- **Workshop Opening** 14
- **Monitoring of Contaminated Sites I** 16
- **Data Quality Assessment and Inversion** 23
- **Monitoring of Landslides I** 30
- **Hydrology I** 35
- **CO_2 Monitoring** 41
- **Infrastructure Monitoring** 46
- **Monitoring of Landslides II** 55
- **Monitoring of Contaminated Sites II** 59
- **Hydrology II** 65

Poster Presentations 69

List of Participants 86

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Preface

It is a pleasure for the Geological Survey of Austria to host The GELMON conference for the 3rd time here in Vienna.

We are honoured to welcome around 100 international scientists from 17 countries, not only from Europe but also from around the world, like from South Korea, Canada, Russia and Mexico.

It is now for the 3rd time that this conference takes place. As this book of abstracts shows, the method of geoelectrical monitoring has significantly emerged as one of the most innovative methods in applied geosciences since the first workshop in 2011. This success honours the work performed by all of the individual contributors, but also highlights the effectiveness of international cooperation established over the recent years. It is not least the merit of the GELMON conference, that several small working groups, sparsely distributed all over the world, came together and have developed a close international cooperation network, leading to a combined research effort which would not have been possible within each individual group alone.

As the topics of the contributions to this conference show, geoelectric monitoring can contribute to many of the key challenges society faces today, especially in the areas of sustainable environmental development, societal protection and of developing resilience to climate change. The applications of geoelectrical monitoring presented at GELMON 2015 span over a wide range of different themes like monitoring of contamination, landslides, permafrost, CO_2 injection, dikes and dams, tracer movements, infrastructure, mine areas and saline intrusions. However as the importance of the underlying process monitored by geoelectrics, i.e. variations in the subsurface water content and salinization, suggests, the demand for further applications of the method will significantly grow over the next decade. Therefore, it is also the goal and commitment of the GELMON conference to coordinate the future development of the geoelectrical method by fostering international cooperation and to establish geoelectrical monitoring as a reliable, commonly accepted methodology for monitoring of subsurface processes.

The excellent scientific contributions, summarized in this abstract book, and held in the form of outstanding talks and poster presentations at the GELMON 2015 conference, as well as the vivid and stimulating discussions were of paramount importance for making this conference a great success. Therefore we wish that the ideas developed during the discussions might develop, thus leading to a significant progress in the application of the geoelectrical method within the years to come.

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 (BMWFW), the Austrian Geophysical Society (AGS) and last but not least of Stefanie Gruber, who did most of the preparation work…

…and we hope to welcome you again at the 4th edition of GELMON in 2017.

ROBERT SUPPER
GEOLOGICAL SURVEY OF AUSTRIA

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General Workshop Program Overview

Tuesday, Nov. 24th

10.00-10.30	Workshop Opening
10.30-12.00	Monitoring of Contaminated Sites I
13.30-15.20	Data Quality Assessment and Inversion
15.50-17.00	Monitoring of Landslides I
17.30-18.00	POSTER SESSION: Short Presentations
18.00-21.00	Question Time and Icebreaker Party

Wednesday, Nov. 25th

09.00-10.30	Hydrology I
11.00-12.10	CO2 Monitoring
13.30-15.20	Infrastructure Monitoring
15.50-17.00	Monitoring of Landslides II
19.00-24.00	Conference Dinner at "Wiener Rathauskeller"

Thursday, Nov. 26th

10.00-11.50	Monitoring of Contaminated Sites II
13.30-15.00	Hydrology II
15.00-15.30	Closing of Workshop

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Conference Program GELMON 2015

Tuesday, Nov. 24th

10.00 -10.30	**Workshop Opening** **R. Supper:** Strengthening the role of geoelectric monitoring in addressing societal challenges: Past achievements and recent developments at the Geological Survey of Austria		
MONITORING OF CONTAMINATED SITES I			
10.30 -10.50	Resistivity-IP Monitoring at Landfills in Southern Sweden	T. Dahlin and M.H. Loke	**01**
10.50 -11.10	ERT monitoring of water infiltration process through a landfill cover layer	G. Dumont, T. Pilawski, T. Robert, T. Hermans, S. Garré and F. Nguyen	**02**
11.10 -11.30	Electrical Resistivity Tomography for monitoring the contamination from Olive Oil Mills' Wastes: Application in disposal sites of Crete, Greece	N. Papadopoulos, K. Simyrdanis, S. Kirkou, P. Soupios, P. Tsourlos, J.-H. and Kim	**03**
11.30 -11.50	Resistivity monitoring contribution to hydrogeological risk assessment in a reclaimed landfill in Thessaloniki (Greece)	G. Vargemezis, P. Tsourlos, I. Fikos and N. Kazakis	**04**
11.50 -12.00	**Discussion**		

DATA QUALITY ASSESSMENT AND INVERSION			
13.30 -13.50	Analysis and evaluation of ERT data reliability in long-term geoelectric monitoring	J.-H. Kim, R. Supper, D. Ottowitz and M.-J. Yi	**05**
13.50 -14.10	A new measurement protocol of ERT data	J.-H. Kim, R. Supper, D. Ottowitz, B. Jochum and M.-J. Yi	**06**
14.10 -14.30	Analysis of Large ERT Monitoring Datasets with a Time Series Perspective	O. Kaufmann and A. Watlet	**07**
14.30 -14.50	Optimizing time lapse ERT measurements using the Jacobian matrix approach	P. Tsourlos, C. Tsakirbaloglou, G. Vargemezis and P. Louvaris	**08**
14.50 -15.10	Time-lapse inversion of ERT monitoring data using variogram-based regularization	T. Hermans, G. Dumont, A. Kemna and F. Nguyen	**09**
15.10 -15.20	**Discussion**		

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Tuesday, Nov. 24th

MONITORING OF LANDSLIDES I			
15.50 -16.10	Active landslide monitoring using structurally constraint 4D ERT monitoring	S. Uhlemann, J.Chambers, P. Wilkinson, S. Hagedorn, H. Maurer, T. Dijkstra, B. Dashwood and D. Gunn	**10**
16.10 -16.30	Inversion of long time series landslide movements from geoelectrical monitoring data	P. Wilkinson, J. Chambers, S. Uhlemann, P. Meldrum, N. Dixon and M.H. Loke	**11**
16.30 -16.50	Analysis of gravitational slope cycles by means of geophysical monitoring	E. Palis, T. Lebourg and M. Vidal	**12**
16.50 -17.00	**Discussion**		
17.30 -18.00	**Poster Presentations**		

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POSTER PRESENTATION

Integrating electrical resistivity with multi-compartment sampler techniques to study heterogeneous solute transport in the unsaturated zone	E. Bloem, P. Fernandez and H.K. French	**P01**
Combining multi-scale surface ERT for fast and robust shallow hydrostratigraphic units delineation at catchment scale	L. Gourdol, R. Clément, C. Hissler, J. Juilleret and L. Pfister	**P02**
Spatializing of soil water content measurement at the scale of the agricultural field, using geoelectrical monitoring and geostatistical method	H. Henine, R. Clément, H. Jaegler, N. Forquet, C. and Lauvernet	**P03**
How to achieve a good evaluation of soil moisture content at different depths with available measuring techniques?	U. Sauer, H. Borsdorf, C. and Schuetze	**P04**
Comparative Study of a Sulfate Tracer Monitoring Experiment Using Geoelectrical and Hydrogeological Survey Techniques	C. Schütze, M. Pohle, M. Kreck, U. Werban, P. Dietrich and T. Vienken	**P05**
Geoelectrical monitoring of a fresh water injection into a limestone aquifer	R. von Bülow, N. Klitzsch, D. Burs and F. Wellmann	**P06**
Evaluation of Dam Seepage Problems Using Geological and Geophysical Methods, Republic of Korea	S.-K. Lim, Y.-K. Cho, D.-H. Kim, K.-H. Lee and S.-J. Kang	**P07**
Results and further investigations based on the LAMOND Landslide Monitoring Network. Case study Bagnaschino Monitoring site: Soil water flow model based on Geoelectric Monitoring inversion results.	S. Hoyer and D. Ottowitz	**P08**
Geoelectrical monitoring during waste biodegradation process	T. Jouen, R. Clément, S. Moreau and L. Mazéas	**P09**
Case study: Long-term permafrost evolution at the Schilthorn monitoring site, Swiss Alps, using electrical resistivity tomography (ERT) monitoring	C. Mollaret, C. Hiblich and C. Hauck	**P10**
The ATMOperm – project: Atmosphere - permafrost relationship in the Austrian Alps - extreme atmospheric events and their relevance for the mean state of the active layer	S. Pfeiler, W. Schöner, A. Flores-Orozco and S. Reisenhofer	**P11**
Crystalline rocks time-lapse behavior via geophysical methods	J. Jirku, J. Barta, J. Vilhelm, M. Broz and K. Sosna	**P12**
Exploration of underground utilities for electric field analysis in jointed rock mass with anomaly	H.-H. Ryu, K.-I. Song, D.-S. Lee, G.-C. Cho and K.-Y. Kim	**P13**
Monitoring water infiltration in an experimental mine rock waste pile with time-lapse ERT and multi-parameter data collection	M. Chouteau, A. Dimech, B. Plante, F. Medina, V. Martin, S. Broda, B. Bussière and M. Aubertin	**P14**
Processing of geoelectrical monitoring data. Unconventional approach to detection of local subsurface heterogenety	D. Makarov, M. Marchenko and I. Modin	**P15**
Electrical monitoring on construction sites in Russia	M.I. Bogdanov and I.N. Modin	**P16**

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Wednesday, Nov. 25th

HYDROLOGY I			
09.00 -09.20	Resistivity assessment of an earth-filled dike with a permanent hydraulic head (Canal de Roanne à Digoin, France): 4D effects on 2D ERT monitoring	G. Bièvre, L. Oxarango, R. Clément, T. Günther, D. Goutaland and M. Massardi	**13**
09.20 -09.40	Monitoring water saturation in earth levees with a customized resistivity system	D. Arosio, S. Munda, G. Tresoldi, L. Zanzi, L. Longoni and M. Papini	**14**
09.40 -10.00	Time-lapse ERT of water infiltration in the context of soil aquifer treatment	K. Haaken, A. Furman, N. Weisbrod and A. Kemna	**15**
10.00 -10.20	Tracer moment tracking and forecasting in time-lapse electrical resistivity tomography	W. Ward, P. Wilkinson, J. Chambers and L. Bai	**16**
10.20 -10.30	**Discussion**		

CO2 Monitoring			
11.00 -11.20	Technical and methodological requirements for a permanent downhole geoelectrical measurement system as CO2 monitoring tool – A review from the Ketzin pilot site	C. Schmidt-Hattenberger, P. Bergmann, T. Labitzke, D. Rippe and F. Wagner	**17**
11.20 -11.40	Insights on CO2 migration by means of a fully-coupled hydrogeophysical inversion	F. Wagner, B. Wiese, C. Schmidt-Hattenberger and H. Maurer	**18**
11.40 -12.00	Surface-downhole geoelectrics for post-injection monitoring at the Ketzin pilot site	D. Rippe, P. Bergmann, T. Labitzke, F. Wagner and C. Schmidt-Hattenberger	**19**
12.00 -12.10	**Discussion**		

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Wednesday, Nov. 25th

INFRASTRUCTURE MONITORING			
13.30 -13.50	Proactive infrastructure monitoring and evaluation (PRIME): a new electrical resistivity tomography system for remotely monitoring the internal condition of geotechnical infrastructure assets	J. Chambers, P. Meldrum, D. Gunn, P. Wilkinson, S. Uhlemann, O. Kuras and R. Swift	**20**
13.50 -14.10	Geoelectrical Imaging of Moisture Dynamics in Engineered Slopes	S. Uhlemann, J. Chambers, P. Wilkinson, D. Gunn, R. Stirling and R. Hen-Jones	**21**
14.10 -14.30	Long-term Geophysical Monitoring for Leakage Problems at Reservoir Dams, Republic of Korea	S.-K. Lim, Y.-K. Cho, D.-H. Kim, Y.-S. Song, M.-J. Nam, S.-J. Kang and S.-Y. Song	**22**
14.30 -14.50	Successes and challenges of geoelectrical monitoring at Sellafield, UK – a retrospective	O. Kuras, P. Wilkinson, P. Meldrum, L. Oxby, S. Uhlemann, J. Chambers, A. Binley, J. Graham, N. Smith and N. Atherton	**23**
14.50 -15.10	Time-lapse resistivity measurements in an undermined area (case study of Dětmarovice, Czech Rep.)	P. Bláha, R. Duras and P. Táborík	**24**
15.10 - 15.20	**Discussion**		

MONITORING OF LANDSLIDES II			
15.50 -16.10	Permanent electrical resistivity measurements for monitoring water circulation in clayey landslide	J. Gance, J.P. Malet, R. Supper, P. Sailhac, D. Ottowitz and B. Jochum	**25**
16.10 -16.30	Clustering the apparent electrical resistivity data of permanent ERT monitoring	E. Palis, T. Lebourg and M. Vidal	**26**
16.30 -16.50	Evaluation of 2-year TL-ERT monitoring of a landslide (case study of Čeřeniště, Czech Rep.): towards understanding precipitation, saturation and resistivity changes	P. Táborík F. Hartvich, T. Belov, L. Vlček and J. Blahůt	**27**
16.50 -17.00	**Discussion**		

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Thursday, Nov. 26th

MONITORING OF CONTAMINATED SITES II			
10.00 -10.20	First leachate injection monitoring in farm scale solid state anaerobic digestion plant by electrical resistivity tomography	R. Clément, A. Degueurce, S. Moreau and P. Peu	**28**
10.20 -10.40	Laboratory tests using electrical resistivity monitoring to study biogas and leachate migrations in waste mass	S. Moreau and B. Duval	**29**
10.40 -11.00	Development of a methodology to constrain hydrodynamic models by time-lapse ERT monitoring: Application to leachate flow into waste landfills	M. Audebert, R. Clément and S. Moreau	**30**
11.00 -11.20	Geoelectrical monitoring of dense non-aqueous phase liquids with surface-to-horizontal borehole ERT	C. Power, J.I. Gerhard, P. Tsourlos, P. Soupios, K. Simyrdanis and M. Karaoulis	**31**
11.20 -11.40	3D time-lapse ERT monitoring of an experimental simulation of olive-oil mills' waste movement	S. Kirkou, P. Tsourlos, P. Soupios, N. Papadopoulos and K. Simyrdanis	**32**
11.40 -11.50	**Discussion**		

HYDROLOGY II			
13.30 -13.50	4D ERT monitoring for the hydrological characterization of the rocky unsaturated zone	L. De Carlo, M. Berardi, M. Vurro and M.C. Caputo	**33**
13.50 -14.10	ERT monitoring of the vadose zone of a karst system sounds like a challenge!	A. Watlet, O. Kaufmann, O. Francis, M. Van Camp, P. Wilkinson, P. Meldrum and J. Chambers	**34**
14.10 -14.30	Cost-efficient saltwater monitoring of a shallow aquifer using long-electrode ERT	M. Ronczka, T. Voss, C. Rücker and T. Günther	**35**
14.30 -14.50	Coupled hydrogeophysical modelling and ERT monitoring using pyGIMLi	C. Rücker, T. Günther and F. Wagner	**36**
14.50 -15.00	**Discussion**		
15.00 -15.30	**Closing of Workshop**		

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GELMON 2015

Oral Presentations

Workshop Opening

Strengthening the role of geoelectric monitoring in addressing societal challenges: Past achievements and recent developments at the Geological Survey of Austria (GSA)

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Geoelectrical monitoring is an emerging geophysical method which rapidly developed in the recent past. This success can be contributed to a great extent to the development of reliable, remote controlled data acquisition systems. In the year 2001, scientist at GSA, in cooperation with the Torrent and Avalanche Control of Vorarlberg, started to develop a geoelectrical system specifically designed for monitoring of landslides. A prototype system was installed in 2002 at the landslide of Sibratsgfäll, but a lot of improvements were necessary until in 2007, when the GEOMON4D-II was finally ready for operation. This system, providing full remote control and operation, raw data recording, automatic data transfer and grid autarchy due to a combined solar - fuel cell power supply, represented the basis for the set up of an international landslide monitoring network, installed and operated within the SAFEland (FP7) and TEMPLE (Austrian Science Fund) projects. Experiences from 8 different monitoring sites operated between 2009 and 2014 suggested that several improvements to the system were still necessary: further lowering the power consumption, avoiding Windows system, increasing measuring speed, improving AD converter resolution, switching to constant current injection, recording of the full time-domain signal (including IP) and performing raw signal quality analysis directly during the data acquisition process. These requirements triggered the development of the GEOMON4D-HR system, finally ready for testing in late 2015. However, another backbone for reliable application of the method is data interpretation. Therefore, in parallel to the GEOMON development, based on preliminary contacts established at the NSG conference in Dublin, a fruitful cooperation was initiated between GSA and KIGAM on the development of the proper data inversion routines for monitoring data:

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specifically designed for the GEOMON a software bundle, including so far 4D data inversion, data inversion with changing electrode positions, advanced raw data analysis tools and weighted 4D inversion, was developed. The high data quality from the GEOMON system combined with the advanced data analysis capabilities make it now possible to derive reliable information about changes in the subsurface. In 2013 geoelectrical monitoring was applied for the first time during a disaster operation (landslide and dam protection). The success in monitoring and the significance of the method for different applications was recently acknowledged by the Ministry of Science, Research and Economy (BMWFW) by releasing funds to setup a permanent GEO-monitoring data centre in Vienna, which can provide access to external user and to establish an emergency task group. Furthermore, funds could be raised by GSA to apply this method to the monitoring of permafrost, acid mine dumps, groundwater pumping, dams and developing IP monitoring as an extension of the methodology.

Due to the wide range of different applications, today international cooperation is essential to further enhance the acceptance of the method. Therefore, the first GELMON conference was organized in 2011 in Vienna and successfully repeated in a 2 years cycle since then. This conference significantly fostered the international cooperation in this emerging field of geophysics. Due to the wide area of applications it is not surprising that several calls on EC level published for the next years include ground based earth observation. This could give geoelectrical monitoring the chance to be established as a standard core methodology for observing subsurface processes.

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Monitoring of Contaminated Sites I

01

Resistivity-IP Monitoring at Landfills in Southern Sweden

T. Dahlin[(1)*] and M.H. Loke[(2)]

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DCIP (DC resistivity and time-domain induced polarisation) short term monitoring surveys were carried out at a number of landfills in southern Sweden. Resistivity results from these experiments have been presented earlier by Dahlin et al. (2011) and Loke et al. (2014), where details concerning experimental setup and test sites can be found. Now analyses of the IP part of the monitoring data are presented.

We use the 4-D inversion method by Kim et al. (2009) that carries out a simultaneous inversion of the different time-lapse data sets. The data misfit and model roughness vectors can be weighted if the L1-norm inversion method is used (Loke et al., 2003). The complex resistivity method (Kemna et al., 2000) is used to calculate the apparent resistivity and I.P. values in the data misfit vector. The finite-element method is used so that 2-D or 3-D models with topography and arbitrary resistivity and IP structures can be modelled. The time-lapse inversion implementation by Loke et al. (2014) is modified to use a two-step inversion algorithm. In each iteration, the resistivity model is first optimised. In the second step the resistivity model is fixed and the chargeability model is optimised.

Tests were carried out with synthetic models to ensure that the inversion algorithm showed the expected changes in the model resistivity and I.P. Then results from a field survey at the Filborna landfill monitoring site were inverted. An inversion of the resistivity data mapped the flow of water from a rainfall event up to the water table at depth of about 5 m. The results show a low resistivity permeable zone shown in the 3rd to 5th layers through which rainwater flowed from the surface to the water table in the 6th layer. The I.P. model section shows some anomalies of up to about 10 mV/V in the top layer that might be due to variations in the clay and organic compost content in the topmost cover material. The cause of the I.P. variations in the deeper layer is uncertain, they could be due to metallic waste or artefacts due to noise as there is poorer data coverage and resolution at depth. Significant changes in the resistivity due to the rainwater infiltration relative to the initial data set are evident. In contrast, the I.P. sections show relatively small variations of generally of less than 1 mV/V. This is expected as the materials are initially moist and the addition of more water would not significantly change their I.P. characteristics.

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02

ERT monitoring of water infiltration process through a landfill cover layer

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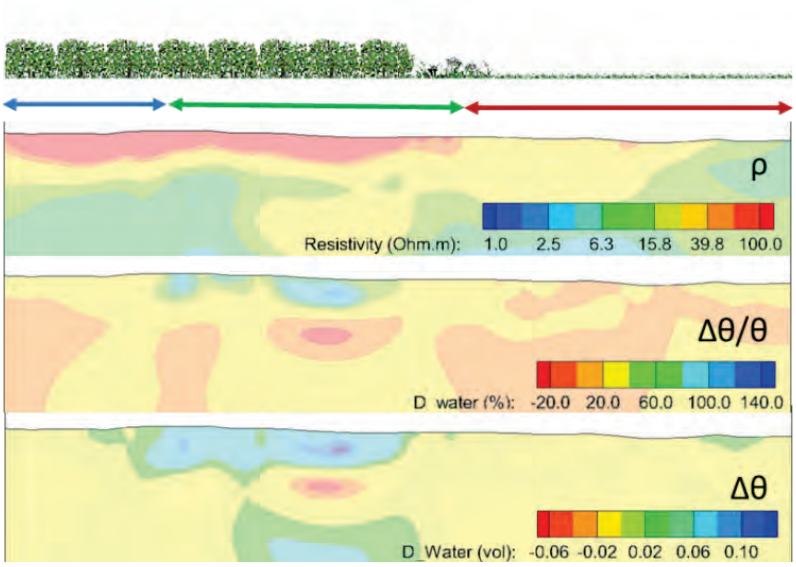
The electrical resistivity tomography is a suitable method to estimate the water content of a waste material and detect changes in water content. Various ERT profiles, both static data and time-lapse, where acquired on a landfill during the Minerve project.

Firstly, we estimated the water content of the waste from the resistivity data. For that purpose, we used petrophysical laws (namely Archie's law and Campbell's law) calibrated with laboratory experiments. The waste temperature was measured in a borehole and the leachate electrical conductivity was measured on waste samples collected during the drilling process.

Secondly, we investigated water content changes in the waste material after a rainfall event in order to better characterize the water infiltration and runoff process. In the literature, the relative change of water content is generally computed. Indeed, this parameter directly is linked to the relative change of resistivity through one single parameter: the Archie's law exponent. Working solely with difference inversion avoid considering the complexity of the initial state (difference in lithology, the initial water content, etc.). However, the absolute change of water content cannot be computed from the relative change of water content only.

During our investigation, a major rainfall (20-30 mm in 2 hours) occurred on the test site, characterized by a vegetalized and relatively dry zone and a devegatelized and humid zone. We intended to prove that most of the information contained in relative change of water content distribution is the initial water content distribution in the ground. Water addition in dry zones resulting in large relative changes. The computation of the absolute change of water content is necessary to demonstrate preferential infiltration through the capping in the vegetalized area.



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As further perspectives, the method could be used in less complex areas (e.g. corn field) to analyze in details the water infiltration process (interception storage on the foliage, water retention, infiltration, runoff, etc.) and help in assessing the system water balance.

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03

Electrical Resistivity Tomography for monitoring the contamination from Olive Oil Mills' Wastes: Application in disposal sites of Crete, Greece

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Olive oil industry is considered to be one of the driving sectors of the agricultural economy around the Mediterranean countries. During the last 15 years Greece produced annually an average of more than 300x103 tons of olive oil, thus rendering it the third olive oil producing country worldwide after Spain and Italy. From an alternative perspective this brings the whole European Union to a leading place within the international olive oil market thus comprising an important financial activity for the producing countries. Especially the island of Crete contributes about 5% of the world's olive oil production.

Olive oil is a key element in the well-known Mediterranean diet and beneficial on the human health. However the extraction process of olive oil is associated with the production of large amounts of solid and liquid wastes with high organic load and rich in inorganic constituents. One of the main characteristics lies on the fact that these wastes are accumulated within the relatively short harvest period in winter (November to late February). Olive Oil Mill Wastes (OOMW) have dark brown color with unpleasant smell, they are characterized by low resistivity, and their high concentration of phenolic compounds renders them toxic for the environment and human health. The lack of specific legislation has led to the common practice of disposing the OOMW in man-made evaporation ponds or directly to the surface water systems such as streams, torrents or rivers. Unfortunately in reality these ponds are poorly constructed which results in the OOMW either to overflow on the ground or leak into the subsurface.

This work describes the efficiency and ability of electrical resistivity tomography to map and monitor the subsurface contamination caused by OOMW. The spatial distribution and temporal variation of these wastes are investigated through an integrated methodological flowchart composed of numerical modeling, supervised tests in experimental tanks and real data collected from three active waste disposal sites in Crete. Synthetic modeling was used to simulate and reconstruct the movement of the olive oil mills' wastes (OOMW) as a conductive target within a layered resistive medium using both surface and cross-borehole configurations. The flow of an OOMW liquid was also monitored in a saturated sandy layer through cross-hole ERT. Finally the mapping and monitoring results from three different OOMW sites in Crete validated the efficiency of ERT in real situations.

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In all cases the results show that time-lapse ERT is a robust geophysical method for monitoring the spatial distribution and the temporal variation of the contaminant's movement into the subsurface. The mapping and monitoring was made feasible due to the electrical signature of the "target" which is more conductive in comparison with the environment. In general numerical, experimental and real data results show a high degree of correlation suggesting the ERT as a powerful tool to map and monitor the subsurface contamination resulted by the byproducts of the olive oil industry.

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04

Resistivity monitoring contribution to hydrogeological risk assessment in a reclaimed landfill in Thessaloniki (Greece)

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Old non sanitary landfills can become a major source of pollution for surface water bodies and groundwater. Even if old landfills are subjected to reclamation, there are cases in which highly variable local hydrogeological conditions are a constant environmental threat which needs to be taken into account to avert environmental accidents and to improve the reclaimed landfill management. In the case of Derveni landfill (city of Thessaloniki) which was subjected to reclamation in 2006, leachate still outflows from the main waste body. Before operation, no bottom sealing liner was used to protect groundwater from leachate, and, even during reclamation no top liner was placed. Therefore, it is under question whether the outflowing leachate is a fluid produced by lateral groundwater flow contaminated by the waste disposal or by the infiltrated rainwater.

As part of a wider study, geoelectrical monitoring has been applied to investigate the hydrogeological conditions of the area involving: (a) SP and resistivity changes during pumping of two observation wells existing within the site, (b) resistivity changes over more than two years in four selected locations within the landfill.

Continuous recording during pumping allowed the cross examination with the water table variation and resulted in understanding the aquifer distribution and its relation with the waste body and leachate, while resistivity changes within the waste body have been interpreted along with the precipitation recorded in situ for more than a two years period.

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Data Quality Assessment and Inversion

05

Analysis and evaluation of ERT data reliability in long-term geoelectric monitoring.

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High quality in geophysical measurements is a prerequisite condition to know the ground truth. It is much more demanded in geophysical monitoring for understanding ground condition changes in time since the temporal changes in geophysical responses are very weak. Even in cases that we are able to obtain the data having fairly high S/N ratio, careful examination and assessment of measured data reliability are still necessary as field data are always contaminated with noise. In a pre-inversion stage, accordingly, the data are edited, but usually by eye-inspections and/or through inversions in a trial-and-error manner. This approach to enhance data quality is hard to be systematically applied to long-term monitoring where data are regularly and continuously collected, since consistency in data editing is difficult to be achieved and considerable time should be consumed. As a more advanced approach, reciprocal measurements have frequently been adopted to assess the degree of data uncertainty or reliability. This method needs to perform additional repeated measurements, which consumes extra costs and time in data acquisition. Furthermore, electrode charge-up effects due to the reciprocal measurements may also introduce measurement errors.

To alleviate these difficulties and further to achieve enhanced imaging capabilities in geoelectric monitoring, we have developed algorithms firstly for filtering data outliers and secondly for accurately evaluating data reliability. The main functions are listed as:

- automatic evaluation of electrode status and filtering of the data associated to bad electrodes,
- filtering of anomalous data,
- time-series data filtering,
- interactive and graphical editing, and
- automatic evaluation of data reliability.

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The filtering and editing methods are designed to provide the data with high S/N ratio to actual inversion process, while the evaluated reliabilities are to weight the data actually used in inversion according to their reliabilities. The data and parameters used for filtering and reliability assessment are not only usual ones measured in an ERT survey such as potential differences, injected currents, resistances, etc., but also the parameter values estimated from analysis of full time-series curves of injected current and sensed potential, e.g., S/N ratio, standard deviation of resistance, representative slopes of time-series curves, etc.

To easily implement the functions, two programs have been encoded: the first is to investigate and analyze a data set of a particular time-lapse in detail, while the second is to examine the 4-dimensional data on the whole and to process them along the time axis. Particularly addressed is to make various kinds of filtering (except graphical editing) and data quality evaluations automatic so that little efforts and time would be spent in pre-inversion stage. In addition to this, data weighting factors are always automatically evaluated taking account of the statistics of the measured data so that we are able to reconstruct more reliable and enhanced subsurface images as well as their changes in time.

The performance and effectiveness of the developed algorithm is examined and demonstrated with the field data monitored at the Gresten site, Austria.

Acknowledgements

This work was supported by the Basic Research Program of the Geological Survey of Austria as well as by the Basic Research Project of the Korea Institute of Geoscience and Mineral Resources funded by the Ministry of Science, ICT and Future Planning, Republic of Korea.

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06

A new measurement protocol of ERT data

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DC resistivity methods are generally based on the measurements of electric potentials or potential differences caused by the current injected into the ground. However, measured potential differences can be severely contaminated by spurious potentials originating from a wide variety of external sources. Spurious potentials usually contain a DC component, several components at distinct frequencies (e.g., the 50/60 Hz frequency from power lines and its multiples), linear and nonlinear drifts and a non-coherent noise component. This parasitic potential (noise) may sometimes be substantially larger than the potential solely caused by the current (signal). Thus, it is important to eliminate this noise from the measurements.

Noise components of distinct frequencies can easily be eliminated either by filtering or adapting the measuring interval to multiples of the noise period. Non-linear drifts usually originate from bad electrode contacts or technical problems with the instrument. Therefore, such measurements should be either repeated or removed from the final data set. A common strategy for eliminating the DC noise component is to conduct measurements in forward and backward directions of the current flow, which can be accomplished by injecting current in square wave form. This method has historically been used as the basic framework for Earth resistivity meters. In this protocol, the difference between two consecutive readings during one cycle of +/- square-wave current is regarded as the target signal for measurement. In addition, the mean of the forward and backward potentials are regarded as spurious DC potentials that bias the true response. Spurious DC potentials measured in this manner must be identical to potentials measured without injecting current; this is a necessary condition for the validity of the resistivity measurement principle. Because self-potential (SP) is the observed potential when no current is injected, we refer to this spurious DC potential as SP estimated from DC resistivity measurement, although SP would be contaminated by noise (e.g., electrode polarization effects). However, in field measurements, SP estimated from resistivity measurement can be sometimes noticeably different from that measured without the current source, and the estimated SP may contain responses to the current (e.g., polarization effects) injected into the ground to measure resistances. Resistances obtained in this manner may be erroneous.

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In this study, we propose a new protocol for measuring DC resistivity data, where SP data are obtained immediately prior to measuring DC resistivity. Measuring SP at this time allows to define two different resistances: forward resistance (i.e., a normalized potential difference caused by forward current injection) and backward resistance (i.e., a normalized potential difference caused by backward current injection). This allows for the quantification of errors in the measurements of DC resistivity in the field survey as well as distortions in the DC resistivity potential field caused by all unknown mechanisms but SP sources. In addition, we devised a new data-weighing scheme (based on forward and backward resistances) to obtain more reasonable subsurface structures. We validated this proposed method through inversion experiments.

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07

Analysis of Large ERT Monitoring Datasets with a Time Series Perspective

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Imaging temporal variations is the key motivation for setting up a permanent ERT monitoring system. Running such a system over long periods generates large datasets that generally consist in repeated surveys at regular intervals. Conventional processing approaches are based on separate data filtering of each survey followed by inversion strategies such as difference of separately inverted surveys, difference inversion, time-lapse inversion or, more recently, 4D inversion. Here we propose an approach of data processing that focuses on the temporal nature of the dataset.
Depending on the phenomenon of interest, erratic events and short or long period phenomena may obliterate the targeted variations. Using time series analysis methods on measured data and inverted sections we tried to improve the imaging the monitored area of the targeted with respect to targeted variations. This approach allows including external time series such as additionally monitored environmental parameters (e.g. effective rainfall, soil humidity, temperature) in the analysis. As this processing includes modelling temporal variations of measures it may also be used to fill gaps associated to instrumental maintenance or breakdowns.
Handling large datasets in this way requires efficient storage and retrieval structures as well as semi-automated (or fully automated) processing workflows. For data management, we use a hierarchically formatted file structure allowing efficient data storage, append and retrieval. This allows to efficiently manipulate the dataset as successive surveys but also as multivariate time series. Python routines have been developed to integrate all the steps prior inversion: data acquisition, append of the hierarchically formatted file, standard filtering and time series pre-processing. Datasets are then generated for inversion program such as BERT. After inversion, results are appended in a hierarchically formatted file for further time series processing.
This approach was both applied to synthetic datasets and to field data from the daily hydrogeophysical monitoring of the vadose zone at the Rochefort Cave Laboratory. A comparison of results with and without applying the present approach is proposed.

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08

Optimizing time lapse ERT measurements using the Jacobian matrix approach

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In this work we present an algorithm for optimizing time-lapse ERT measurements. Single time-step measurement optimization is being carried out by selecting optimum measurements on the basis of their sensitivity matrix value in relation to the subsurface parameters. The optimized data-set is being selected form a comprehensive data set which involves all independent combinations of several widely used surface 4-electrode arrays (i.e. dipole-dipole, multiple-gradient, etc.). The number of the maximum number of measurements is being predefined by the user. The performance of the optimized arrays which is produced is being tested with synthetic data and benchmarked against standard electrode arrays.
Further optimization for time-lapse data was achieved by assigning higher optimization weights to the parameters which belong to regions in which changes are taking place. In particular very fast approximate data inversion is used to define areas that resistivity changes are more likely (or expected) to take place and then measurement optimization process is focused into to them in order to obtain customized data sets for each time step. The applicability of this procedure is demonstrated again with synthetic data examples. The presented optimization method proved effective having the advantage of being extremely fast as it is solely based on the calculation of the Jacobian matrix for homogeneous earth.

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09

Time-lapse inversion of ERT monitoring data using variogram-based regularization

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Hydrogeophysics has become a major field of research in the past two decades and time-lapse electrical resistivity tomography (ERT) is one of the most popular techniques to monitor passive and active processes in subsurface reservoirs. Time-lapse inversion schemes have been developed to refine inversion results; but, in contrast with static inversion, they mostly still rely on the spatial regularization procedure based on the standard smoothness constraint. In this contribution, we propose to apply a variogram-based regularization operator in the time-lapse ERT inverse problem, using the model difference covariance matrix to replace the standard smoothing operator. The variogram of resistivity variations can be computed through independent borehole data, such as electromagnetic logs or hydrogeological monitoring, which is often available during monitoring experiments.

We first illustrate the method for surface ERT with a synthetic case and compare the results with the standard smoothness constraint solution. This example shows that the variogram-based constraint images better the assumed anomaly both in terms of shape and amplitude. The improvement is largely higher than the one obtained with more classical anisotropic smoothness constraint. This synthetic example also shows that an error made in the range of the variogram has a limited impact on the resulting image, which still remains better than the smoothness constraint result. Anomalies located in various part of the tomograms were tested. Although more crucial in low-sensitivity zones, improvements are observed everywhere in the tomograms.

The method is then applied to cross-borehole ERT field data from a heat tracing experiment, where the comparison with direct temperature measurements shows a strong improvement of the breakthrough curves retrieved from ERT. Using the variogram-based regularization, it is possible to reduce the smoothing of resistivity variations in low sensitivity zones and therefore to avoid overestimation of temperatures. The proposed method could be extended to the time dimension which would allow the use of variogram-based constraints in 4D inversion schemes.

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Monitoring of Landslides I

10

Active landslide monitoring using structurally constraint 4D ERT monitoring

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Future environmental and climate change will affect the frequency and magnitude of landslide occurrences. A major focus of research is therefore to gain an improved understanding of the processes leading to slope instability. This study considers the use of a combination of one-off seismic and 4D (i.e. 3D time-lapse) geoelectrical monitoring measurements, from a 34 month period, to gain detailed understanding of the hydrological conditions leading to landslide reactivation and first time failure.

The study site is the Hollin Hill landslide field observatory that comprises a suite of geophysical, geotechnical and environmental sensors, thus offering the opportunity to compare and inform interpretation of the different data streams. 4D electrical resistivity tomography (ERT) inversion was structurally constrained employing results of a combined P- and S-wave seismic refraction tomography (SRT). As mass movements of up to 3.5 m were recorded during the monitoring period, a workflow was developed to integrate variable electrode positions in the 4D inversion.

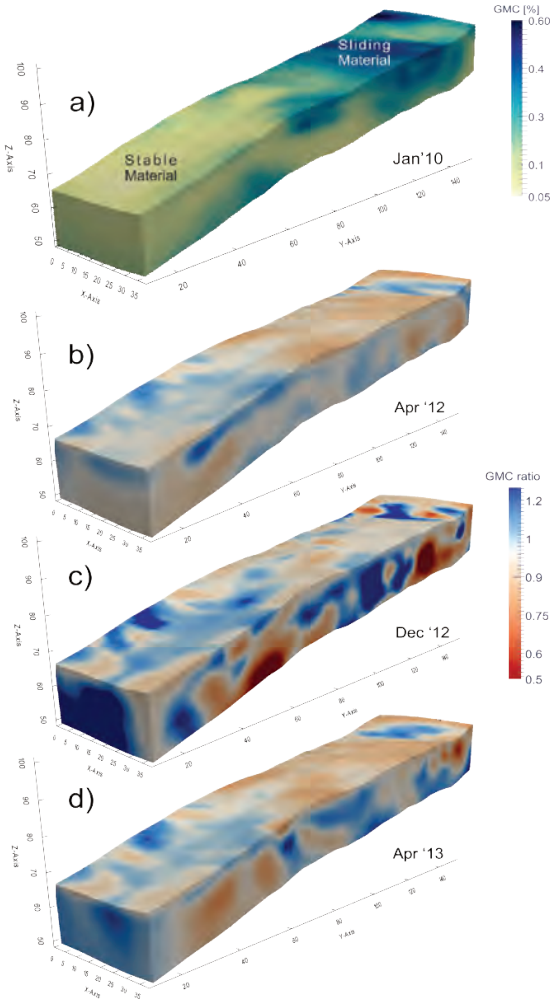

Figure 1 a) Baseline image of gravimetric moisture content (GMC). b)-d) Ratio images showing changes in moisture content compared to baseline image. b) before reactivation, c) during reactivation, d) after reactivation.

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The ERT results were temperature corrected and translated into values of gravimetric moisture content (GMC) using laboratory derived GMC-resistivity relationships. The GMC models show seasonal effects for the first two years of monitoring, followed by imaging of crack build-up and deep moisture penetration leading to failure of the back scarp. Elevated moisture contents and thus pore water pressures, caused by prolonged rainfall, were imaged throughout the landslide during its reactivation, and in particular in areas of accelerated movements beneath two lobes.

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GELMON 2015

11

Inversion of long time series landslide movements from geoelectrical monitoring data

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As part of a landslide observatory, BGS have been operating a permanently installed 4D geoelectrical monitoring system since 2008 to examine hydraulic precursors to movement. The landslide is an active slow to very slow moving multiple earth slide – earth flow with a mean slope angle of 14°, which typically exhibits movements of 1 – 2 m per year. To obtain reliable inverse geoelectrical models of the subsurface, it is vital that we know where the electrodes are located as a function of time. Currently we rely on repeated site visits to measure the positions of the electrodes in the known-active regions of the site by GPS, coupled with more frequent GPS monitoring of a series of sparsely distributed marker pegs, which are used to interpolate the positions of moving electrodes at intermediate times.

We report the development and testing of an inverse method, using a simplified forward model, to reconstruct the electrode movements in both surface directions on a geoelectrical monitoring grid from the time-lapse apparent resistivity data. The inversion technique was able to recover sequences of movement over short (days) to long (years) timescales. Comparing the reconstructed positions with GPS measurements indicated that the results were typically accurate to within 10 % of the electrode spacing, which was comparable with the accuracy obtained by interpolating marker peg locations. It was also sufficient to correct the majority of artefacts that occurred in the image reconstructions when incorrect positions were used. Over short timescales where the corresponding subsurface resistivity changes were smaller, the constraints could be relaxed and an order-of-magnitude better accuracy was achieved. This enabled the onset and acceleration of landslide activity to be detected within an accuracy of a few days.

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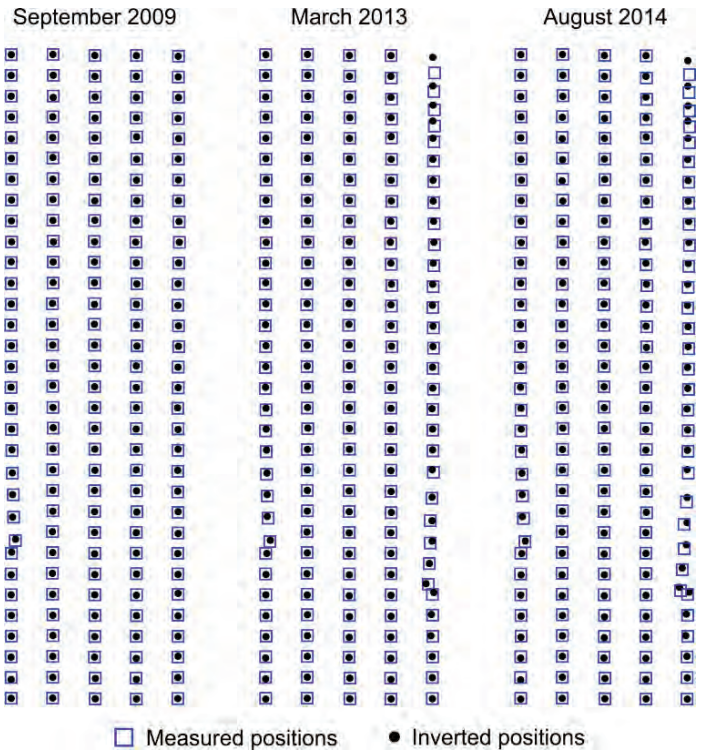

Figure 1 Comparisons of measured and inverted electrode positions

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12

Analysis of gravitational slope cycles by means of geophysical monitoring

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Since several years of studies on landslides, we realized the role and subtle interactions that existed between the structural complexity, masses dynamics and complex internal circulation of fluids. Thus, to gain a better understanding of the processes taking place during the evolution of an unstable slope, an observational study is necessary. In this perspective, our team currently monitors slow moving landslide zones. The aim of such a monitoring is to gain a better knowledge of the links between external forcing (meteorological, seismological) and signals going out of the slope (kinematic, vibrations, electrical resistivity). We present here two examples of instrumented landslides from several years.

The La Clapière DSL (Deep-Seated Landslide), at Saint-Etienne-de-Tinée village (Alpes Maritimes, France) is now very well known by the scientific community (volume, impact, challenges, observations...), but since 2007, the Versant Instabilities Multidisciplinary Observatory (OMIV, National Service of French Observation (SNO)) allowed the installation of permanent and autonomous (self-powered) measuring stations: GPS, meteorology, seismology, water chemistry sources. For three years now, a permanent electrical tomography line is installed at the bottom of the slope to complement the current monitoring system, and allowed a deeper understanding of the physical changes in the massif.

The sandy/clayey landslide named Pra de Julian, in the suburbs of Vence (Alpes Maritimes, France) has been instrumented from 10 years by our team. Since 2006, this unstable zone is equipped with a permanent ERT line. The daily acquisitions are now accompanied by continuous measurements from boreholes (thermometers, piezometers, tiltmeters) and pluviometry. All the data from these two sites are transmitted in near-real time to our lab.

The analysis of these large amounts of data over large time series allows observations of different dynamic regimes, as well as different response times to external factors: instantaneous, delayed, long-term variability. The purpose of this synthesis observational study is to analyze the temporal and spatial evolution of the apparent electrical resistivity, the displacement, the seismologic endogenous events, the hydrometeors variability and the links between these signals for these two study sites.

This new study explains the major role of the faults within the landslide, as well as the chronology of the water flow in the massif, inducing a delay between atmospheric solicitations and the movement itself. This allows a better understanding of the complex and uneven in time dynamic in such areas.

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GELMON 2015

Hydrology I

13

Resistivity assessment of an earth-filled dike with a permanent hydraulic head (Canal de Roanne à Digoin, France): 4D effects on 2D ERT monitoring

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Several geophysical and geotechnical techniques were tested on an earth-filled canal dike in the framework of a French research program (labelled DOFEAS). The aim of this program was to test the ability of geophysical techniques, first, to image the body of the dike and to detect weak zones associated with known leakages and, second, to monitor the evolution of geophysical parameters (mainly electrical resistivity) with time in relation with the evolution of water circulation and internal erosion. The chosen site is an earth-filled dike (3 to 4m high) relying upon Jurassic marly limestones. The dike contains a permanent hydraulic head and exhibits 2 leakage zones in the study area. Repair works, conducted after the canal was emptied, allowed to visually identify the seepage entries (a few tens of cm each in diameter) within the canal. Drillings, in situ and laboratory tests allowed to build a hydrogeotechnical model of the site. Probes were installed in boreholes to monitor the water table variation over time. Active geophysical experiments including seismic refraction and tomography (P- and S-waves), surface wave inversion (SWI) and electrical resistivity tomography (ERT), were used to characterize the geometry of the sub-surface. Concerning the time-lapse ERT survey, 128 electrodes, spread each 1 m, were permanently installed on the dike crest. Measurements were conducted using a Wenner-Schlumberger protocol (around 3600 measurements). 7 sequences were acquired during 2 months prior, during and after repair works. These works induced variations in the water level within the canal. The combined effects of the complex 3D geometry of the dike and of the varying water level were numerically determined to correct the geometric factor k. Compared to the analytical k, the geometric factor corrected from the topographic effects induced complex resistivity variations between 8 and 18%, depending on the electrode spacing but also on the water level into the canal. Furthermore, numerical simulations also showed that, depending on the water level into the canal, the electrical current density within the dike could also be affected by a factor of up to two. This indicates that a more or less important part of the measured resistivity carries information which originates from the water. However, a full 3D correction of the measured apparent resistivity would require to know the 3D resistivity distribution within the ground.

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The time-lapse inversion of the ERT data allowed to locate the main pipe within the dike, at a depth of around 3.4m, just above the interface between the bedrock and the dike body. This location was in agreement with the visual location of the seepage. Corrected resistivity were found to be more realistic than with the analytical k factor and allowed a better detection of the main pipe. However, the second and smaller pipe was not detected, probably because of a too low contrast.

These results confirm the applicability of calibrated geophysical techniques for assessing earth dike geometry. They also suggest that the correction for the 3D to 4D effects provides a better detection of anomalies (i.e. seepage pipe) evolving with time.

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GELMON 2015

14

Monitoring water saturation in earth levees with a customized resistivity system

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This work rests on the assumption that a resistivity meter can effectively monitor the level of water saturation in earth levees and can be used as a warning system when this level exceeds the expected seasonal maxima. The potential of this method to diagnose critical areas where seepage is exceeding a safe level and consequently the structural collapse risk is growing was preliminary validated at the startup of the project by performing time-lapse ERT tomographic measurements on a real site where a short segment of a levee affected by a well-known critical seepage was regularly controlled by the local authority managing the irrigation infrastructures.

Preliminary time-lapse measurements with a commercial resistivity meter were also performed on some other sections of the artificial water canal to evaluate the impact of temperature oscillations on resistivity maps and to select the most interesting site for the installation of a customized pre-commercial resistivity meter. Results show that temperature oscillations have no significant impact below one meter. Although the top meter of the levee is above the target depth, a temperature correction algorithm has been implemented based on resistivity-temperature relations reported in literature that seem consistent with our observations. For the installation of the permanent monitoring system, we selected a segment of the irrigation canal which, according to ERT maps, is apparently highly saturated during the irrigation season although the internal sides of the levees were grouted to protect the structure from erosion and excessive seepage. A further reason for monitoring this site consists of its location within a small village which would increase the impact of a structural collapse compared to other critical sites where flooding would affect only the agricultural fields.

The preliminary measurements with the commercial system were very useful to draft the specifications of the new monitoring equipment. Commercial resistivity meters have specifications, performances and costs that are largely beyond the needs and the affordable costs for this specific application on artificial canals. By customizing the equipment according to the required investigation depth, lower than 10m, and to the measured current and voltage ranges observed on these earth embankments, proper electrical components can be selected with remarkable savings.

The final arrangement of the pre-commercial system consists of a new resistivity meter piloting a spread of 48 stainless steel plate electrodes (20x20cm) that were buried in the middle of the levee cross-section by excavating a half-meter deep trench. Electrode spacing is 1m and the measurement configuration is Wenner. A dielectric rodent-resistant casing protects the cables.

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A weather station equipped with air and soil temperature sensors, hygrometer, rain gauge, ultrasonic water level sensor and TDR (1m deep) was installed in order to analyze the correlation of apparent resistivity with temperature, rainfalls and water level seasonal variations and to calibrate a resistivity-moisture conversion curve.

Both weather station and resistivity meter use cellular modems to transmit data to the control room where a dedicated prototype software performs quality control, displays resistivity maps, compares time-lapse measurements, updates measurement parameters such as injection current, injection time, stack number, minimum voltage, measurement interval, etc..

After the deployment of the permanent prototype system, the commercial resistivity meter was still used several times to compare the measurements and to validate the new equipment. Considering the small difference in electrode depth, results from the two arrays are fairly consistent.

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GELMON 2015

15

Time-lapse ERT of water infiltration in the context of soil aquifer treatment

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Global concerns such as climate change and population growth make soil aquifer treatment (SAT) an important and likely increasingly used technology for water and wastewater purification and storage. SAT means the cyclic infiltration of pre-treated wastewater in ponds for further treatment within the vadose zone. The Shafdan site in Israel is one of the largest SAT facilities in the world. However, it is approaching its limits due to increasing amounts of wastewater. Our study investigates the infiltration process in association with SAT with regard to improving its efficiency using time-lapse electrical resistivity tomography (ERT) in combination with hydrological methods. Therefore, we equipped one selected infiltration pond close to the city of Yavneh, south of Tel Aviv, with three ERT lines, each containing 96 electrodes. The electrodes are separated by 0.5 m in two of the profiles and 2 m in another profile. ERT monitoring was performed every hour over a time period of almost two month in spring/summer 2014 for different infiltration scenarios. The averaged apparent resistivity data show a clear response over time which can be related to the overall water content dynamics in the vadose zone. Already the raw data shows that ERT is able to track the water infiltration under very high fluxes. The inverted difference images of the electrical conductivity show nicely the spatial water movement close to the surface and with increasing depth of the profiles. They indicate that the infiltration is affected by subsurface heterogeneity. By analyzing the transient behavior of the drying curves derived from the time-lapse ERT images, we are able to characterize the heterogeneity in a hydraulic manner. The study shows that time-lapse ERT helps to better understand the dynamics of water infiltration processes in the context of SAT.

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GELMON 2015, Vienna, 24.-26.11.2015

GELMON 2015

16

Tracer moment tracking and forecasting in time-lapse electrical resistivity tomography

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Quantitative analysis of ERT investigation and monitoring images can assist in the interpretation of shallow subsurface physical properties and processes. Regions of contrasting electrical properties can be automatically identified using machine vision and computational imaging techniques. Feature extraction allows for the identification of distinct resistive regions representing the underlying structures. In time-lapse monitoring, using 2-D and 3-D ERT imaging, these approaches can be used to identify ongoing changes to the imaged volumes.

In experiments where a saline tracer is monitored over a time-series of ERT images, the tracer plume can typically be distinguished as a region of low resistivity against the background. This study looks at combining quantitative properties of the tracer plume, automatically extracted from inverted resistivity images, with motion models to track and forecast fluid flow. Due to issues of resolution and smoothness resulting from the inversion process, a level of uncertainty is present in the ERT images. This is also true of the mathematical models used to describe the dynamic systems, and so in combining them with the ERT, the detected results can be used to correct the model, while the model allows accommodation for error in the detections.

It has been possible to use the spatial distributions of detected tracer regions to create a semi-axial representation of centralised second-order tracer moments. A Kalman filter-based approach is used to match the detected regions between time-steps using motion models and tracking information, which allows forecasting of the proceeding tracer movement. This also enables a robust handling of the artefacts present in ERT, as well as other regions-of-interest, in the automated detection scheme. Independent tracks are maintained for each distinct contrasting feature and where these deviate from the expected motion models, they are discarded as part of the ongoing tracking system. The results show the effectiveness of this approach in tracking and predicting tracer motion through a system, as guided by mutual validation of model and observation.

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GELMON 2015

CO_2 Monitoring

17

Technical and methodological requirements for a permanent downhole geoelectrical measurement system as CO2 monitoring tool – A review from the Ketzin pilot site

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At the Ketzin pilot site, Germany, electrical resistivity tomography (ERT) is part of a multi-disciplinary geophysical monitoring concept, which has been established in order to image CO_2 injected into a saline aquifer (Martens et al., 2015). Since more than seven years, a borehole electrode array is operated as a permanent reservoir monitoring tool for continuous ERT measurements. This so-called vertical electrical resistivity array (VERA) consists of a behind-casing installation of permanent electrodes in three Ketzin wells and is used to conduct highly frequent crosshole ERT measurements and periodic surface-downhole surveys (Schmidt-Hattenberger et al., 2014; Bergmann et al., 2012). The VERA system is deployed in the depth range of 590-735 m with 15 electrodes per well (electrode spacing of 10 m), covering the reservoir formation (depth 630-650 m) and parts of the adjacent formations. On the basis of this long-term application, the review presents the technical and methodological requirements for a ERT system in order to perform successful CO_2 plume imaging.

Since 2008, the VERA system has accompanied all stages of the CO_2 storage operation: (1) Start of injection and detection of CO_2 arrival at the observation wells, (2) intermediate phases of reduced injection rates as well as shutdowns due to technical operations, and, since August 2013, (3) the injection stop and its subsequent post-injection phase. In addition, ERT monitoring was also performed for a controlled CO_2 back-production test as well as a brine injection experiment, both of which were conducted in the context of potential remediation techniques for CO_2 storage sites. During all of these operational phases, ERT measurements aimed at resolving the various reservoir processes of relevance and were, therefore, demanded to provide sufficient flexibility regarding temporal and spatial data acquisition. Advanced numerical tools, which allow for an improved pre-processing, efficient time-lapse inversion, and an integration of further types of monitoring data into the imaging process, have been established. Moreover, integration with operational injection data, petrophysical relations, and well logging data has been performed, leading to valuable interpretations on ongoing reservoir processes and estimated CO_2 saturation levels.

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From a technical point of view, the ERT array components, i.e. electrodes, multi-conductor cables, centralizers, and insulated casing pipes are discussed in view of cost aspects, capability for downhole installation, and durability under demanding subsurface conditions. Regular contact resistance checks provided useful information about the fidelity of the subsurface electrodes, particularly with regard to the detection of possible degradation effects. Given the long-term CO_2-brine exposition, some 7 electrodes (out of the 45 electrodes in total) have been identified to have technical issues, such as damaged or degraded cable break-outs.

Finally, we conclude the multiple benefits of using permanent ERT downhole arrays for monitoring the CO_2 storage operations. Experiences from further pilot-scale applications are deemed necessary in order to advance the presented ERT monitoring technology towards industrial scales.

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GELMON 2015

18

Insights on CO_2 migration by means of a fully-coupled hydrogeophysical inversion

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Permanent crosshole electrical resistivity tomography has received consideration as a powerful and cost-effective tool for continuous monitoring of CO_2 storage reservoirs, as the electrical subsurface properties are highly sensitive to fluid substitution processes. In conventional approaches, geoelectrical data sets are collected at specific points in time and processed independently. Obtained tomographic images can then be used to derive information on the spatiotemporal development of CO_2 saturation. While this approach has proven its feasibility and practical value at several test sites worldwide, it suffers from the common merits of ill-posed tomographic inversions and strongly depends on data quality, data coverage, and regularization constraints. We circumvent the need for repeated geoelectrical inversions by directly feeding the entire time-lapse ERT data into a fully-coupled hydrogeophysical inversion in order to constrain a multi-phase flow simulation of the CO_2 storage reservoir at Ketzin, Germany. Modeled changes in CO_2 saturation are translated to changes in electrical resistivity, honoring an experimentally determined petrophysical relation, and subsequently used for geoelectrical forward modeling. Transport relevant parameters of the Ketzin reservoir are then estimated based on an iterative comparison between measured and simulated apparent resistivity curves.
Finally, we integrate our results with other observational data including hydraulic pumping tests, CO_2 arrival times, and pressure observations and discuss their individual sensitivities on the estimated parameter distribution.

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GELMON 2015

19

Surface-downhole geoelectrics for post-injection monitoring at the Ketzin pilot site

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The Ketzin pilot site in Germany represents Europe's longest operating on-shore CO_2 storage site. From June 2008 till August 2013, a total of ~67,000 tonnes of CO_2 were safely stored in a saline aquifer at depths of 630 m to 650 m. Within the national project "CO_2 post-injection monitoring and post-closure phase at the Ketzin pilot site" (COMPLETE), the storage site has now entered the abandonment phase. Continuation of the multi-disciplinary monitoring provides the unique chance to participate in the conclusion of the complete life cycle of a CO_2 storage site.

The geoelectrical surveillance concept at the Ketzin pilot site consists of permanent crosshole measurements and non-permanent large-scale surveys (Kiessling et al., 2010). During the CO_2 injection, a continuous series of weekly crosshole data were measured at near-wellbore scale. These data were complemented by six surface-downhole surveys at a scale of 1.5 km. In the derived time-lapse geoelectrical tomographies, a noticeable resistivity signature within the target storage zone was observed, which was attributed to the CO_2 plume (Schmidt-Hattenberger et al., 2011) and interpreted in terms of the relative CO_2 and brine saturations (Bergmann et al., 2012).

Analysis of the previous surface-downhole measurements have shown that these can extend the imaging volume for monitoring the CO_2 plume and brine interaction in the near-wellbore area. However, resolution was limited due to the sparse acquisition geometry of 16 surface dipoles deployed on two concentric circles. A key task within the COMPLETE project is therefore the further development and verification of optimized surface-downhole acquisition geometries offering efficient and flexible operational performance without compromising image quality.

Synthetic modeling studies of a sparse array of surface electrodes have been conducted with particular focus on (i) optimized surface-downhole acquisition geometries and efficient data processing, (ii) improved resolution within the target storage zone and (iii) quantitative constraints on the lateral extent and the detection limit of CO_2 within the target storage zone.

One important aspect of developing an optimized surface-downhole acquisition geometry is the deployment of a permanent set of surface electrodes at the injection site, which will allow for regular current injections without the demand of an extensive field survey. In particular, which geometries provide a compromise between the costs, operational performance, broad azimuthal coverage and resolution within the target storage zone? Another important aspect of the synthetic modeling is the application of the optimized surface-downhole acquisition geometries to other test sites, in particular if only a single well is available for downhole data acquisition.

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In the future, it is planned to evaluate the results of the synthetic modeling using real data from additional surface-downhole measurements from the Ketzin site. This will allow for further improvement of the adapted processing, time-lapse interpretation and integrative evaluation of the deployed optimized surface-downhole acquisition geometries.

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GELMON 2015

Infrastructure Monitoring

20

Proactive infrastructure monitoring and evaluation (PRIME): a new electrical resistivity tomography system for remotely monitoring the internal condition of geotechnical infrastructure assets

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We describe the development of a new low-cost, low-power, electrical resistivity tomography system (PRIME - Proactive Infrastructure Monitoring and Evaluation), designed particularly for the remote monitoring of infrastructure earthwork assets. PRIME is designed to provide continuous near-real-time information on the internal condition of the earthworks, helping to predict failures and enable timely intervention. Conventional asset monitoring involves examining the surface (either by people on the ground or from aerial photos) and using point sensors, such as moisture content and tilt meters, which only give information in the immediate vicinity of the sensor. But PRIME will use imaging for the volumetric tracking of moisture content changes and the detection of ground movement, thereby identifying problems at a much earlier stage.

The development of PRIME is driven by the increasing rate and severity of infrastructure earthwork failures. This is due to aging assets (many canal and rail earthworks are over a hundred years old) and more extreme weather events (e.g. the extreme UK rainfall during winter 2013-14). Asset failures are enormously expensive, costing hundreds of millions of pounds per year in the UK alone, not to mention risks to human health and disruption of services, transport systems and the wider economy. There is growing recognition among asset owners, managers, and consultants that remote monitoring technologies have the potential to reduce these costs and risks by providing continuous condition information and early warnings of failure.

To this end, PRIME hardware has already been successfully developed and is being demonstrated on two test sites within the railway and canal networks respectively: the first system has been installed on a railway cutting, which has been affected by instability; the second system is being used to monitor a leaking canal embankment. Here we describe the system architecture of the new monitoring instrument, system installation and operation, and the monitoring results from the two sites. In particular, we discuss the automation of the data processing and interpretation workflow, including data filtering, electrode displacement tracking (using the measured resistivity data), inversion, and automated image analysis (using computer vision approaches).

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The goal of this work is to produce an integrated monitoring instrument and information delivery system – which operates automatically with minimal manual intervention - that can volumetrically track infrastructure asset deterioration and provide early warning of potential failure events.

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GELMON 2015

21

Geoelectrical Imaging of Moisture Dynamics in Engineered Slopes

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Understanding construction quality and state of embankments used for road and rail infrastructure is critical in the effective management and maintenance of our transport network. Future climatic changes are predicted to lead to up to 20% more precipitation (with strong increases in winter), more flash floods, and drier summers. These environmental changes will have inevitable consequences for the serviceability and maintenance of our engineered infrastructure. Yet, current assessment of asset condition is mainly informed by failure events and remediation measures initiated in response to emergencies. New intelligent platforms and science to monitor current embankment state and risk are required, to enable proactive remediation before failure occurs.

Electrical resistivity tomography (ERT) is a geophysical technique that is sensitive to lithological and mineralogical heterogeneity and changes in ground temperature and soil moisture content. When corrected for temperature changes, repeated resistivity measurements employing permanently installed electrodes will highlight changes in moisture content over time.

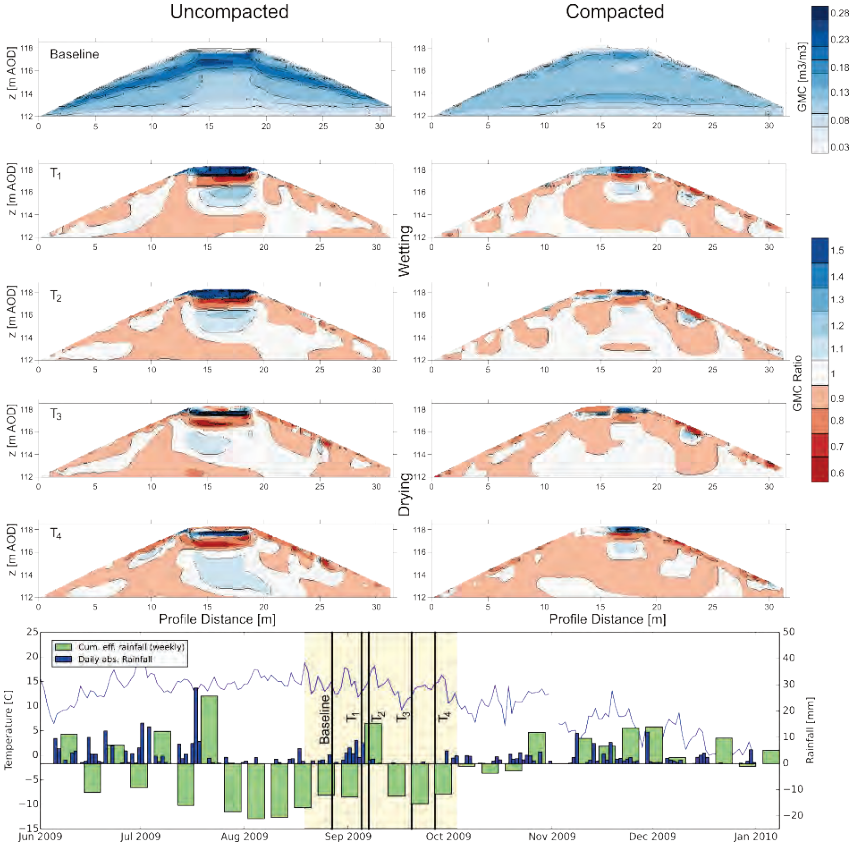

Figure 1 (Top) Baseline GMC data sets for the compacted (left) and (right) uncompacted panel. Below, images of GMC ratio between data sets acquired at different dates and the baseline data set. Note the deeper moisture penetration in the uncompacted panel.

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Therefore, ERT monitoring can be used to image moisture movements in slopes, giving information about accumulation and drainage areas, as well as preferential flow paths. This provides a tool to assess the hydrological state of an embankment, which can be used as an indicator for its geotechnical state.

We compare ERT monitoring data acquired on a section of the BIONICS research embankment, which was built according to modern Highways England specifications, with data from a section representing the building standards of Victorian railway embankments (i.e. poor compaction). These sections show distinct differences in moisture movements and penetration, highlighting an accelerated weathering impact for the poorly compacted section. Thus, the embankment compacted to standard levels will show slower deterioration than historic structures, resulting in a longer life time and lower whole-life-costs.

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GELMON 2015

22

Long-term Geophysical Monitoring for Leakage Problems at Reservoir Dams, Republic of Korea

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Dam safety has increased in importance all over the world due to the recent failures that have occurred and the increased consciousness among the people and society and media interest. In Korea, The safety assessment of earth fill dams has been dealt by Korea Rural Community Corporation(KRC) largely. Most of them are worried about the safety due to the deterioration and seepage because the many reservoirs and embankments were built more than half a hundred years ago. The seepage rate depends mainly on the hydraulic conductivity of the core which is strongly dependent upon the core material and its compaction. The identification and investigation of internal erosion is by visual inspection, pore-pressure measurements and measurement of seepage water volumes in dikes below the dam. It is crucial for dam safety to be able to detect condition of dams, in part for safety reasons, dams need to be inspected and monitored regularly. Supervision and regular monitoring of the dams impoundment with suitable techniques are probably the most important requirements to obtain a high level of dam safety.
The use of geophysical techniques is generally appealing due to their non-destructive and often cost-effective advantages over other methods. Geophysical methods may thus play important roles in monitoring the integrity of the dam and detecting anomalous seepage conditions on the dams at the early stage of their development. Resistivity monitoring has been performed at a reservoir dam in Korea. The data were collected by a Resistivity monitoring automatic data acquisition system that was developed by KRC. SP monitoring has been performed at sea dike on the Korean peninsula. The data were collected by a SP monitoring automatic data acquisition system that was developed by KRC. The number of sea dikes is 190 facilities and SP monitoring systems have been installed to the number of 47 sites now in Korea. At sea dikes, the target of my study, the leakage flows should be strong enough to generate appreciable SP anomalies, particularly where the tidal change is significant. During the SP monitoring at a sea dike, the measurements of sea level, conductivity and temperature are gathered at the same time. The primary purpose of long-term geophysical measurements in this study is the dam safety assessment by inspecting anomalous seepage zones and, if possible, quantitative estimation of seepage amount. Electric resistivity survey has proven successful to get information of internal resistivity structure of dam associated with material inhomogeneities and water saturation. SP data have important information about streaming potentials associated with seepage flows through a sea dike if a good tool is used for analyzing SP monitoring phenomena with tide.

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GELMON 2015

23

Successes and challenges of geoelectrical monitoring at Sellafield, UK – a retrospective

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A challenging field experiment applying 4D cross-borehole Electrical Resistivity Tomography (ERT) to the monitoring of simulated subsurface leakage has been undertaken at a legacy nuclear waste silo at the Sellafield Site, UK. The experiment constitutes the first application of geoelectrical monitoring in support of high-hazard decommissioning work at a UK nuclear licensed site. Images of resistivity changes occurring since a baseline date prior to the simulated leaks have revealed likely preferential pathways of silo liquor simulant flow in the vadose zone and upper groundwater system. The geophysical evidence was found to be compatible with historic contamination detected in permeable facies in sediment cores retrieved from the ERT boreholes. Our results suggest that laterally discontinuous till units forming localized hydraulic barriers can substantially affect flow patterns and contaminant transport in the shallow subsurface at Sellafield. We conclude that only geophysical imaging of the kind presented here has the potential to provide the detailed spatial and temporal information at the (sub-)metre scale needed to reduce the uncertainty in models of subsurface processes at nuclear sites.

Amongst the many achievements of this work since 2009 has been the full acceptance of geoelectrical monitoring by the UK nuclear industry and the recognition of its value as a tool for environmental site assurance within the safety case for decommissioning. Our work has directly led to the endorsement of 'Technology Readiness Level 6' by Sellafield Ltd for future use on the UK nuclear estate.

Further advances arose from a detailed consideration of the effects of the long monitoring periods required to support nuclear decommissioning (25 years and more). Geoelectrical arrays that, once installed in permanently grouted boreholes, cannot be retrieved or replaced due to the immense cost and logistical effort associated with drilling at Sellafield.

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Results of a study of advanced alternative electrode materials suggest that, besides aqueous metallic corrosion, the formation of surface scales is the principal mechanism responsible for the deterioration of stainless steel sensor performance over time. Novel sensors with noble metal coatings displayed outstanding properties and easily surpassed the performance of stainless steels. Stability of these electrodes in all aspects was found to be remarkable and their susceptibility to ERT noise was only marginally greater than that of stainless steels. These observations are regarded as a milestone achievement for ERT methodology, as they open a new perspective on sensor longevity, providing a real design alternative where contact resistance growth is a threat to the long-term viability and cost-effectiveness of geoelectrical monitoring.

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24

Time-lapse resistivity measurements in an undermined area (case study of Dětmarovice, Czech Rep.)

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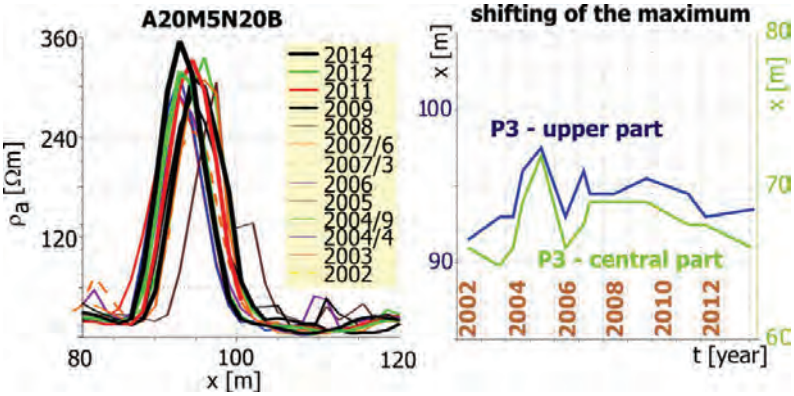

Two electrode distances of symmetric resistivity profiling were used within field measurements in an undermined area, affected also by slope processes (Dětmarovice area – Czech Republic). The results of used deeper measurement range (A20M5N20B), i.e. with estimated real depth range of 10-15 m, are presented in the figure. The figure shows a relocation of the maxima of resistivity anomalies. The left graph of apparent resistivity indicates that location of the maximum of resistivity anomaly is significantly changing. The anomaly was detected at the toe of the slope deformation; however, we cannot assume that fossil landslide, or even active landslide, could cause such resistivity changes. At the toe of slope deformation, we cannot expect tensile stress, which could cause increase of apparent resistivity. A difference of anomalous values reaches ca. 260 – 330 Ωm, compared to surroundings, thus it is higher by orders than surrounding resistivity field. Considering the fact that this anomaly is more significant with use of deeper array than with the one of shallower geometry (A5M5N5B), we have to search for its explanation among processes, which run in deeper parts of rock massif. Firstly, we have to examine possible effects of changes induced by undermining and to investigate the processes that can originate during formation of a subsidence basin. On the right part of the figure, we can observe a relocation of the maximum of the resistivity anomaly in time. Similarly to other processes, resistivity changes in subsidence basin are not monotonous. A time course of the shift of the maximum is uneven with rapid changes in its position. Another phenomenon, discovered within repeated geoelectrical measurements, is the existence of time-limited anomalies. We would like to remind that it concerns processes within the rock massif, not on its surface or within the near-surface layer. At the moment of detection of such anomaly, we did not find out its geological explanation. Measurements during next phase showed that the anomaly did not last for a long time. However, it was a unique case; therefore this fact remained out of our interest.

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Finding of another similar anomaly at locality Ujala I finally attracted our attention. Searching for its explanation contended with the fact that such anomalies occur only with use of deep-range geometry of measurement. No such anomalies were found in near-surface layers. A character of the survey did not enable us to perform field measurements in sufficiently short intervals to be able to describe genesis of the anomaly, its time course and termination. Firstly, we supposed that the anomalies could have been related to tensile zones of newly formed slope deformations. Other anomalies were, nevertheless, detected far from the areas of possible landslide origin. Such explanation is, thus, low probable. We have to search for a connection with other processes running inside the rock massif. Time-limited resistivity changes related to the changes of groundwater regime represent one of the possibilities. We suppose that groundwater level variates in time within individual rock blocks or, alternatively, preferred pathways of groundwater change. Another possible explanation is an effect of tension zones originated in relation to a formation of subsidence basin. In the presented study, we would like to perform the results of repeated geoelectrical measurements by means of symmetric resistivity profiling. The repeated measurements in the area highly affected by deep mining of black coal (besides the influencing by mass movements) showed that the apparent resistivity field is not constant in time. Some of the anomalies change their location both “upslope” and “downslope”. Other anomalies are time-constrained and we registered them either in single case or, some of them, in more than one moment. We have not succeeded in exact explanation of such processes yet. We suppose that they can be provoked by changes caused by dynamic processes related to the changing situation of slope deformations or with processes connected with development of subsidence basin. These changes can also affect groundwater regime.

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Monitoring of Landslides II

25

Permanent electrical resistivity measurements for monitoring water circulation in clayey landslide

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Landslides developed on clay-rich slopes are controlled by the soil water regime and the groundwater circulation. Spatially-distributed and high frequency observations of these hydrological processes are important for improving our understanding and prediction of landslide triggering. This work presents observed changes in electrical resistivity monitored at the Super-Sauze clayey landslide with the GEOMON[4D] resistivity instrument installed permanently on-site for a period of one year. A methodological framework for processing the raw measurement is proposed. It includes the filtering of the resistivity dataset, the correction of the effects of non-hydrological factors (sensitivity of the device, sensitivity to soil temperature and fluid conductivity, presence of fissures in the topsoil) on the filtered resistivity values. The interpretation is based on a statistical analysis to define possible relationships between the rainfall characteristics, the soil hydrological observations and the soil electrical resistivity response. During the monitoring period, no significant relationships between the electrical response and the measured hydrological parameters are evidenced. We discuss the limitations of the method due to the effect of heat exchange between the groundwater, the vadose zone water and the rainwater that hides the variations of resistivity due to variations of the soil water content. We demonstrate that despite the absence of hydrogeophysical information for the vadose zone, the sensitivity of electrical resistivity monitoring to temperature variations allows imaging water fluxes in the saturated zone and highlighting the existence of matrix and preferential flows that does not occur at the same time and for the same duration. We conclude on the necessity to combine electrical resistivity measurements with distributed soil temperature measurements.

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26

Clustering the apparent electrical resistivity data of permanent ERT monitoring

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Landslides have been studied for several years thanks to electrical resistivity tomography (ERT). This technique allows to image the internal structure and discontinuities of the land-sliding bodies (fractures, layers, base…). The dynamic of such objects is mainly influenced by fluidification phenomena of the medium, mostly due to meteorological precipitations (high rainfall regime, snow melt). Water infiltration then plays a key role in the dynamic of landslides.
Furthermore, we know since Archie's works (1942) that resistivity data are influenced by water content of the investigated soil. The ERT acquisition then help to evaluate and understand the water content within the studied slope.
In this work, we use apparent resistivity data (to avoid inversion uncertainties) from two monitored landslides in the French Southern Alps (La Clapière rockslide and Vence landslide). Permanent electric lines have been installed for many years now on the two unstable slopes (3 and 9 years respectively). This has permitted us to (1) identify different internal areas within the ERT profiles (surface, base, aquifers, faults…) and (2) observe and appreciate fluids' flows between the interpreted areas. To do so, a separation had to be made between the apparent resistivity data in terms of values (conductive Vs resistive) and variability (stable Vs changing) for each point of daily pseudo section.
Associated with the stability changes recorded on these moving areas, we looked at the signals of these different clusters corresponding to different areas of the ground. From this, we observed a decoupling between a shallow and a deep signal, responding with a certain delay to atmospheric solicitation (rapid and delayed respectively). Infiltration time has to be invoked here to explain this difference. We also show that landslide's movement accelerations are associated with changes in the signal of the deeper cluster.
In this study, we observe the interactions that exist between masses dynamics and complex internal circulation of fluids. This new study images the major role of the water flow in destabilization of a massif. This allows a better understanding of the complex dynamic of such problematic objects.

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27

Evaluation of 2-year TL-ERT monitoring of a landslide (case study of Čeřeniště, Czech Rep.): towards understanding precipitation, saturation and resistivity changes.

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Presented contribution is aimed at present progress in application of a complex geophysical and geotechnical monitoring of the active slope deformation Čeřeniště (České Středohoří Mts.). Čeřeniště landslide is situated in the České středohoří middle-mountains (Czech massif) and belongs to the Czech Tertiary Neovolcanites. The main scarp of the studied landslide as well as toppled ridges, forming the upper part of the complex slope deformation, are - according to our geophysical survey - predisposed by tectonic structures and further affected by deep-seated gravitational processes (spreading, toppling). Central part is formed by a large platform which is followed by an active flow-like landslide composed of weathered colluvium. The main goals of the long term monitoring of the Čeřeniště landslide are i) to describe dynamics of the complex slope deformation, and ii) to reveal a connection among predispositions (tectonics, lithology), triggering factors (extreme precipitations, soil humidity changes, long-term climatic oscillations) and landslide activity. For a description of a long-term landslide activity the geotechnical measurements of displacements by means of 3-D spatial dilatometers (TM-71 3-D optical-mechanical crack gauge) have been performed at the Čeřeniště landslide since 1998. Since August 2013, it has been successively complemented by (i) extensometric measurements, (ii) geodetic measurements and (iii) repeated laser scanning. In order to identify relations between triggering factors and landslide activity, the following techniques were established (in 2013) on the landslide: (i) time-lapse resistivity measurements, (ii) hydroclimatic monitoring (precipitation, air moisture and temperature) and (iii) pore-water pressure measurements. Variations in resistivity distribution are measured by means of electrical resistivity tomography (ERT). The time-lapse resistivity survey would serve as an effective tool which can yield information on subsurface water saturation and its changes and, also, it could help to reveal relations within the system „precipitation – subsurface saturation – mass movement activation“.

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Furthermore, using the monitoring of movement velocity based on repeated geodetic measurements we shall be able to determine the causal connection among precipitations, soil saturation and (re)activation of mass movements. Last but not least, the studied locality serves also as a testing site for the repeated resistivity measurements in terms of i) measuring parameters optimization, ii) different electrode configurations testing, iii) data processing optimization. Research was supported by following grant projects: IRSM internal project no. 2015/505 and GAUK 862213.

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Monitoring of Contaminated Sites II

28

First leachate injection monitoring in farm scale solid state anaerobic digestion plant by electrical resistivity tomography

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Anaerobic digestion (AD) has a high growing potential worldwide due to its combined environmental benefits such as reducing greenhouse gas, producing renewable energy, organic amendment and fertilizer. In France, 400 plants were recorded in 2015 which mainly handle agricultural residues using both liquid and solid state processes. The successful and efficient degradation of organic matter in AD needs balanced physical-chemical conditions for microbial development. Moisture content in the media, particularly, was found to be of great importance. Nevertheless, no information is available on the hydrodynamics of the circulation of the leachate through cattle manure or other agricultural residues. Moreover, agricultural residues and mixtures are particularly porous and heterogeneous and no data was found on the efficiency of those systems to humidify homogeneously such a substrate.

The hydrodynamic flow characteristics and transfer time of the leachate are essential to design the optimal liquid injection system that will permit to reach uniform moisture content. Already applied in landfills for in-situ characterization of leachates flow through municipal solid waste (MSW), ERT was proven to give reliable results. The results led to the enhancement of the leachate injection system design and enriched the knowledge of MSW behavior. The non-intrusive, non-destructive and 3 dimensional response of the ERT method seems adapted to the study of the leachate infiltration through agricultural effluents in a SSAD plant. We present the first results of the use of 3D time-lapse electrical resistivity tomography performed during a leachate injection in a waste deposit cell in France (20 m3 of leachate was injected during 10 h). 72 electrodes and a Syscal PRO resistivity meter was used. For the inversion, the apparent resistivity have been interpreted taking into account (i) the boundary condition of the waste deposit cell (insulating boundary around the waste deposit cell) and (ii) the effects of temperature (indeed between the surface and the bottom of the waste deposit cell , we measured the variation of temperature in the range of +/-25 °C). The result highlighted the conductive character of this porous media with a resistivity included between 0.5 ohm.m and 10 ohm.m depending on the saturation state; we will show that the infiltration is clearly located by electrical resistivity tomography and that this media is very heterogeneous with complex infiltration shape. The first results suggest the interest of the 3D electrical resistivity tomography to study injection leachate injection in a SSAD plant.

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29

Laboratory tests using electrical resistivity monitoring to study biogas and leachate migrations in waste mass

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Waste management is a major issue in France controlled by strict rules to guarantee the reduction of the toxicity of the waste and to limit the impact on the environment and on the human health. The storage is the oldest waste treatment used by the operators and it must be considered as an industrial process when we observe the technologies and the management tools applied.
Biodegradation of Non-hazardous household waste is mainly controlled by two key parameters: moisture content and temperature. Whereas temperature is impossible to modify by any process economically profitable, moisture content can be modified by liquid reinjection in waste mass. This technic of leachate recirculation is associated to "bioreactor landfill" where horizontal pipes or wells are used to achieve this goal. For industrial operators, the objective is to find techniques of measurement to evaluate at large-scale, the diffusion of leachate in the porous medium. Among the geophysical methods available, the electrical resistivity tomography (ERT) has demonstrated its potential. The leachate recirculation events are considered as short periods of time compared to the kinetic of waste biodegradation or to the evolution of their mechanical characteristics. This assumption allows to associate electrical resistivity variations recorded to moisture content modifications. Whereas increasing of moisture content is linked to decreasing of electrical resistivity, positive variations of resistivity have been often observed and attributed to artefacs of inversion process or to a potential effect of biogas migration, which is the aim of this study.
Laboratory tests have been conducted in order to follow the evolutions of electrical resistivity measurements for various conditions of saturation and drainage of waste mass and variations of biogas pressure. Waste samples were collected before landfilling, and then shredded to 10 mm of diameter, mixed with water to achieve initial volumetric water content equal to 0.34 m3/m3 and compacted in a cylindrical cell of 0.220 m3 to achieve a density equal to 0.45.
Distributions of apparent electrical resistivity were recorded from 52 electrodes allowing 524 quadrupoles with current circulations mainly horizontal, vertical and diagonal. The inversion process used BERT software with cell geometry taken into account as well as an optimization of the inversion parameters carried out for the laboratory tests performed.

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Evolutions of electrical resistivity distributions were clearly observed for the different hydraulic conditions from dry state to saturation and the field capacity. At field capacity, the test cell was closed from the atmospheric pressure and the waste mass has been saturated progressively from the bottom to the top to increase the biogas pressure in the unsaturated waste. From laboratory tests, no variation of electrical resistivity was notified during the increase of biogas pressure, even for value around 0.300 bars, higher than the range of pressure recorded in landfill.

These laboratory tests were performed with no leachate flows and biogas migration which are the conditions of recirculation event in bioreactor landfill. Research works are in hand to continue the understanding of ERT monitoring results recorded during leachate flows or biodegradation of waste body.

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30

Development of a methodology to constrain hydrodynamic models by time-lapse ERT monitoring: Application to leachate flow into waste landfills

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Leachate recirculation is a key process in the operation of municipal solid waste landfills as bioreactors. To ensure optimal water content distribution, bioreactor operators need tools to design leachate injection systems. Prediction of leachate flow by subsurface flow modelling could provide useful information for the design of such systems. However, hydrodynamic models require additional data to constrain them and to assess hydrodynamic parameters.
Many studies have shown that time-lapse ERT monitoring is a suitable method to study infiltration flow into a porous medium at the field scale. It can provide spatially distributed information which is useful for constraining hydrodynamic models. However, this geophysical method does not allow ERT users to directly measure water content. To avoid the use of empirical petrophysical relationships for the study of infiltration flow by time-lapse ERT, Audebert et al. [2014] developed the MICS ("multiple inversions and clustering strategy") methodology, which is based on a razor-sharp delimitation of the infiltration area on the time-lapse ERT results.
The aim of this study is to propose a new methodology to constrain hydrodynamic models from the infiltration shape delimited by MICS on the ERT results. This methodology could improve the understanding of infiltration flow into porous medium, such as waste landfills.
Time-lapse ERT field data are used to estimate infiltration shape and volume affected by infiltration using MICS. Then the subsurface flow model is run using a wide range of hydrodynamic parameters. Finally, the range of hydrodynamic parameters is constrained to those for which the infiltration shapes obtained by subsurface flow modelling and extracted with MICS are in good agreement.
This methodology is applied to both single and dual continuum hydrodynamic models to compare their ability to reproduce hydrodynamic information obtained with MICS at the field scale and consequently to improve the understanding of leachate flow into waste porous medium. Finally, the constraint methodology has been developed in this study to improve the understanding of leachate flow into the waste porous medium. Future research could be considered in applying this methodology for the study of infiltration into porous medium, such as fractured medium for example.

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31

Geoelectrical monitoring of dense non-aqueous phase liquids with surface-to-horizontal borehole ERT

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Geoelectrical methods, particularly electrical resistivity tomography (ERT), have long been proposed to improve characterization and monitoring at sites contaminated with dense non-aqueous phase liquids (DNAPLs). However, ERT has not become a common tool for mapping such contaminants or tracking their remediation, due to the complexity of the DNAPL target coupled with the inherent limitations of traditional (surface and cross-hole) ERT configurations. Horizontal boreholes are being increasingly incorporated into remedial strategies at contaminated sites. This work presents a novel surface-to-horizontal borehole (S2HB) ERT configuration and explores the benefits and performance of 2D S2HB ERT (i.e., surface line to horizontal borehole) for mapping the spatio-temporal evolution of DNAPL mass during remediation. A coupled DNAPL-ERT model was employed to simulate a realistic, field scale DNAPL remediation scenario, and this initial theoretical evaluation demonstrated improved imaging of S2HB ERT over surface ERT, particularly at depth. A laboratory experiment was then performed to validate the S2HB ERT approach in a physical system involving a changing NAPL distribution over time. The experiment confirmed that S2HB ERT provides significantly improved monitoring of NAPL changes relative to surface ERT. Confirmation of the actual NAPL distribution was obtained by excavation of the tank at the end of the experiment, increasing confidence in the ERT responses. Independent simulation of the experiment with the DNAPL-ERT model also demonstrated that the model is a reliable tool for simulating real systems. Four-dimensional ERT inversion (applied to the 2D monitoring datasets) was employed throughout for both numerical and experimental data. Current work is investigating the S2HB ERT configuration in 3D mode (i.e., 2D surface grid to single horizontal borehole), with preliminary results again demonstrating the improved performance of S2HB ERT for time-lapse monitoring of DNAPL mass changes during remediation.

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32

3D time-lapse ERT monitoring of an experimental simulation of olive-oil mills' waste movement

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In this work 3D ERT was evaluated for the monitoring of a conductive saline tracer in a controlled experimental environment. This is part of a larger scale research project which aims to the study of the transfer mechanisms of the geoelectrically conductive olive-oil mills' wastes (OOMW) which can be a serious source of contamination in olive oil producing countries as they are being typically disposed to open ponds. The particular experiment was aiming into verifying the measurement, processing setup in order to be transferred into a real scale experiment. In the first place, some preliminary tests have taken place in a smaller scale tank (almost 2D) that formed the basis to design and execute a full 3D time-lapse ERT experiment in a larger scale using a bigger 1x1x1m tank.
Geoelectrical monitoring involved using a set of 6 boreholes as well as a single surface to horizontal borehole pair. Optimized 3D ERT data sets were obtained for every 100ml injection of the colored tracer into permeable sand surrounded by fine grained well compacted material. Data were processed using a 4D inversion algorithm. Subsequent excavation helped to evaluate the geoelectrical images. The resulted geoelectrical 4-D time-lapse images followed the movement of the saline tracer successfully and verified the applicability of the entire measurement set-up. Current work involves further processing of the geophysical data to extract hydrogeological parameters and create a model of the saline tracer flow and evaluate the applicability of ERT monitoring in this context.

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Hydrology II

33

4D ERT monitoring for the hydrological characterization of the rocky unsaturated zone

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In recent years geophysics is increasingly used to study the flow and transport processes in the vadose zone.
Particularly, when the vadose zone is constituted of rocks, it is very difficult to install sensors to measure directly hydrological properties of the subsurface. In these cases, Electrical Resistivity Tomography (ERT) could be an useful tool to monitor hydrodynamic of the infiltration and to predict some parameters such as water content and hydraulic conductivity, that affect the mentioned processes.
The study case describes a 4-D ERT monitoring of an infiltrometer test in order to provide a quantitative information about infiltration and redistribution of water in the rocky subsurface. The field activities have been performed in a quarry of sandstone near the town of Canosa, in the South Italy.
Infiltrometer test has been conducted for many hours at variable head condition using a metallic ring of 0.5 m in diameter, installed directly on the rock, poured with about 8 l of water. The falling of water levels has been measured by means a pressure transductor (PXT – DRUNK ENGLAND) and a metric rod connected to the ring.
Around the ring, 96 steel electrodes, 0.4 m spaced have been installed in a symmetrical position with respect to the center of the infiltrometer ring in order to image a true 3D electrical resistivity distribution of the subsurface. Three days time-lapse ERT monitoring allowed to collect more than 20000 data to obtain reliable geophysical model of the subsurface investigated.
In order to convert images of electrical resistivity in water content a specific calibration function, using four electrodes array, has been obtained in the laboratory on sandstone samples drilled in the same quarry.
The hydro-geophysical results have been supported by means a numerical model.

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34

ERT monitoring of the vadose zone of a karst system sounds like a challenge!

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Geoelectrical monitoring has proved its efficiency to provide valuable information in multiple contexts such as active landslides, landfills pollution, dam infiltration or permafrost melting. In other environments, such as karsts, ERT monitoring has not been broadly used.
In karst systems, the vadose zone plays an important role in the water dynamics. In particular, temporary perched aquifers can appear in the subsurface due to changes of weather conditions, reduced evapotranspiration and the vertical gradients of porosity and permeability. Seasonal water variations in the infiltration zone of a karst system should then be observable with ERT. Monitoring these variations may help separate the hydrological signature of the vadose zone from that of the saturated zone. This information is thus required for understanding hydrological processes that occur in a whole karst system. However, such hard rock environments can be very heterogeneous, which makes ERT monitoring quite challenging.
We present a case study where ERT monitoring is being used to track groundwater changes at the Rochefort Cave Laboratory (RCL), located in the Variscan fold-and-thrust belt (Belgium), a region that has many karstic networks within limestone units. Our investigations cover two years of hydrogeophysical monitoring.
The permanent ERT monitoring takes place on a daily basis and is composed of an unconventional combination of a 2D ERT profile with a pronounced topography, and a vertical borehole crosscutting the vadose zone. Recent work on ERT survey optimization applied to this specific case is discussed, and conventional surveys (e.g. dipole-dipoles) are compared with the optimized surveys. Data inversion is performed using BERT.
For validating the assumptions based on ERT data analyses of the RCL site monitoring, we are especially focusing on groundwater changes that can be correlated with microgravimetric monitoring installed at the same site, integrating both vadose and saturated zone signatures. Correlation with direct measurements of dripping within the underlying cave network is also investigated.

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GELMON 2015

35

Cost-efficient saltwater monitoring of a shallow aquifer using long-electrode ERT

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Saltwater intrusion is a threat to local groundwater resources in coastal regions but it appears increasingly inland as a result of natural or man-made changes in the hydraulic system. ERT is a well suited technique for monitoring saltwater but on a larger, three-dimensional scale significant effort is needed. Our recently finished research project used an approach that utilizes steel-cased boreholes as long electrodes to cover scales of a few hundred metres to kilometres. The effect of the casings is accounted for by the Shunt Electrode Model (SEM). Synthetic studies and sensitivity analyses show that typical intrusions can be resolved if differently long boreholes can be used and target-adapted parameterization and regularization are applied (Ronczka et al., 2015a).
We present monitoring data from a 500x300m sized test field in Eastern Brandenburg. Thirteen boreholes and 6 surface electrodes have been permanently cabled. An optimum array layout was measured every 3 months over a period of 2 years along with in-situ fluid conductivity measurements that enable a conversion of bulk resistivity into fluid salinity. The inversion result of a reference time step agrees well with the geology, with classic 2D ERT data and with the fluid samples that prove the existence of a saltwater body at the bottom of the aquifer. Furthermore, the temporal behaviour of the fluid salinity, i.e. a slight dilution of the intrusion, is reproduced even though the changes are very small (Ronczka et al., 2015b).

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GELMON 2015

36

Coupled hydrogeophysical modelling and ERT monitoring using pyGIMLi

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Among hydrogeophysical methods, Electrical Resistivity Tomography (ERT) is particularly suited for monitoring tasks as it represents a cheap and fast method resolving changes in fluid salinity. For analyzing the data, flexible inversion schemes are required that consider the specific circumstances and subsurface properties. Target is often the understanding of flow and transport processes that can be described by hydrological models. However, up to now ERT and groundwater modelling are two completely disjunct scientific fields which make a joint analysis of data or flexible experimental design impossible.

We present PyGIMLi – A Python Package for Inversion and Modelling in Geophysics, which is an open-source framework that provides tools for modelling and inversion of various geophysical but also hydrological methods. PyGIMLi uses complete Python bindings to the C++ class library GIMLi and includes generalized physical solvers and various tools for pre- and post-processing. The C++-library supplies runtime relevant numerical basics for forward simulation, inversion and discretization management and provides finite-element- and finite-volume-solvers for elliptic, parabolic and hyperbolic problems in 1D, 2D and 3D on arbitrary structured or unstructured meshes. The inversion is generalized and physic independent, solves the minimization problem with a Gauss-Newton algorithm and provides tools for analyzing uncertainty and resolution. More general requirements, such as flexible regularization strategies, time-lapse processing and the petrophysical or structural coupling of various geophysical methods are thereby held independently of the various methods. The BERT software package for resistivity modelling and inversion is a set of specialized applications that is completely based on the pyGIMLi package.

We show a synthetic groundwater modelling example where a saltwater tracer is injected into an aquifer under regional flow boundary conditions. Transport of the dense tracer is simulated using finitevolume-solver for a simplified Navier-Stokes equation and monitored by geoelectrics. We show how the whole simulation process is done within a few lines of scripting code. Furthermore, we demonstrate how the modeled and noisified data are inverted in different ways with the aim of deriving hydrogeophysical parameters from the ERT measurements.

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GELMON 2015

Poster Presentations

P01

Integrating electrical resistivity with multi-compartment sampler techniques to study heterogeneous solute transport in the unsaturated zone

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Soil and groundwater contamination is a major concern. Agriculture, industry, airport activities all have impact on the water quality. Soil heterogeneity, fingered flow and macropore flow cause solutes to spread out in time and space as they move downwards from the soil surface with infiltrating water. To improve risk assessment, monitoring, and treatment strategies, we require a better understanding of the effect of soil heterogeneity on contaminant movement and methods for monitoring the effects of this heterogeneity at contaminated sites. During this presentation, we will show a newly developed instrument, which combines multi-compartment sampling with electrical resistivity measurements.

Solute monitoring is often limited to observations of resident concentrations, while flux concentrations govern the movement of solutes in soils. Bloem et al. (2010) developed a multi-compartment sampler (MCS) which is capable of measuring fluxes at a high spatial resolution under natural conditions. The sampler is divided into 100 separate compartments of 31 by 31 mm. Flux data can be recorded at a high time resolution (every 5 minutes). Tracer leaching can be monitored by frequently sampling the collected leachate while leaving the sampler buried in situ. Recently this instrument has been extended with 121 electrodes. The electrodes are mounted at each corner of each compartment to measure the electrical conductivity above each individual compartment while water percolates through the compartments. By using different electrode couples, the setup can also be used to image above the multi-compartment sampler.

The instrument can be used both in the laboratory and in the field. For laboratory experiments a transparent column is used which fits perfect on top of the MCS. We present a selection of the integrated electrical resistivity and MCS results from our laboratory setup. The performance and capabilities of this instrument will be explained.

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Bloem, E., Hogervorst, F.A.N., de Rooij, G.H. & Stagnitti, F. (2010): Variable-suction multicompartment samplers to measure spatiotemporal unsaturated water and solute fluxes. – Vadose Zone Journal, **9**/1, 148–159.

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P02

Combining multi-scale surface ERT for fast and robust shallow hydrostratigraphic units delineation at catchment scale

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A reliable understanding of catchment hydrology requires an accurate knowledge of the structure and composition of underlying soil and bedrock. Factors such as the depth and composition of the soil cover, and the weathering and features of the bedrock, all determine the pathways of infiltrating rainfall, the residence times of water in the subsurface and its subsequent interactions with surface water bodies. However, the complexity and spatial variability of the subsurface make its characterisation very challenging. In this context, surface ERT is now a well-established and commonly used method in hydrological studies to grasp the spatial variability of subsurface properties. This technique eventually allows to overcome the limited spatial resolution of the conventional "point-scale" drilling approach. In many cases, though, the subsurface structure is shallow and has to be measured with a precise vertical scale, requiring a small electrode spacing. In these circumstances, ERT measurements remain time-consuming. Contrariwise, when the aim is to carry out large horizontal surveys, a set-up with larger electrode spacing is preferred. In our study, we show that oversized electrode spacing can significantly affect our perception of a shallow subsurface structure by missing important surficial layers (this has already been demonstrated in several studies). More precisely, we document how a thin surficial layer can influence ERT results and cause a resistivity bias, both at the surface and at deeper horizons. First, we simulate a soil / weathered bedrock / fresh bedrock system to identify the resistivity bias produced as a result of electrode spacing. Second, this evidence is documented with a field dataset characterising a slate catchment in Luxembourg. Finally, we introduce a method to improve 2D inversion results for large units of electrode spacing. Our method incorporates interpolated apparent resistivity surficial values based on a limited number of ERT profiles at plot scale and carried out at finer units of electrode spacing. When applied to our field dataset, this combination of multi-scale surface ERT shows significantly improved inversion results. We suggest that our method should be considered to improve the inversion reconstruction for delineating hydrostratigraphic units at catchment scale in a cost-effective and more robust way.

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GELMON 2015

P03

Spatializing of soil water content measurement at the scale of the agricultural field, using geoelectrical monitoring and geostatistical method

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The knowledge of spatial and temporal variation of soil water content is important in several fields of water management and soil nutrient transfer. However, its spatial distribution is costly and hard to obtain using classical hydrological measurements (e.g. tensiometers, TDR probes …). The geophysical methods (e.g. ERT, EM ...) allow a spatial measurement of physical variables (e.g. soil electrical resistivity) sensitive to soil water content but less accurate. The main purpose of this study is to test the Bayesian Maximum Entropy (BME) approach to merge the two datasets in order to predict the spatial distribution water content: (1) punctual measurements of soil water content, which are considered as accurate data, and (2) indirect spatial measurements using geophysical method, which is considered as uncertain data. This approach has been tested on four synthetic datasets obtained with a vertical 2D domain. The simulations of soil water content were carried out with Hydrus-software with homogeneous and heterogeneous hydraulic conductivity, and continuous and punctual infiltrations. From these simulations, a conceptual resistivity models were built using forward modeling approach and punctual sampling, vertically ranged, of water content were done. These two datasets was adapted and introduced to BME method to predict the soil water content distribution and compared to initial values.

The results indicate that BME method creates more reliable model of water content distribution, closer to the initial one. This approach seems to be a powerful method integrating ERT and TDR measurements to improve the spatial distribution of water content. The approach developed in this study will be applied to an experimental dataset carried out in agricultural field to estimate infiltration and pollutant transfer from the surface to deep groundwater table. The experimental monitoring contains daily measurement of 2D-ERT (Electrical Resistivity Tomography) and two vertical profiles of soil water content using TDR probes.

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P04

How to achieve a good evaluation of soil moisture content at different depths with available measuring techniques?

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Soil moisture is a key variable in the soil-vegetation-low atmosphere system. It is seen as an impact factor for several exchange processes such as soil gas diffusion and migration. Higher soil moisture leads to constrained gas diffusion and to some extent even to soil gas accumulation. Therefore, it is indispensable to measure soil gas concentration or fluxes jointly with soil moisture. The Time Domain Reflectometry (TDR) has become a standard method for field measurements of the soil moisture content. However, field TDR measurements show a high spatial and temporal variability. On the other hand, it is also difficult to implement this method in probes for depth oriented measurements in boreholes/wells.

Therefore, an alternative approach to estimate the soil moisture content was demanded. The work was carried out within the “RATIEF” project, funded by the German Federation of Industrial Research Associations (AIF), aiming in developing a measuring device and a modular probe system to measure depth oriented soil gas concentration and fluxes (especially CO2 and 222Rn) by taking into account the relevant influencing parameters (e.g. soil temperature, and soil moisture).

Field data indicate a strong correlation of contact resistances measured during self-potential measurements and TDR data. The derivation of soil moisture data using this observed linear fitting function achieved a valuable prediction for these data. However, this is a site specific approach and a lot of data are needed to obtain reliable fitting results. Laboratory experiments in conjunction with modelling showed that a certain soil moisture range (0-30%) has the greatest impact on soil gas migration processes. Therefore, an approach is needed to assess the variability of soil moisture within this range.

Since resistivity measurement can measure data simultaneously providing integral information from different depths and locations, several studies used this method for estimating the soil moisture variability. Ongoing studies determine explicit relationships between soil moisture and resistivity parameters and therefore, offer a potential for assessing the in-situ soil moisture condition.

This poster presentation will show results of laboratory experiments investigating the application of contact resistance measurements and resistivity methods within the modular probe system to estimate the soil moisture content. In addition, it will also discuss influencing parameters which need to be assessed for a reliable interpretation.

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P05

Comparative Study of a Sulfate Tracer Monitoring Experiment Using Geoelectrical and Hydrogeological Survey Techniques

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Reactive walls within the groundwater zone or the infiltration of reactive additives are applied within the frame of Enhanced Natural Attenuation (ENA) remediation procedures for groundwater contaminations based on current state of the art. The cooperation project KOPOXI (Development of an in-situ groundwater remediation procedure supporting natural contamination remediation processes within a contamination plume using a combination of permanently installed oxidizer emission wall and oxidant injections), funded by the German Federation of Industrial Research Associations (AIF), was established with the research focus on an application of the innovative combination of both, a permanently installed subsurface reactive wall and additional injections of reagents with the aim to substantially increase remediation efficiency carried out at a pilot site characterized by hydrocarbon contaminations.

Therefore, innovative monitoring strategies for the observation and subsequent process driven optimization of reagents injection procedures are required to be verified and adapted. These monitoring approaches are based on the acquisition of highly spatial-resolved in-situ hydraulic data within observation wells combined with borehole geophysical surveys in order to determine the spatial and temporal extent of the reagents.

Sulfate injections represent the supplement of potential reactive oxidants for remediation. Hence, a tracer test using 350l magnesium sulfate solution was conducted in a medium-scale experiment. The field set-up consisted of one injection well and four fence-lined observation wells for sampling and in-situ measurements of electrical conductivity and temperature. Additionally, 48 borehole electrodes for geoelectrical monitoring were installed at the PVC casing of the four observation wells. A single geoelectrical measure¬ment was carried out once per hour and consisted of a set of 642 borehole electrode configurations. The tracer was injected within a depth between 12.5 to 15.5 m b.g.l. over a period of 100 minutes. Three weeks before injection the geoelectrical observations had been started obtaining a data set including the resistivity variations due to natural processes within aquifer and to estimate the influence of disturbances caused by accompanying hydrogeological measurements. The whole experiment lasted 2 months.

First results of the experiment display a distinct decrease in apparent resistivity data observable within the first measurements after injection. Hence, the test reveals the suitability of geophysical monitoring in terms of process observation. The geoelectrical measurements provided valuable data for a comprehensive interpretation of hydraulic processes driven by the tracer behavior within the aquifer.

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P06

Geoelectrical monitoring of fresh water injection into a limestone aquifer

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We present results of a field study investigating the possibility to detect fresh water, injected into a limestone aquifer, using geoelectrical methods. Our analysis is based on a threedimensional subsurface model for a complex aquifer domain located in the Hastenrather Graben near Eschweiler, NRW.
As only few direct groundwater monitoring wells exist in the area, an injection test was performed with the aim to ensure and validate groundwater flow direction and to infer permeabilities in a part of the aquifer, strongly deformed by tectonics. Since the injection borehole is in a groundwater protection area, the only allowed tracer is water with a lower salinity than the groundwater. During injection, we performed geophysical monitoring with electrical resistivity tomography (ERT).
Prior to the field study, we investigated the feasibility for detecting the injected water in a numerical experiment. We performed a flow simulation which also considers injection in a discretized model of 250 m x125 m x 40 m in size, using SHEMAT-Suite. The geological model was extended from three to four layer cases to cover possible scenarios with varying properties. The salinity concentration of groundwater and injected water reflected actual field conditions. After the simulation, concentrations were converted into resistivity values and tested against varying ERT survey designs using the codes DC2DInvRes and Res3DMod. In order to monitor the injected plume, a spacing of 2 m and a monitoring rate of 2 days seemed to be sufficient under the applied assumptions.
Based on the results of this feasibility study, we performed a field test in November 2014. We injected approximately 390 m³ of drinking water into the limestone aquifer over a time period of 9 days with a mean injection rate of 1.8 m³/h. In total, 300 electrodes were used on 5 parallel profiles on 15 m interval with 2 m spacing for the geoelectrical measurements. In addition, one borehole electrode was placed into the injection well. Groundwater sampling and ERT measurements in Dipole-Dipole and surface-borehole configuration were performed within 2-3 days interval over a total period of 16 days.
First quality assessment took place in the field. We repeated measurements with negative or unrealistic large values or divergent currents larger than 5. The data was kept for the upcoming inversion when it was reproducible in the field and when it was similar to its neighbor values.

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Furthermore, we excluded all data points where the ratio between data and the reference measurement exceeded 25% of highest simulated ratios. We processed the remaining data points as timelapse series using the software Res3DInv.

Changes in resitstivity over time are not only visible in the top layer but also within the aquifer. Here, resistivity increases over time driven by the higher resistive pore filling of the less saline injected water and decreases again after the injection stopped. Our results suggest that the injected water spread out laterally into all directions, even against the steady-state groundwater flow direction.

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P07

Evaluation of Dam Seepage Problems Using Geological and Geophysical Methods, Republic of Korea

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The precise safety assessment for seepage detection in reservoirs dam and embankments started in Korea in the late 1990's(Song et al., 1999). There are 68,000 agricultural-based facilities and 19,590 locations need to be maintained periodically in Korea. First class facility to conduct regular safety assessment every five years is 1,016 locations and second class facility to conduct safety assessment if necessary is 18,574 locations. Reservoirs are accounted for 90.5 percent of the whole target assessment facilities. Recently, due to the continued adverse weather and earthquake events of countries adjacent to the Korean peninsula, the many lives and untold property damage were occurred eventually.

We have performed the electrical resistivity method to delineate leakage pathways through the abutment of earth fill dams located in Korea. Electrical resistivity survey is one of the oldest and most popular geophysical techniques in electrical exploration. By applying electrical resistivity survey to investigate the condition of the core material, we could expect to get information on the variation of the electrical anomaly pattern due to the saturation of the soil. The objective of survey was to delineate the weak zone of the dam wall and estimate the status of core zone. In other to evaluate the engineering geological properties of the soil deposits, two boreholes a dam were drilled to the bedrock that exceeds the height of the dam. A large set of field tests including standard penetration tests(SPT) and in-situ permeability tests were carried out along the boreholes. Also, a series of laboratory tests were conducted on the undisturbed soil samples obtained using the split-spoon sampler and thin wall tube sampler to determine their engineering characters. Electrical resistivity obtained from the results of the survey is a physical quantity associated to the electrical properties of the ground and can vary from locations to locations. Mostly it is affected by grain size, porosity, permeability and clay mineral contents of ground. Therefore it is very important to examine the properties of the soil of dam sites for safety assessment. So we have the measured resistivity values of undisturbed soil samples which were obtained using the single tube core barrel together with the split-spoon sampler of SPT.

As a result of these studies, seepage pathways have been identified in the most of the dam by using the electrical resistivity method and the safety level of the dams can be estimated. It may indicate that the deficiency of fine particles like soils may cause an increase of resistivity value, and results in the weakening of the core material, which appeared as low N values. And it may lead to the failure of the reservoir dam due to piping and excessive seepage through the core zone.

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P08

Results and further investigations based on the LAMOND Landslide Monitoring Network.

Case study Bagnaschino Monitoring site: Soil water flow model based on Geoelectric Monitoring inversion results.

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The LAMOND Monitoring Network is the continuation of the Landslide monitoring activities from the last 8 years (EC FP-7 project SAFELAND, FWF project TEMPEL). Within the LAMOND project additional Monitoring sites had been deployed, namely Navis (Tyrol) and Gresten (Upper Austria). Hence, the network consists of 5 sites where Geoelectric monitoring and additional geotechnical methods (Inclinometers, Photo monitoring, soil moisture, eg) are applied.

At the Bagnaschino site geoelectric monitoring results are available from 2011 on. During and after heavy rainfall events the infiltration of rainwater is clearly visible in the geoelectric profiles. Numerical modeling is applied for estimation of underground hydraulic properties, the resistivity pattern and its change in time is used for calibration of the numerical model. High-impedence areas are generally interpreted as regions with low-water content. At the present stage of the project, the comparison between modelled saturation and measured resistivity is only done quantitatively on a visual basis. Implementation of parameter estimation using the COMSOL Optimization module is planned in a later project stage.

Another application of numerical modelling is the implication of heat transport for assessment of the temperature dependency of the resistivity.

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P09

Geoelectrical monitoring during waste biodegradation process

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Waste storage is the waste treatment method most commonly used around the world because it is a relatively simple and economical way for solid waste disposal (Erses et al., 2008). For this reason non-hazardous waste disposal facilities formerly operated as mere filling pits, nowadays are 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 could allow the characterization of solid waste biodegradation state in landfill. Geophysical methods have long been used on landfill for the location of pollution plumes, the mapping of internal and external structures, or more recently for the study of leachate recirculation process. The transformation of solid waste into biogas carried out by all 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 that could be detected by geophysical methods. For these reasons four geophysical methods have been chosen to become an indicator of the biodegradation waste state on landfill:

(i) Self-potential,
(ii) Electrical resistivity,
(ii) Induced polarization,
(iii) Spectral induced polarization

In order to evaluate the potential and limits of the chosen geophysical methods an experimental device have been build allowing us to study the influence of the different steps of waste biodegradation on measurements of the four methods. Municipal solid waste have been shred, poured in a laboratory column and moistened with biowaste digestate. The cell was then saturated with water and placed at 35° C in order to increase the biodegradation kinetic. Monitoring of the four geophysical methods as well as the cell gas production and composition is carried out since early September and will allowing us to determine the relevance of the geoelectrical methods to characterize a waste biodegradation state.

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P10

Case study: Long-term permafrost evolution at the Schilthorn monitoring site, Swiss Alps, using electrical resistivity tomography (ERT) monitoring

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Permanently frozen ground is a very sensitive climate change indicator. A better understanding of mountain permafrost degradation implies a temporal and spatial permafrost distribution monitoring, which is of major importance regarding high mountain slope stability.

ERT is broadly applied in the context of permafrost. Subsurface resistivity temporal variations depend on temperature and pores content (ice, water or air). Several orders of magnitude discriminate the electrical resistivity of ice and water, allowing a distinction between frozen and unfrozen ground.

We focus this study on the Schilthorn permafrost monitoring site (Swiss Alps), which includes a 17-year discontinuous resistivity dataset, as well as temperature ground truth data available from 2 boreholes. Both apparent resistivity and inverted specific resistivity are analysed in space and time. A special effort dedicates to temporal resistivity changes comparison between different depth levels: from shallow (active layer) to deeper levels (permanently frozen ground). The effects of the 2003 and 2015 summer heatwaves are investigated in detail in comparison with in-situ air and ground temperatures at several depths.

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P11

The ATMOperm – project: Atmosphere - permafrost relationship in the Austrian Alps - extreme atmospheric events and their relevance for the mean state of the active layer

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Permafrost is a forming element of the high mountain landscape, subject to considerable degradation due to global climate change. In the Alps infrastructure facilities such as roads, routes or buildings are affected by the changes of permafrost, where modification often cause enormous costs. However, the understanding of the permafrost changes inducing processes is still insufficient. In particular, the energy exchange with the atmosphere in the interplay with processes in the soil, is weakly recognized and understood. This is especially true for the influence of extreme atmospheric events such as a summer heat wave (e.g. 2003), early-winter cold wave or events relating to the snow thickness. This scientific deficit is not only due to the complexity of permafrost processes, but also because of the relatively short period of establishment of alpine permafrost research (especially in Austria).

The geophysical method of geoelectrics (Electrical Resistivity Tomography ERT) is a innovative approach for the detection of thermal structures in the subsurface. ATMOperm has the goal of further exploring the method of geoelectrics for estimation of thawing layer thickness (Active Layer Thickness) for mountain permafrost and to optimize it for long time monitoring. It is clearly necessary to further optimize the transformation of ERT data to thermal structures in the ground - a significant innovation of ATMOperm. The measurement of the thawing layer by the geoelectric method is complemented by measurements of the energy fluxes between the atmosphere and soil. This allows to investigate the effects of energy exchange between the atmsosphere and the ground on the thickness and the thermal structure of the thawing layer in an ideal way. The use of an energy and mass transfer model of the soil (Coupling Model) allows to simulate exchange processes between the atmosphere and the ground and so to understand the effect of atmospheric energy fluxes on the temperature distribution in the soil.

The ATMOperm monitoring will be developed for the Sonnblick mountain(Austrian Central Alps). This is mainly for the fact that for Sonnblick an extensive permafrost monitoring already exists and that the atmospheric monitoring network is highly developed there. In addition to Sonnblick the data from the already existing monitoring locations Schilthorn (Bernese Alps , Switzerland) and Kitzsteinhorn (Austrian Central Alps) will also be used, as these sites offer longer geoelectric measurement time series essential for model improvements.

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P12

Crystalline rocks time-lapse behavior via geophysical methods

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Geophysical methods (such ERT) as a tool for monitoring the processes and time-related changes in geological environments have made great progress in recent years and have become standard for observing natural phenomena. These methods are often simple to use and provide high-quality results that are well interpreted.

Our research is based on observing time-lapse changes of the physical parameters (conductivity, IP or elastic parameters) of joints systems (mostly in crystalline massifs). The primary aim is to develop a monitoring system mostly for the needs of deep repositories of nuclear waste. Geophysical research of such repositories has so far dealt only with one-off research (no time-monitoring) of potential host rock´s properties. Contrary to this, our developed system and methodology is unique in continuously measuring the physical properties of the rock massif. This system will be permanently fixed in the field and by observing changes in measured data reports if any remarkable occurrence in the EDZ zone is or was happening (for example, opening or closing of the joints or micro-fractures).

In our research, we are trying to get complex insight in the time-lapse behavior of granite massif (our field base is at the Bedrichov gallery in Jizera Mts.). We got very dense ERT data, which was continuously measured during two months, every six hours. We have found very interesting short and long-term changes in measured resisitivites. Right now we are trying to nail down the particular geological phenomena connected with these changes and narrow our interpretation – we did our laboratory measurement (resistivity dependence on the water saturation and sample´s disruption), we are comparing our results with dilatometers and 3D geophones placed close to our field base.

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P13

Exploration of underground utilities for electric field analysis in jointed rock mass with anomaly

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Rapid urbanization and industrialization have caused increased demand for underground structures such as cable, and other utility tunnels. Recently, it has become very difficult to construct new underground structures in downtown areas because of civil complaints, and engineering problems related to insufficient information about existing underground structures, cable tunnels in particular. This lack of information about the location and direction-of-travel of cable tunnels is causing many problems. To solve these problems, this study was focused on the use of geophysical exploration of the ground in a way that is theoretically, different from previous electrical resistivity surveys. An electric field analysis was performed on the ground with cable tunnels using Gauss' law and the Laplace equation. The electrical resistivity equation, which is a function of the cable tunnel direction, the cable tunnel location, and the electrical conductivity of the cable tunnel, can be obtained through electrical field analysis. A field test was performed for the verification of this theoretical approach. A field test results provided meaningful data.

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P14

Monitoring water infiltration in an experimental mine rock waste pile with time-lapse ERT and multi-parameter data collection

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Waste rock piles are made of non-economic coarse-grained rock mined to reach the ore and disposed in piles at ground surface. If small amounts of sulphide minerals are present in the waste rocks, flow of water and supply of oxygen in the pile may generate contaminated neutral drainage (CND) capable of leaching, transporting, and releasing metals in the environment. In order to limit generation of CND, an original way to construct waste rock piles with thin inclined compacted layers was proposed. The thin inclined layer made of finer-grained material placed over the coarse waste rocks can act as a capillary barrier, diverting and channelling water downslope, and leaving the reactive core with little moisture. The modified design was numerically modelled. In order to test the concept, an experimental waste rock pile has been build at the Lac Tio ilmenite and hematite mine site in 2014-2015. The waste rock pile is 60 m-long, 10m-wide at the top, and its top surface dips at 5%. Waste rocks are made of low reactive anorthosite (low sulphide content). A 70cm surface cover made of two layers of fine-grained material (crushed anorthosite overlying medium-fine sand) has evenly been laid at the pile surface. The waste rock core reaches 7m-high and it lies over a horizontal 70cm fine-grained layer at the base. Below the last layer, 6 lysimeters are used to collect infiltrated water to monitor physico-chemical properties, such as water volume, geochemistry and electrical conductivity.

To model water moisture content with time and therefore to monitor water flow in the pile, TDR and suction probes have been inserted in the pile, including top and bottom sand layers. Two layers of electrodes, consisting each in 96 circular stainless steel disks spaced every 2m, were installed: one in the surface anorthosite layer and one in the sand layer at the bottom of the pile. Within the uppermost waste rock and sand layers, as well as within the sand layer at the bottom of the pile, a DTS fiber optic cable has been laid to monitor temperature distribution, which will enable to deduce the water content of the rock along the cables. Monitoring of all these parameters is done using a dedicated acquisition system. Some specific induced infiltration tests are also being carried out. Time-lapse electrical resistance tomography (ERT) data collection will be processed and multi-parameter data integrated in order to map volumetric water content and water flows. Special ERT acquisition protocols are needed to optimize high resolution imaging of water content within the coarse core and the upper and lower fine-grained layers. In this poster, we will present the experimental waste rock pile and how we are planning ERT measurements.

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P15

Processing of geoelectrical monitoring data. Unconventional approach to detection of local subsurface heterogenety

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Time-lapse electrical resistivity tomography (ERT) has proved to be an effective electrical monitoring tool. The use of ERT predefines techniques of the time-lapse data processing and interpretation. Common approach considers some inversion scheme to be used first to obtain resistivity cross-sections or volumes. Then difference images are analyzed to monitor time-related changes in resistivity. Unfortunately, despite numerous attempts currently no effective way exists to completely avoid inversion artifacts. The presence of noise in the field data and the lack of sensitivity of ERT with depth make things even worse. We investigated various approaches, using both real and model data, and have come to a conclusion that working with the original data, i.e. apparent resistivity, in many cases, may lead to more stable results.

Here, we present an approach to analyze non-inverted apparent resistivity data as a possible way for identification and monitoring time-related changes in the subsurface. The field data is expected to be acquired using forward and reverse pole-dipole array. This allows us to convert the apparent resistivity to a difference parameter (specifically, by point-to-point subtracting one pseudosection from another one). The difference parameter has proved to be very sensitive to time-related local subsurface heterogeneity. We also investigated how temperature and moisture affected this parameter to perform correction of monitoring data. To distinguish between time-lapse noise and true anomalies, we applied a statistical technique.

The proposed methodology has been tested on both synthetic and real field data and showed its efficiency. Among others, we monitored the process of near-surface tunnel drilling (diameter - 1.5 m at depth - 6 m). Using fixed monitoring system with just 2 current and 19 potential electrodes we were able to track tunnel face location with fairly high accuracy (spatial - 1 m, temporary - 3 h).

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P16

Electrical monitoring on construction sites in Russia

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The great amount of construction sites located throughout the huge territory of Russia requires a constant monitoring of the state of their constructions. First of all this is a requirement for oil and gas facilities in the North and East of the country. Sites for oil and gas well clusters, access roads, pipelines, temporary sites of civil engineering, frozen dams and reservoirs dams are built on permafrost containing high rates of ice in most of the cases. Very often the situation is aggravated through a dissected relief with landslides, heavy rain showers in the summer, slight snowfalls in winter, enormous temperature differences within the year (for example, in Yakutia the difference may be 80 – 100º C). In a number of Eastern Siberia regions, the depth of the seasonal soil freezing reaches 3 – 3.5 m. For objective reasons geoelectrical monitoring is the most suitable method for monitoring the state of the constructions. Years of experience with conventional devices, including electro-tomographic stations, has shown their low efficiency, for such climatic characteristics impose special requirements for the equipment in use.

The new generation of equipment for electric monitoring is based upon the following principles:

- the arbitrary geometry of the equipment is suited for investigation on a specific object;
- any number of current and measuring electrodes can be used;
- switches and electrodes are combined in one sealed enclosure;
- electrical signals are measured through multiple channels;
- the process is fully automated according to the chosen connection protocol between current and measuring electrodes and to the algorithm, that decides whether there is need to conduct further measurement for enhancing accuracy and reliability of data;
- prescribed accuracy and quality control measurement is possible due to rapid re-measurement;
- possibility of remote access to the measuring station via Internet;
- a high input impedance ensures a high quality of signals received;
- temperature variations do not affect main parameters of the device;
- measuring electrodes with built-in temperature sensors.

Currently, the station has passed factory and field-testing and is being installed at one of the oil and gas fields in Central Yakutia.

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