BACHELOR'S THESIS - **DEGREE PROGRAMME IN ENVIRONMENTAL ENGINEERING**
SAVONIA UNIVERSITY OF APPLIED SCIENCES

MEASURING WATER FLOW IN SOIL USING ELECTRICAL IMPEDANCE TOMOGRAPHY

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SAVONIA-AMMATTIKORKEAKOULU

OPINNÄYTETYÖ

Tiivistelmä

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Tiivistelmä

Tässä opinnäytetyössä tutkittiin maaperän veden virtauksen mittaamista impedanssitomografiaa käyttäen. Työn tavoitteena oli selvittää impedanssitomografian soveltuvuutta veden virtaamisen mittaamiseen laboratorio- sekä kenttämittausten avulla. Mittausten perusteella kuvannettiin veden virtausta maaperässä kolmessa dimensiossa.

Maaperän sekä siellä kulkeutuvan veden ja muiden nesteiden kuvantamista voidaan hyödyntää pohjavesivarojen tutkimisessa. Kuvantamisella voidaan parhaimmillaan arvioida ja ennustaa varantojen suuruuden kehitystä, sekä mahdollisesti paikantaa sinne kulkeutuvia haitta-aineita (esim. kaatopaikkavuodot, öljyonnettomuudet). Mitä luotettavimmin kyseisiä ilmiöitä pystytään todentamaan, sitä paremmin ihmiselle ja luonnolle tärkeää veden laatua pystytään ylläpitämään. Yleisesti maaperän kuvantaminen on mutkikasta johtuen vaihtelevista pinnanalaisista rakenteista sekä erisuuntaisista veden virtauksista. Nykyisin käytettyjen, maaperässä veden kulkeutumista kuvantavien menetelmien ongelmana on usein se, että niistä saatava tieto on harvoin tarpeeksi tarkkaa ja luotettavaa, ja monesti kuvantaminen on kaksiuloitteista. Luotettavalle, kolmiuloitteiselle kuvantamismenetelmälle olisi siis selkeä tarve.

Tämän työn maaperän kuvantamistutkimus aloitettiin vuonna 2011. Inversio-ongelmien tutkimusryhmässä oli jo aiemmin tehty maaperään ja veden virtaukseen liittyvää tutkimusta sekä maaperämittauksissa käytettävää laskentaa. Tarkoitus oli edetä tutkimuksessa siten, että jo käytössä olevan laskennan ja mittauslaitteiden toimivuutta tutkittaisiin käytännön mittauksilla. Aluksi työtä varten tehtiin taustatutkimusta, johon kuului hydrogeologian ja impedanssitomografian teoriaan, nykyisin käytössä oleviin mittausmenetelmiin sekä yleisesti mittaustarpeeseen tutustumista. Seuraavaksi suoritettiin laboratorio- sekä kenttäkokeet, joista rekonstruoitiin MATLAB-ohjelmalla tulokset. Rekonstruoimisessa hyödynnettiin tutkimusryhmältä saatuja MATLAB-laskentakoodeja. Lopuksi arvioitiin impedanssitomografian hyödyntämismahdollisuuksia maperässä kulkeutuvan veden mittaamiseen.

Työn lopputuloksena saatiin mittausten perusteella lasketut kolmiulotteiset rekonstruktiot maaperän sähkönjohtavuudelle useissa eri testitilanteissa. Lopuksi voitiin päätellä, että tulokset ovat käyttökelpoisia, ja että impedanssitomografialla on mahdollista kuvantaa maaperässä virtaavan veden kulkeutumista. Tuloksissa esiintyi kuitenkin virheitä, jotka johtuvat todennäköisimmin mittauslaitteesta. Tulokset asettavat pohjan tulevalle tutkimukselle ja mahdolliselle laskennallisten menetelmien kehittämiselle. Käytetyllä menetelmällä on potentiaalia nykyisten mittausmenetelmien rinnalle maaperässä kulkeutuvan veden kuvantamisessa.

Avainsanat

Veden virtaaminen, maaperä, impedanssitomografia

SAVONIA UNIVERSITY OF APPLIED SCIENCES

THESIS

Abstract

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Abstract

The topic of this thesis was the monitoring of water flow in soil using Electrical Impedance Tomography (EIT). The aim was to investigate the suitability of EIT for imaging water flow in soil. Laboratory and field measurements were carried out for investigating the feasibility of EIT imaging of water flow in soil. Water flow in soil was three-dimensionally (3D) imaged from the measurements.

Imaging of flowing water and other fluids in soil can be utilized in investigating groundwater resources. Imaging, at its best, could allow analysing and predicting the development of groundwater resources, or even enable locating of hazardous substances, which have been flowed into the soil (e.g. leaks from landfills, oil accidents). The more reliable information of these incidents can be received, the better the quality of water can be maintained, which is important for humans and nature. In general, imaging of soil is complex, because of its variable structures and divergent water movement. Problem with currently used techniques for monitoring water flow in soil is that the information often lack in detail and comprehensiveness, and often the imaging is two-dimensional. There is a need for reliable, three-dimensional imaging method.

The research on imaging of soil for this thesis was started in 2011. In the inverse problems group in University of Eastern Finland, some previous works on imaging water flow in soil had already been carried out, and the codes for computing the data from upcoming geotomography measurements were already made. The next step was to investigate how the codes and measurement devices would work with real data from the experiments. First, some preliminary framework was done. This included getting to know of the theory of hydrogeology and EIT, currently used methods for imaging water movement in soil and the need for such experiments in general. Secondly, laboratory and field experiments were carried out, and based on those, results were reconstructed using MATLAB. Lastly, the feasibility of EIT for imaging water flow in soil was analysed.

The deliverables of the thesis work were the 3D reconstructions of soil conductivity in several measurement cases computed from the measurement data. It was deduced, that the results are feasible, and that EIT has strong potential in measuring water flow in soil. There were some errors in the results, which were most likely caused by the measurement device. The results from these experiments set the base for further research and for possible development of computational methods. The used method has a great potential as an option for the currently used techniques for measuring water flow in soil.

Keywords

Water flow, soil, impedance tomography

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Kuopio 26.5.2014

Paula Kaipio

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1 INTRODUCTION

Groundwater is one of the major sources of fresh water for human and nature. The importance of fresh groundwater increases while the resources diminish overall. Receiving continuous information on hydrology and hydraulics of water movement from the surface of the ground through the vadose zone to aquifers would help to protect the groundwater resources and possibly prevent the groundwater pollution caused by variable sources, and the scope of it even in advance. There are also legislative and economical aspects, which impose the groundwater resources and water safety to be taken care of. This sets a certain need for measuring water flow in soil. In addition, frost heaving and spring flooding after snowmelt cause great costs yearly. The ability to measure these could help preventing the damages.

There are several methods for measuring soil moisture and water flow in porous media. Soil moisture measurements are often based on spot metering. The soil moisture content is often measured using tensiometers, granular matrix sensors or neutron probes. Currently, measuring and imaging of water flow or for example tracers in soil, is mostly based on electrical methods. These measuring methods have been used for imaging the flow of water or other fluids in soil both two and three-dimensionally. There are also some simulation softwares for measuring water flow in soil, based on geographic information of the location. Many of the currently used methods and applications lack in comprehensiveness, and are time as well as money consuming.

Electrical impedance tomography (EIT) is an imaging method, in which electrical conductivity distribution inside a target is reconstructed into a three-dimensional image. EIT has been used for monitoring water movement in soil. Humidity and dissolved salts in soils create electrically conductive volume, due to which, measuring water flow using EIT is theoretically possible. There is certain need for an application with reliable and accurate three-dimensional visualization of water flow in real-time. Convenient application would enable repeatable and cost effective measurements, and it would be suitable for large scale field measurements. Computation plays an important role in development of better imaging and applications for measuring water movement in soil.

The aim of this thesis is to further investigate the capability EIT for monitoring water flow in soil. Especially the study is about wheter three-dimensional (3D) EIT could give accurate and feasible information on the moisture movement, the direction of flow and the amount of water in soil. In the end, the aim is to investige and analyse if 3D EIT could be a competitive imaging method for imaging water flow in soil for the currently available methods, and if it could possibly help protecting groundwater resources as well as preventing groundwater pollution in the future.

As for the progress of this thesis (Figure 1), theoretical framework was done before carrying out the experiments. Theoretical framework included further studying of hydrology in general, former research on the topic as well as getting to know the measurement device. Moreover, theoretical framework included studying about thesis related hydrogeology, such as movement of water and other fluids in porous media, currently existing threads for water resources, as well as EIT as imaging method. After studying such thesis related subjects, laboratory measurements were carried out.

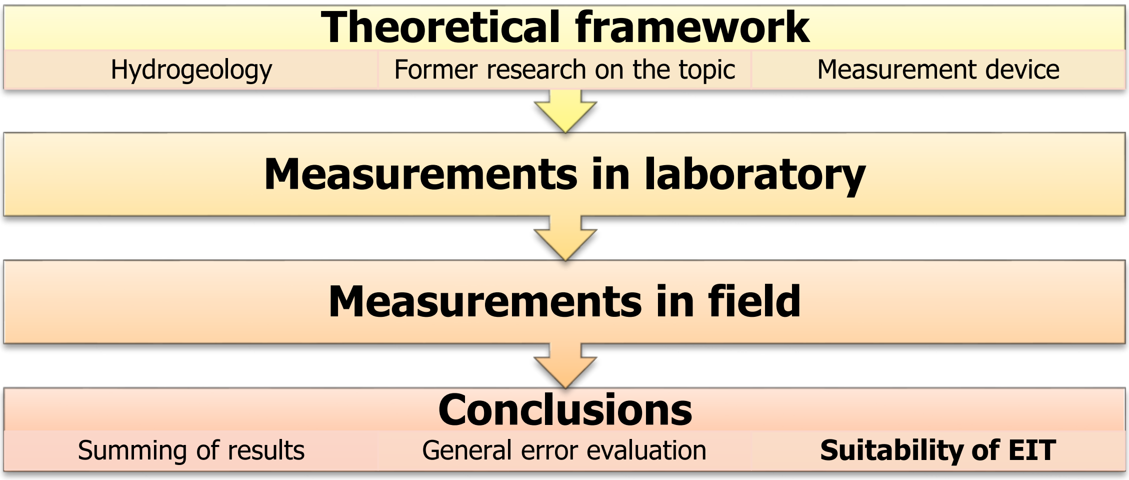

FIGURE 1 Process of this thesis

Several laboratory measurements of water flow in soil were carried out in process tomography laboratory in Kuopio, Finland during 2011-2013. Two field measurements were carried out by a ridge in Maaninka, Finland in October 2012 and August 2013. After all of the measurement data was collected and EIT reconstructions computed, results were analysed. Based on these studies, suitability of 3D EIT for water flow imaging in soil was investigated.

2 THESIS RELATED HYDROGEOLOGY

The main focus in this thesis is on the water movement in porous media, geologically in the vadose zone. In this chapter, some elementary concepts on the hydrologic cycle and profile is introduced to set a background for the content of this thesis.

2.1 Hydrologic cycle

Water cycles in solid, liquid and gas forms in ground, seas, lakes and rivers, as well as in air. There are various inputs and outputs. Precipitation is considered as the input, and evaporation together with transpiration and stream run-offs as outputs. The infiltration through soil is the major source of inflow as well as recharge to ground water resources. (Bear 1979.)

As a whole, groundwater is connected to air, surface waters as well as to ground. The focus in this study is on the infiltration of water in the vadose zone. Vadose zone is the unsaturad zone between the Earth's surface and groundwater.

2.2 Vadose zone

The vadose zone is the volume between the surface of the Earth and phretic water (Figure 2). The vadose zone consists of the soil water zone, intermediate zone and capillary fringe. (Bear 1979.) In vadose zone there is both water and air in the pores. Vadose zone is the unsaturated zone where water is held by soil pores and capillary forces.

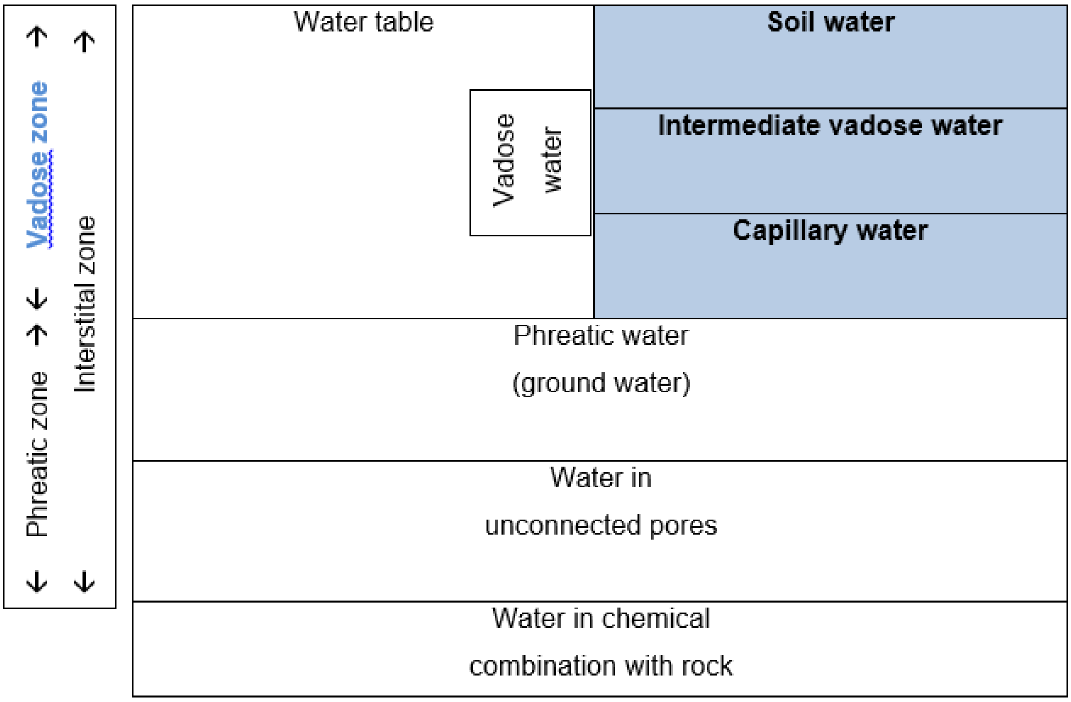

FIGURE 2 Water profile (Based on an image from Kansas Geological Survey, 2004)

2.2.1 Water flow in vadose zone

The water flow in soils is primarily vertical. Water moves through variable structures in ground and is greatly influenced by the atmosphere because of evapotranspiration and rainfall. The solid fabric of the unsaturated zone includes soil, stones, porous rock, and organic matter. (Nimmo 2005.) In addition to vertical flow, water moves through capillary action. In general, water flow increases with the distance from the ground level. (Roth 2012.) The flow process in the unsaturated zone includes transportation of nonaqueous liquids, solid particles and gases. (Nimmo 2005.)

The infiltration of water in soil is the process describing how water on the surface of ground enters the soil. The infiltration rate describes soils ability to absorb rainfall or irrigation. The water infiltration is controlled by gravity, capillary action and soil porosity. (Physical Geography, 2014-5-12) The permeability describes how porous medium conducts or transmits fluids. In this case, this means the ability of soil to allow fluids passing through. The permability is greatly dependent on the pore size as well as infiltration (movement of water into the soil) and percolation (water movement through the soil) rate. (Bear 1972; Bear and Zaslavskiĭ 1968; O'Geen 2012.)

Water tends to move downwards by gravity. On the other hand, the water is moved upwards by the capillary action. The capillarity action in soil describes the attraction of water molecules to soil particles. (Hauksbee 1712.) It appears as water from lower layers is absorbed into the less saturated soil volumes above by capillary forces.

2.2.2 Soil types in the vadose zone in Finland

The focus in this thesis is on the soil types in vadose zone in Finland. Finland's bedrock is ancient, one of the oldest in the world. On the other hand, soil is young. It has been formed during the last few tens of thousands of years by the last ice age. On top of the bedrock there are moraines from the ice age and some graded soils. The latter are glacier-born gravel and sand that appear especially by ridges. There is also clay and other finer soil types, such as fine sand and silt layered in different depths. In addition, there are organic soils such as peat and mud. (Lehtinen, Nurmi and Rämö 1998).

2.3 Aquifers

An aquifer (a ground water basin) is a geological formation, or group of formations, which contains water and permits significant amounts of water to move through it under ordinary field conditions. (Bear 2007). In Finland there are over 6000 aquifers and more than half of these are used as water supply reserves. Approximately 5.4 million cubic meters of water a day is replenishing the aquifers of which 0.7 million cubic meters is consumed by people. This totals 12.6 % of formed water. This means that more water forms than is used. Nevertheless the use has been increasing since 1970s and more restrictions on water safety and quality have been applied. People living in sparsely populated areas are more dependent on groundwater which is taken from springs or wells. (Rusanen, Finer, Antikainen, Korkka-Niemi, Backman and Britschgi 2004; Backman, Luoma, Schmidt-Thome 2007.)

The capacity of natural groundwater resources can be increased by recharging surface water into the ground. Surface water is filtered through the soil, which improves the quality of water. Recharging of groundwater is already used in 25 waterworks in Finland. The use of artificially recharged groundwater was 10 % in Finland in 2009 and is presumably increasing. (Britschg, Antikainen, Ekholm-Peltonen, Hyvärinen, Nylander, Siiro and Suomela 2009.) Due to this, exploring the movement of recharged surface water in soil is vital.

Even though there are a lot of resources in Finland's aquifers, they are not evenly spread around the country. However, approximately 60 % of water used in Finland is from aquifers. Water for example from coastal aquifers cannot be easily extracted. (Lavapuro, Lipponen, Artimo and Katko 2008; Britschgi et al. 2009.) In these areas, water is often heavily consumed, because many large cities are located in the coastal area of Finland, and it has been necessary to extract water from very ferreous aquifers and surface waters. This is also one of the many reasons why surface waters have a huge impact on human health and nature as well. The worst state of surface waters is in Southern Finland, where also the density of population is the largest. On the other hand, by ridges and terminal moraine lands, in gravel and sand areas, such as Salpausselkä in southern Finland, groundwater is good of quality and rich in oxygen. (Lavapuro et al. 2008; Britschgi et al. 2009.)

It is broadly known that the quality of water in Finland's groundwater reserves and glacial deposits is among the best in the world. The groundwater is soft with low concentration of substances and with pH close to neutral, in the level of drinking water (6-7) in general. The purity and quality of groundwater result from being more protected against substances than the surface water as well as from the structure of soil. The soil layers in the vadose zone filters out an amount of substances. Nevertheless, some concentrations or amounts of iron, manganese, salt water, arsenic, fluorine and radon may contaminate and reach the ground water because of extraction as well as geological features. (Oram, Halsor, Redmont 2013-4-4). There are severe risks for groundwater resources and quality. Petrol stations, industrial plants, use of salt for de-icing roads and landfills may cause contamination even though the resources are heavily protected by local authorities and waterworks. Naturally the salinity of groundwater of in some areas increases because of de-icing of roads.

3 NEED FOR MEASURING WATER FLOW IN SOIL

Increasing the knowledge of water and other fluid movement in soil would help the protection of ground water resources. The ability to get real time information and understand more specifically the ground water development indirectly affect the amount of water which could be used. The better the resources can be protected, more of it can be utilized. When soil, through which the water infiltrates is contaminated, groundwater is affected (Bedient, Rifai and Newell 1994). In addition, there are some legislative and economical factors to groundwater resources and water flow in soil. Moreover, also the frost heave is considered as water movement, and it causes yearly costs by damaging buildings, roads and pluming due to ground movements. (Taber 1929). Understanding and improving these processes needs researching and actual infield measuring.

3.1 Groundwater

Groundwater originates from rainfall or snowmelt via precipitation through soil and rock to aquifer, which is also known as the body of ground water. Moreover, water flows from surface waters to aquifers. (Bear, 1979). As noted above, aquifers are the main resources of fresh water which are readily available for general water supply. (EPA: Groundwater 2012-2-3). Water is heavily used for crop production, industrial production and municipal waste removal. Water is also consumed indirectly in food industry. As global estimates from a statistical study show, for example production of one kg of potatoes requires 160 kg of water whereas up to 16,000 kg of water is required for producing one kg of beef (Hoekstra 2003; Roth 2012.)

As the population is growing, water and food consumption in general increase and climate change accelerates, need for fresh water has increased rapidly. (Falkenmark and Widstrand 1992.) Climate change will probably intensify droughts and floods, make changes in precipitation, soil moisture and surface water. (Taylor, Scanlon, Döll, Rodell, Beek, Wada, Longuevergne, Leblanc, Famiglietti, Edmunds, Konikow, Green, Chen, Taniguchi, Bierkens, MacDonald, Fan, Maxwell, Yechieli, Gurdak, Allen, Shamsudduha, Hiscock, Yeh, Holman and Treidel 2012.) Susceptibility of groundwater for surrounding changes is obvious.

Ecological systems also rely on ground water. The aquifers reach the Earth’s surface in places where they form springs and streams. (Alley, Reilly and Franke 1999.) Aquifers help maintaining the moisture balance in soil and providing water to animals and plants. At its best, an aquifer is a longtime fresh water storage and a resource also for ecological populations.

3.2 Pollution impact

Pollutants and harmful substances get to flow through the vadose zone into aquifers. This indirectly reduces the amount of fresh, clean water or make water treatment and usage more complicated. Under these circumstances it is even more important to understand water flow and the formation of ground water (Domenico and Schwartz, 1998.) Pollution impact in ground is normally caused by landfills, contaminated lands, and discharges to land, accidents and spills as well as industries. (Murray, Rouse and Carpenter 1981; Macay and Cherry, 1989). Understanding the water flow might make it possible to follow the route of harmful substances for example when some leaking accidents occur.

3.2.1 Landfills and nuclear waste deposits

Landfills have been identified as one of the major threats to groundwater. (Fatta, Papadopoulos and Loizidou 1999) Solid wastes dumped on a site release contaminating fluids, and the by-products of decomposition get into the flowing water which goes through the landfill site. Such liquid is called leachate. (Mor, Ravinda, Dahiya and Chandra 2006.) Landfills practically without exceptions hold an amount of hazardous substances, and some of the sites are located so that the runoffs from the dumping ground could reach groundwater even if the site is not in directly above the aquifer. Leaks from landfills harm the environment and humans. Usually restrictions and laws require appropriate sealing of the dumping areas and handling of waste and water on site. (FINLEX, 331/2013). Nevertheless, currently used landfills are very likely to leak leachate into ground and surface waters eventually. Widely used landfill sealings and plastic pipes allow chemicals and gases to pass through their membranes, become brittle, swell, and break down. These leaks are not easily predicted or repaired and such actions demand resources. Breakdowns of inappropriate sites and disasters by other causes might lead unwanted, even hazardous chemicals into the ground and the vadose zone. In aforementioned cases water would be the transferor and lead the pollutants into groundwater resources. (SPRINGHILL: Groundwater management plan 2012-4-16; White, Baker 1997.)

As for nuclear waste deposits, the migration of radionuclides in groundwater would be severely harmful for human and environment. Yet the studies have proven that in majority of cases any migration won’t happen unless the water level rises and so moves the nuclides. (Bergeron and Bugliosi 1988; Kowalski: Midwest Energy News 2013-12-12.) However, because groundwater behaviour over 10,000 years is almost impossible to predict, research and imaging development would be convenient. (Krauskopf, K. B. 1988).

3.2.2 Other spills and contaminants in the ground

There are a number of sources for contamination of ground. For example truck or vessel accidents can cause leaks of variable solvents and oils. (Baehr and Corapcioglu 1984). Broad range of industries as well as oil reservoirs cause leaks and pollution to the environment (Alloway 2013). De-icing of roads in the winter increase salinity in land areas. (Ramakrishna and Thiruvenkatachari 2005)

3.3 Frost heave

Heaving and subsidence of the surface cause damage in cold climates to hard-surfaced roads, plumbing, buildings, foundations, and also to certain agricultural crops. Freezing and thawing of soils are the causes of froth heaving. The uplift of the surface soil is due to the change in volume. Frost action is based on the change in phase of soil water between liquid and ice. As water turns into ice the increase in volume between these phases is 9 % causing upward expansion. (Walters Forensic Engineering 2014-3-4.) The expansion is upward since there is less resistance towards the surface.

The magnitude of frost heaving depends on the local climate, availability of water, and soil texture. The heaving is when the ice lenses form in the soil and below large rock fragments. Ice lenses form when diffused moisture in pores and cracks freezes and wedges the surrounding material. The amount of free water in soil determinates the size of an ice lens. (Rempel 2007.) Ice lenses grow parallel to the surface, and the growing continues as long as there is water available. (Nuttall, 2005.) Capillary action makes free water to migrate through the pores. Some soils are more susceptible to the formation of ice lenses than others. Silts or silty clay soils are the most prone to the frost since the small size of its particles enable the capillary action. Silts and such soils with small particles and gradation detain water and permit it to flow supplying it for lenses. Clayey gravel, rock flour and fine sands are also considered susceptible for formation of frost as well as glacial tills, dirty sands and gravels as fairly susceptible. (Earth Manual 2013-4-4)

Frost heave is found for example from over culvert pipes, roadside ditches or water collectors, and transitions from cut to fill. In general there is frost heaving where there is an abrupt change in sub grade material. Predicting of the direction and the scope of moisture movement and the possibility of frost heaving would help avoiding damages. (Sinnott Blacktop, LLC. 2013-4-4.)

3.4 Economical and legislative aspects

Contamination of ground and groundwater cause great costs and heavy actions. The soil contamination is a widespread problem in Europe. It has been estimated that there are 250 000 sites to be cleaned while over 80 000 sites have been cleaned during the past 30 years. (EPA Soil contamination, 2012-15-3; EEA 2013-4-4.) Costs for cleaning or excavating contaminated land are approximately 100-300 € per metric ton. (Myyrä 2006; FRTR Soil Remediation Technology 2014-3-3.) In the EU, there is a directive 2004/35/CE which has been established for liability towards prevention and remedying of environmental damage. Damage is considered as “damage to protected species and natural habitats, damage to water and damage to soil” (Directive 2004/35/CE.)

3.5 Currently used methods

Currently used methods set the base and a possible need for this thesis. There are currently a number of methods for both, measuring humidity and water movement in soil. There are also some applications of electrical methods used in vadose zone, which are related to this thesis, such as mapping nuclear waste depostits and detecting pore size of soil. Some of the methods mentioned are presented in this chapter.

3.5.1 Measuring soil water and flow of water or other fluids

Soil humidity can be measured based on intrusive spot metering. Soil water potential methods measure the tension and how water in held by soil. Soil water tension is measured using tensiometers and soil moisture blocks as well as granular matrix sensors. (Bouyoucos 1947; Richards 1949; Quails, Scott and DeOreo 2007.) Soil water content methods then again measure directly the amount of water. For example neutron probes and capacitance sensors are used for measuring water content. Also the imaging method used in this thesis, electrical impedance tomography (EIT), measures the conductivity of soil. (Coleman and Hendrix, 1949; Dalton, Beck and Flanagan 1984; Corwin 2005; Goss and Madliger 2007; Grisso, Wysor, Holshouser and Thomason 2014-2.) Measuring electrical conductivity has been the method used also in this thesis. There are applications of methods involving gamma-ray measuring, gravimetric measuring and tracers which have been used for determinating soil moisture. (Belcher, Cuykendall and Sack 1950; Plant and Soil Sciences 1999.) Theoretically, water flow in soil can be measured using spot metering. Humidity can be measured repeaditly in several spots during time in the same area, and the changes in moisture indicate the water flow in soil.

There are methods which are used to measure water or other fluid flow in soil. Water movement in soil is currently measured for example using different tracers as indicatiors. (Allison and Hughes 1983; Barnes and Allison 1988.) These tracers have been located using EIT. The method has also been used for monitoring the infiltration of melt water loaded with deicing chemical and the transport of other contaminants in unsaturated zone. (Aristodemou and Thomas-Betts 2000; Wehrer, Lissner, Bloem, French and Totsche 2-2013.) Spectral induced polarization is commonly used in geophysics for measuring and predicting water flow. (Craig and Lee 2004; Ulrich and Slater 2004). It has been used for example for evaluating the storage properties of soil. (Börner, 1996.) Moreover, there are softwares such as FEMWATER, which is used for simulating water flow and transport. FEMWATER is based on fine element method, and it is tool used for saturated and unsaturated water movement with three-dimensional visualization. (Lin, Richards, Yeh, Cheng J. and Cheng P. 1997.)

Electrical impedance tomography has already been used as a method for measuring flow of water or other fluids, such as contaminants in landfill sites, in vadose zone. (Daily 1992; Binley, Shaw and Henry-Poulter 1996; Slater, Binley, Versteeg, Cassiani, Birken and Sandberg 2002; Chambers, Loke, Ogilvy and Melrdrum 2004; Koestel, Kemna, Javaux, Binley and Vereecken 2008; Akinyemi et al. 2012.) Both two- and three-dimensional imaging has been done using EIT and it is one of the most popular techniques for geophysical applications. (Gunther and Rucker, 2012). For example monitoring volumetric moisture content in soil and the before mentioned flow of tracers have been imaged three-dimensionally using EIT. (Beff, Günther, Vandoorne, Couvreur and Javaux 2013). There are some applications of monitoring water flow in vadose zone based on three-dimensional EIT imaging which have been investigated. (Park 1998; Deiana, Cassiani, Kemna, Villa, Bruno and Bagliani 2007). However, almost all of the currently used methods for monitoring water flow are based on two-dimensional imaging.

3.5.2 Oher thesis related applications

There are some applications based on electrical methods, which have been tested and used for mapping soil. Variety of methods are used for example for mapping contaminants in soil. Electromagnetic geotomography is used for finding nuclear waste deposits and spectral indused polarization for oil-contaminated sand (Ramirez, 1983; H. Vanhala 1997; A. Korpisalo 2014). Leaks from landfills have already been examined by several different methods with applications such as vacuum box, air pressure, spark test, dye, and electrical leak location. So far the most accurate and doable has been electrical leak locating. (Colucci, Darilek, Laine and Binley 1999). Locating leaks from under the lining based on electric method, is based on the electrical characteristics of leaking fluids: the electrical conductivity of the soil increases when the contaminated water infiltrates into it. There are also methods for soil structure and pore size mapping (Koh, Kim, Jung, Hahn and Suh 1997; Delerue, Perrier and Velde 1999). In addition, snowmelt water flow is measured (French 2002).

4 ELECTRICAL IMPEDANCE TOMOGRAPHY IMAGING

Electrical Impedance Tomography (EIT, also known as Electrical Impedance Tomography, ERT is an imaging method based on electrical measurements. In EIT, electric currents are injected, into an examined object through a number of electrodes attached to the surface of the object. Electric current usually is injected between two selected electrodes at a time; various current injections between different electrode pairs are used to collect the whole EIT data set. Corresponding to each injected current, potential differences (voltages) between several pairs of electrodes are measured. Based on this information, the conductivity distribution, in this case the distributed conductivity of soil, is reconstructed. EIT is an ill-posed inverse problem, which means that the reconstructions are extremely intolerant for modeling errors and measurement noise. (L. Borcea 1999.)

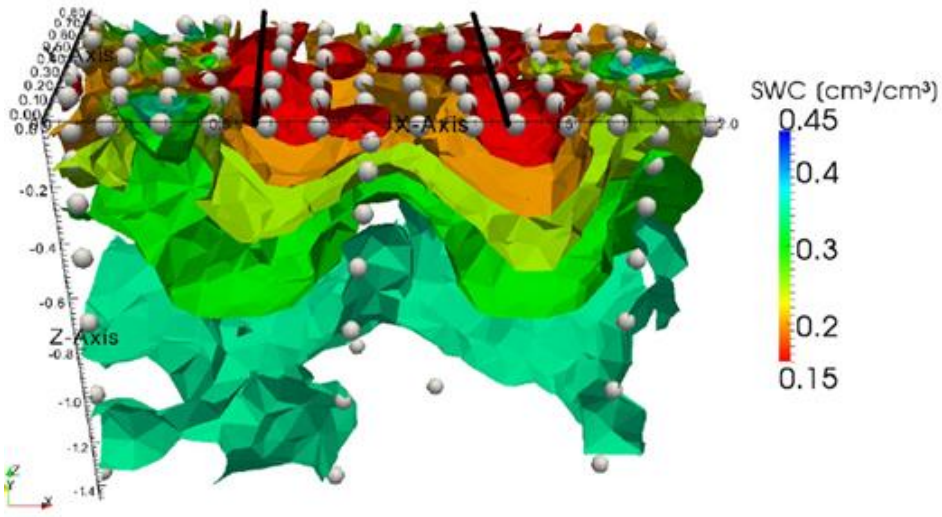

FIGURE 3 Example of EIT imaging of soil (Three dimensional volumetric soil water content reconstructed based on EIT Beff et al. 2013)

EIT has been examined and used as medical imaging technique for example in monitoring human chest and brain. (Holder 1993; Yerworth, Bayford, Cusick and Holder 2002.) In process industry, EIT has been used for imaging flows of fluids in pipes for example in mining and dairy (Scott and McCann 2005.) EIT has also potential applications in non-destructive material testing; for example, the feasibility of EIT for locating cracks in concrete structures has been studied recently. (Karhunen, Seppänen, Lehikoinen, Monteiro and Kaipio 2010). Geophysical applications based on EIT such as mapping an underground structure or moisture content and locating solid rock have already been tested and used for several decades. (Gunther and Rucker 2012.) Vadose zone water movement, snowmelt flow as well as permafrost have been imaged using EIT. (Daily et al. 1992, S. K. Park 1998; French 2002; Krautblatter, Verleysdonk, Flores-Orozco and Kemna 2010). As mentioned before, three-dimensional EIT has already been used for monitoring water content, as shown in Figure 3, and tracers in soil. It has been used for monitoring solute, also known as tracer, transport in soil. For example DNAPL can been used as a solute. (Barnes and Allison 1988; Koestel 2008). DNAPL comes from dense non-aqueous phase liquid, which is organic liquid with contaminants. It is rather insoluable in water; for example transformer oil is DNAPL.

In comparison with various other measurement techniques, an advantage of EIT in examining the content of soil is that there is no need for digging and replacing the soil from area to be measured. It is also a reckoned method for the possibility to see the changes in real-time. If the method and applications would be developed further, the computing and reconstructing images could be made so that the user could see a comprehensive view from underground on a screen in real-time. Currently available commercial devices are based on two-dimensional EIT imaging. However, in reality the conductivity distribution inside an object varies in three dimensions, which means that three-dimensional EIT is required for more reliable imaging.

5 LABORATORY STUDIES

Measuring water flow in soil using EIT was tested in a process tomography laboratory in the University of Eastern Finland. Experimental studies were carried out in Kuopio during 2011-2013.

5.1 Materials and methods

Cylindrical plastic tank with volume of 0.26 m^3 (height 39.5 cm, diameter 46.0 cm) was used in the experiments. Inside the tank, there were 20 electrodes aligned in 4 vertical rows. The electrodes were attached on the inner surface of the tank wall. The measurement device SIPFIN and its remote units were connected to the electrodes (Figure 4). The tank was filled with soil. Water was poured through a tube (⌀ 5 cm) and let absorb into the sample, and measurements were carried out.

FIGURE 4 Left: Photograph of a typical measurement set-up before measuring. Center: Photograph of drying sand between experiments. Right: Photograph of a measurement set-up during experiment. (Photographs Paula Kaipio 2012-2013)

5.1.1 Materials

Experiments were carried out using 3 types of soil. In order to examine the suitability of EIT for imaging different soil types, the experiments were carried out using 3 types of soil. As for selecting and preparing the samples, some constraints had to be addressed:

- Soil samples had to be porous enough for convenient duration of the experiments. Water should be absorbed and the measurements carried out during one day.
- Samples must be electrically conductive in order to use EIT. Samples must be prepared into some level of humidity. Soil also must be packed firmly and evenly in the tank so that there would be not much air. In order to mimic a natural state, the samples should be from nature.

The selected soil types were medium fine sand (Figure 5), fine sand and silty sand. Both fine and medium fine sand were transferred in the laboratory from Noro, Maaninka. The area is located by a natural ridge. The silty sand was digged from steeply sloping terrain at Lukkarila, Varpaisjärvi (Figure 5). Silty sand (SM) is roughly an intermediate of clay and sand. Granularity tests were carried out in geo-technical laboratory in Savonia, in order to determine the soil types. Also the natural moisture content was determined.

FIGURE 5 Left: Photograph of silty sand from Varpaisjärvi. (Photograph Tuomo Savolainen 2012) Right: Photograph of drying the medium fine sand from Maaninka. (Photograph Paula Kaipio 2012)

5.1.2 Sample preparation

In all experiments, a soil sample of 0.26 m^3 per experiment was first dried (Figure 5) and then moisturized with water into the desired level of humidity. A plastic tube was inserted in depth of approximately 1.5 cm from sample's surface. Water was poured through the tube during measurement. Sample was then left to settle in the tank overnight (humidity evens and temperature sets) and the experiment was carried out in the next day. Measurement set-ups and sample handling differedbetween the experiments, depending on the purpose of each experiment. For example, in one test case, an obstacle was inserted into the soil sample.

5.2 Measurement device

SIPFIN system was used in the experiments as the measurement device. It is based on spectral induced polarization. SIPFIN system is modified from a commercially available SIP256 –system. SIP256 –system is used for productive 2-D and 3-D investigations on frequency-dependence of electrical resistivity (amplitude and phase) of rocks and sediments. (Radic research, SIP256-flyer, 2014-5-2) The modified system allows the user to make voltage measurements also on the electrodes connected to the current injection channels. Moreover, the modified system has larger voltage measurement range than SIP256. (Savolainen 2014-5-22.)

5.3 Electrodes and electrical current injections

In the experiments, 20 electrodes were used. The electrodes aligned in 4 vertical rows as shown in Figure 6. As mentioned before, alternating current was injected between electrodes and voltage was measured.

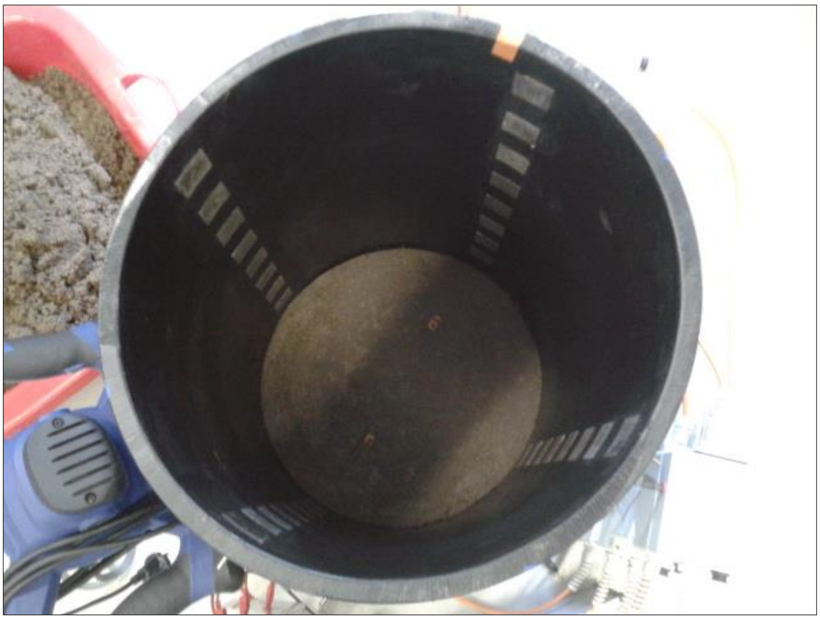

FIGURE 6 Photograph of the tank used in the measurements (Photograph Paula Kaipio 2012)

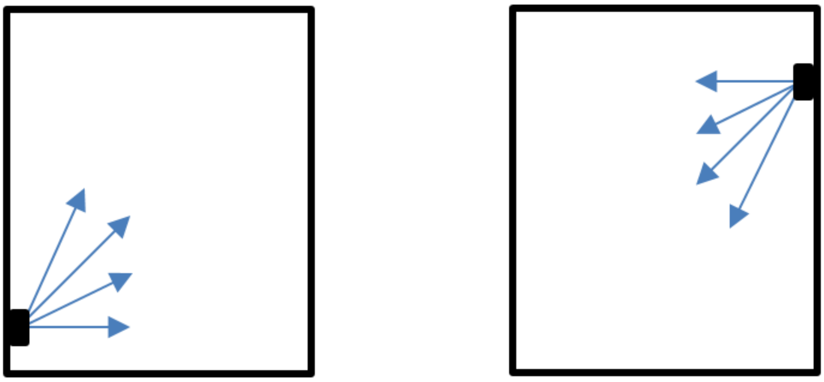

FIGURE 7 Current injections from electrode 1 to all (*left*) and from 18 to all (*right*)

The electrodes were placed and numbered anti-clockwise starting from lowest layer. The currents were injected between electrodes 1-2, 1-3, 1-4… as well as 18-2, 18-3, 18-4... (Figure 6 and 7) Total of 37 current injections were applied. Duration of measuring 37 current injections was 7 minutes. The measurement data corresponding to 37 injections was used for computing one EIT reconstruction. During the infiltration of water, such a set of measurements was carried out about 30 times.

5.4 EIT measurements

SIPFIN's data collecting and transferring remote units around the tank were attached from electrodes from inside the tank to each other and to the main unit. Alternating current was injected from the remote units (20 pc.) through electrodes and the potentials were measured. The main SIP-FIN-unit collects and sends the measured raw data to computer, which has the software for computing the information from the main unit. The data from the measurement system is preprocessed (demodulated) to give the amplitudes of the potentials that are used by EIT reconstructions. After receiving the demodulated data, reconstructions were computed using Matlab.

For every experiment, the first set of EIT data was measured before adding water. This was used as reference data for difference imaging, see below. After this, the experiments were carried out continuously measuring and adding water into the soil. After the wanted amount of water was added, the measuring continued for some time. In general, data was collected before, during and after adding water.

5.5 EIT reconstructions

The data from the experiments was computed using MATLAB. Codes for MATLAB were provided by the Inverse Problems Group, Department of Applied Physics, University of Eastern Finland. (Vauhkonen, Vauhkonen, Savolainen and Kaipio 1999; Karhunen et al. 2010) The image reconstruction problem in EIT is extremely sensitive to measurement noise and errors in measurements and modeling. (Kaipio and Somersalo 2005). In this thesis, most of the results were reconstructed using difference imaging. In difference imaging, a reference data is used for reconstructing the change of the impedance between two data sets. (Kolehmainen, Vauhkonen, Karjalainen and Kaipio 1997). In this case, reference data is measured before adding water, and other data is recognized as the change to the reference data. Difference imaging is a contrast to absolute imaging where the conductivity distribution is reconstructed based on a single data set. There is no reference data in absolute imaging. In the following chapter, the results of the first experiment are reconstructed using absolute imaging. All the other presented results are reconstructed using difference imaging.

Every EIT image reconstruction presented in this thesis is three-dimensional. Most of the reconstructions are presented in two-dimensional vertical cross-sections, to point out the place of water plume inside the tank.

5.6 Results and discussion

The results of the experiments are presented in this chapter. There are four laboratory experiments each representing different purpose for measuring.

5.6.1 CASE 1: Water infiltration in homogeneous sand

The first measurement set-up was made quite simple as it would determine the base for the upcoming experiments. Medium fine, homogeneous sand was used in the experiment due to its suitably high permeability. The sand was evenly packed into the tank. The humidity was set to 7.5 % by mixing the sample, homogenous medium fine sand, and water. After filling and sealing the soil in the tank a tube was inserted in the top soil, 5 cm from the boundary (Figure 8 and 9).

FIGURE 8 Photograph of the experiment in Case 1. (Photograph Paula Kaipio 2011)

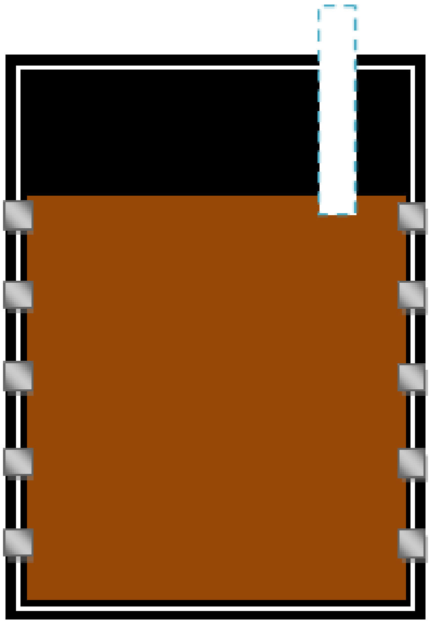

FIGURE 9 Schematic side view at the experiment.

During the first 35 minutes, 2.5 liters of water was injected through the plastic tube. Figure 10 represents the EIT reconstructions corresponding to times 7 min, 14 min,…, 84 min. The first five reconstructions (7-35 min) clearly show the increase of the electrical conductivity due to the infiltration of water. After 35 min, the EIT reconstructions clearly indicate how the moisture spreads in the sample, resulting a relatively uniform conductivity at the end of the experiment (84 min).

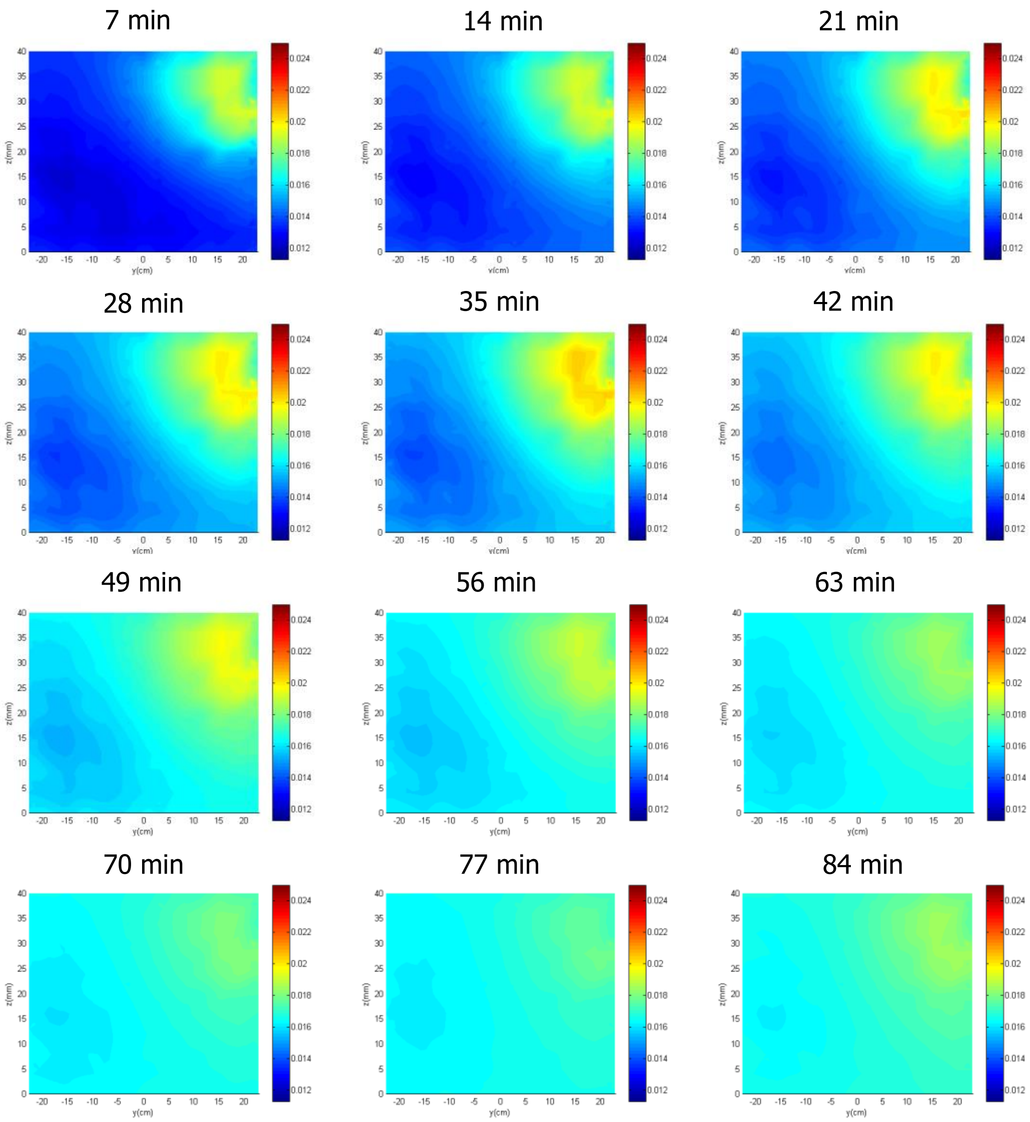

FIGURE 10 Case 1: EIT reconstructions of water infiltration (absolute imaging)

5.6.2 CASE 2: Water infiltration with an obstacle

The aim of the experiment was to figure out if a water plume rounding an obstacle can be seen in EIT reconstructions. A 1 cm thick clay slab was used as an obstacle in the background. Difference imaging was used as a reconstruction method, so the reference data was measured as the clay slab had been inserted in the soil and before water was injected.

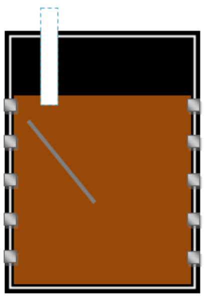

FIGURE 11 Left: Photograph of the experiment in Case 2. (Photograph Paula Kaipio 2012) Right: Schematic side view at the experiment.

Clay slab (33 cm x 17 cm) was inserted in medium fine sand as shown in Figure 11. The clay slab was put to reach over a half the tank. 2.5 liters of water was injected through a plastic tube during 77 minutes. The plastic tube was inserted in the top soil right above the clays lab (Figure 11).

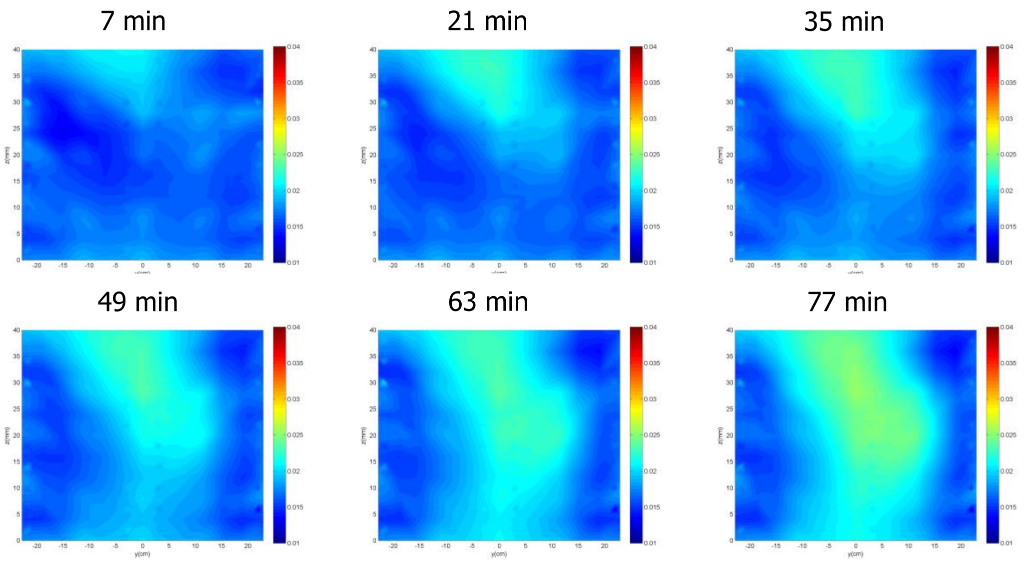

FIGURE 12 Case 2: EIT reconstructions with clay slab (difference imaging)

The EIT reconstructions in Figure 12 represent the water infiltration in this case of a clay slab obstacle, corresponding to times 7 min, 21, min,…, 77 min. Again, the EIT images clearly show the movement of the moisture as higher electrical conductivity during the water infiltration. The images also clearly show how the direction of the flow is affected by the clay obstacle. While in Case 1, the water flow was mostly vertical, in Case 2 the water moves around the obstacle.

5.6.3 CASE 3: Water infiltration with two soil layers

In a natural state of vadose zone, differents soil types are layered. In this experiment two different soils were packed on top of each other harshly mimicking natural soil layers. In addition, soil volumes are rarely homogenous. Silty sand, used in this experiment, was a poorly permeable, non-homogeneous soil type and fine sand is more permeable. The bottom half of the tank was filled with silty, non-homogeneous soil as shown in the Figure 13. The top half of the tank was filled with fine sand (Figure 13). Plastic tube was inserted in the soil from 10 cm from the wall of the tank for adding water. Amount of 400 ml of water was injected into the sample during 5 hours. Difference imaging was used for reconstructions, and reference data was measured before adding water.

FIGURE 13 Left: Photograph of the bottom layer (silty sand) Right: Photograph of the bottom layer (fine sand) of CASE 3 (Photographs Paula Kaipio 2012)

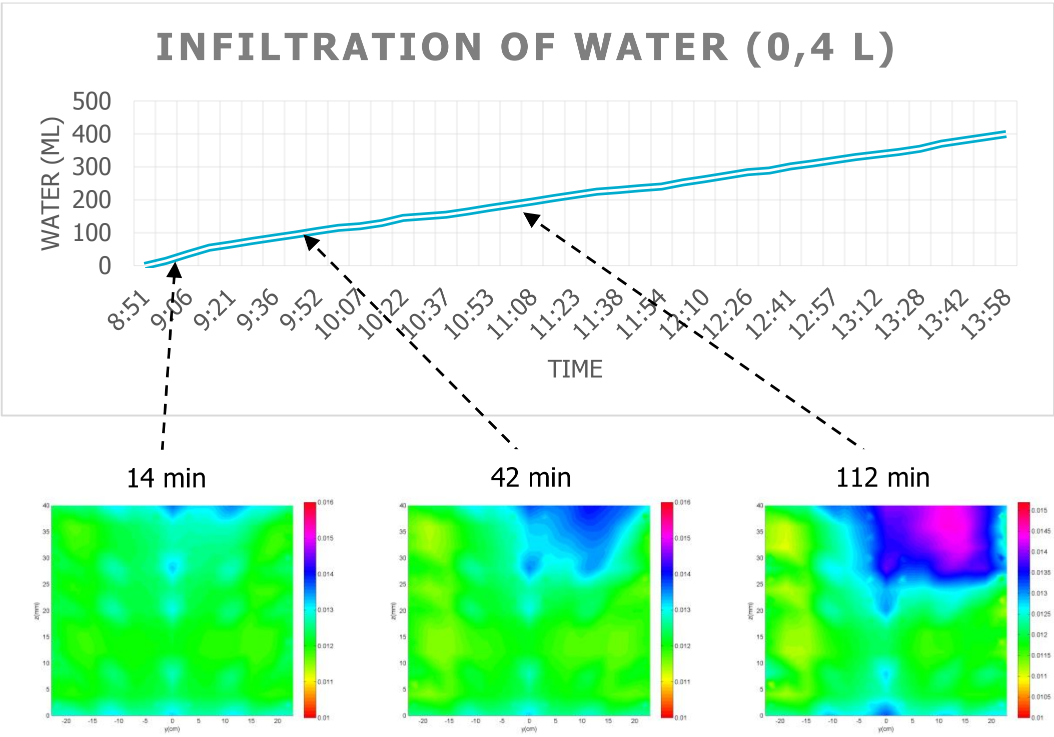

FIGURE 14 Case 3: EIT reconstructions.

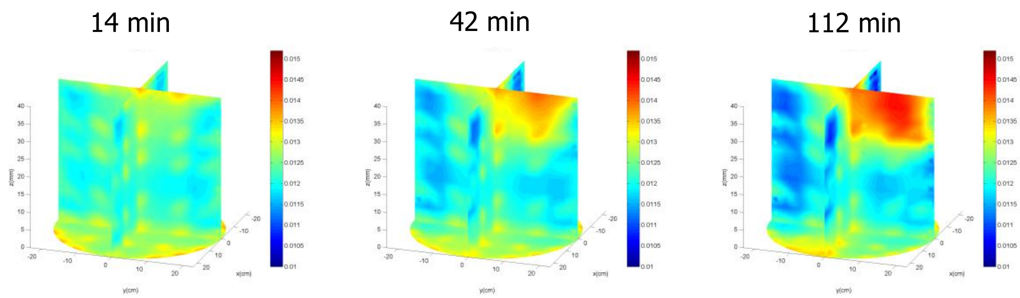

FIGURE 15 Case 3: EIT reconstructions in different color scales and view.

Figures 14 and 15 represent the EIT reconstructions in Case 3, where water was infiltrated through two types of soil. The reconstructions correspond to times 14 min, 42 min and 112 min. The EIT images clearly show the movement of the water during water infiltration. It is also clearly shown, that the water refrains and the electrical conductivity increses on top of the silty soil. While in Cases

1 and 2, the water flow continues towards the bottom of the tank, in Case 3 the water plume only reaches half way of the tank. The later reconstructions of the experiment, which are not presented in these results, look almost equally the same as the third reconstruction at 112 minutes. The volume of higher electrical conductivity doesn't notably spread after 11:08.

5.6.4 CASE 4: Locating substances

Saline fluids or substances in water, which are infiltrated into the soil, are conductive and theoretically suitable for EIT imaging. The ability of imaging water flow in soil using EIT is based on contrasts in electrical conductivity caused by the increase of water content. As a soil sample is moisturized and water is added into the soil, the sample is conductive, and there are changes in conductivity (more saturated soil is more conductive). Electrical conductivity of water depends on the amount of dissolved salts. (R. D. Moore, G. Richards and A. Story, 2008)

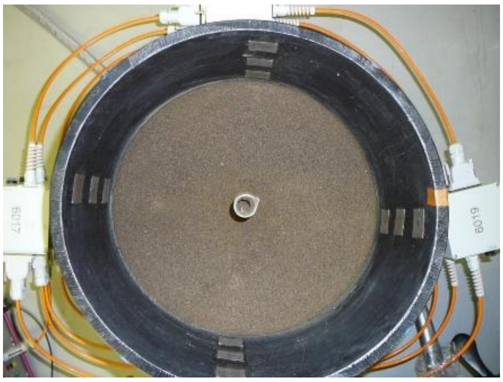

FIGURE 16 Left: Photograph of the experiment in Case 4. Right: Photograph of the amount of salt put in the water. (Photographs Paula Kaipio 2012)

Figures 17 and 18 represent the EIT reconstructions of Case 4, where salt water was infiltrated into the soil. The EIT images correspond to times 21 min, 50 min and 100 min. The movement of the salt water is clearly shown in the middle of the soil volume as the electrical conductivity is notably increasing. The contrast between higher and lower conductivities is clearly seen in the EIT images, which indicate how the salt water is much more conductive than the water used in Cases 1, 2 and 3. In Case 4 the flow in soil is more noticeable in comparison to the previous cases.

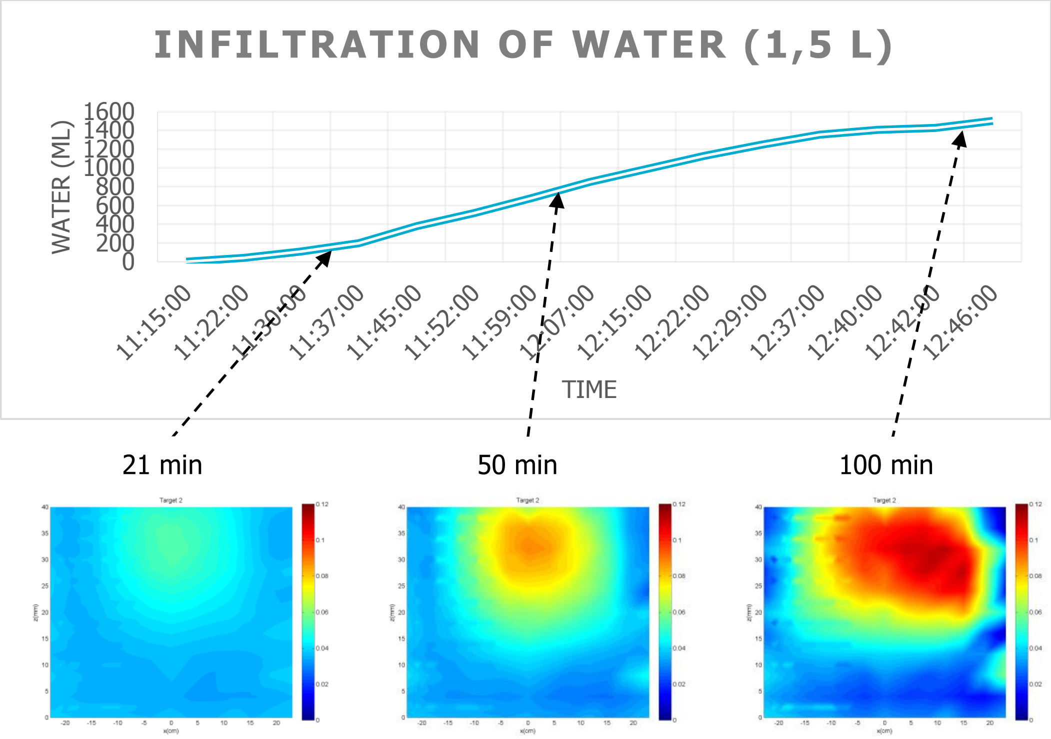

FIGURE 17 Case 4: EIT reconstructions of salt water infiltration

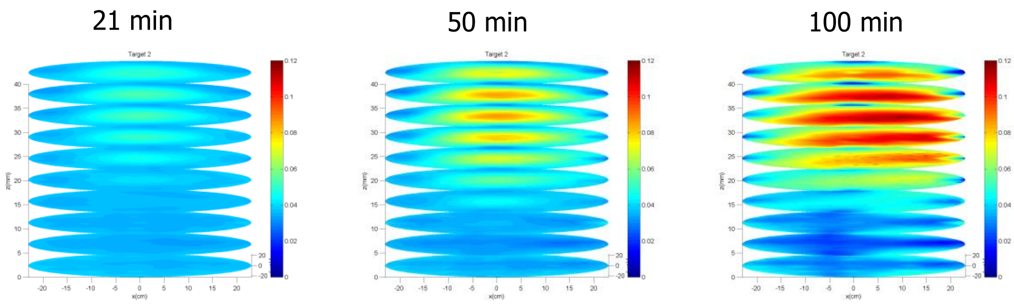

Figure 18 Case 4: EIT reconstructions of salt water infiltration in slices

5.7 Discussion of laboratory experiments

The results of laboratory experiments presented in this chapter are reasonable in general. The direction of water flow and amount of moisture are somewhat visible and deduceable. EIT as an imaging method is extremely sensitive to measurement and modeling errors. Alltogether there are number of factors which might cause errors in the results. Due to this, the results are admittedly good.

Nevertheless, there are errors in some of the reconstructions. There are some artefacts in the three-dimensional EIT reconstructions, which cannot be seen in the presented two-dimensional cross-sections of the EIT reconstructions. Tens of experiments were carried out during the thesis project, of which a few interesting case was selected to be presented this thesis. A few of the test cases of all the experiments resulted faulty EIT reconstructions. These unsuccessful cases as well as some of the artefacts mentioned above have most likely been caused by the measurement device.

In this work, the major source of measurement errors appeared to be the malfunctioning of the SIP-FIN measurement device used in the experiments: at the end of the project, it was noticed that the device measures occasionally the electric current incorrectly. Sometimes this results in relatively large systematic errors which EIT does not tolerate.

In addition, setting up and preparing a measurement can cause errors to the EIT reconstructions. The surface of the electrodes could be too dry causing poor contact impedance, which can cause error. Naturally, user might make mistakes for example while using the software. The user must choose some of the measuring parameters from the software which are used in the Matlab codes. It is possible to make a mistake in selecting these parameters. There is a possibility to make humane mistakes before and during, even after an experiment. Preparation of set-up requires attention in several issues. These preparation issues are such as drying, watering and mixing a sample, keeping the tank and electrodes clean and unbroken as well as cheching the connections between tank and devices. During the experiment paying attention is required; water is poured evenly throughout the measurement, starting measurement and saving data by computer is exactly every 7 minutes (time between data sets) and for example bookkeeping of the added water is done. After measurement, it is important to carefully empty the tank minding the electrodes.

As for modeling errors, EIT is an ill-posed inverse problem, which means that the reconstructions are extremely intolerant modeling errors, as mentioned before. Difference imaging method is usually more tolerant to modeling errors than absolute imaging, and was thus used in most of the above cases. However, it has been shown that with some novel computational methods (especially so-called approximation error method), it is possible to improve the tolerance of the absolute imaging with respect to modeling errors. (Kaipio J. and Somersalo E. 2005) Application of such methods to the experimental data collected in this thesis is one of the next steps in this research. In addition, measuring each data set for 7 minutes results in inaccuracy in the EIT reconstructions: the conductivity of the target is substantially changing due to continuous infiltration of water. However, there are recently developed computational methods also for improving the accuracy of EIT reconstructions affected by the duration between data sets. (Voutilainen, A. Lehikoinen, A. Vauhkonen, M. and Kaipio, J.P. 2011)

6 FIELD MEASUREMENTS

For studying the suitability of EIT for measuring water flow in the vadose zone it is vital to see, how the method works in field studies. The suitability of EIT was tested for measuring water flow in field in Noro, Maaninka, Finland.

6.1 Experiments in general

The field measurements were carried out in Maaninka, Northern Savonia. Part of Northern Savonia's ridge reaches in the area where a stone processing company, Rudus Oy, has its material resource site in Noro, Maaninka. In collaboration with the company, the field measurements was carried out in Noro in October 2012 and August 2013. The aim was to measure water flow in natural state.

FIGURE 19 Maaninka, Northern Savonia

Figure 19 shows the location where the field experiment was carried out. Maaninka is located approximately 44 km North-West of Kuopio. The ridge is presented in Figure 20.

FIGURE 20 Photograph of ridge, Maaninka (Tuomo Savolainen 2012)

The set-up was somewhat comparable to the laboratory scale measurements since the number of electrodes, both lines and rows, depth from the surface, as well as the measuring parameters such as current injection array and frequencies were the same. However, while in the laboratory, rectangular electrodes were used for imaging the contents of a finite sized tank, in the field the electrodes were made of copper tape strips wrapped around four poles that were sticked into the soil. This causes error to the EIT reconstructions because in this work, the electrodes were modeled using the same geometrical pattern as in the laboratory experiments.

6.2 Field measurement October 2012

First field measurement was carried out in October 2012. As shown in Figure 21, the tank used in laboratory experiments was replaced by measurement poles in the field set-up.

FIGURE 21 Photograph of the measurement set-up of the field experiment (2012) (Photograph Paula Kaipio 2012)

As shown in Figure 22, four poles (red) including five electrode strips under surface were inserted into the soil. The soil around the poles was compressed by hand so that there would be no loose or airy gaps, neither difference in compactness around the poles and the area which was to be measured. The tube (green) through which the water was poured was inserted in 3 cm depth.

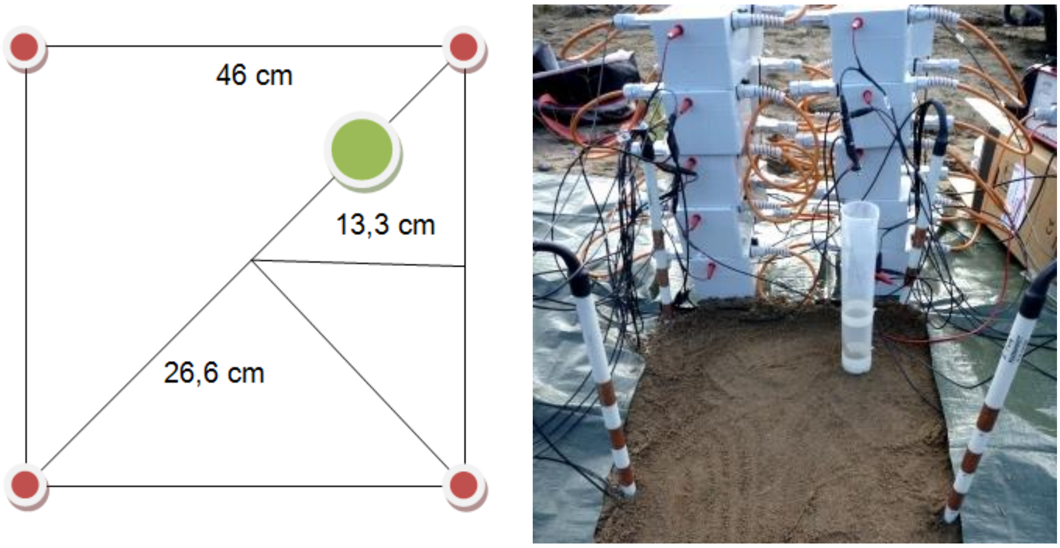

FIGURE 22 Left: Schematic view of electrode pole placement Right: Photograph of measurement set-up of the field measurement (2012) (Photograph Paula Kaipio 2012)

Salt water was injected into the soil during the whole experiment (45 min). Figure 23 represents the EIT reconstructions corresponding to times 7 min, 15 min,…, 45 min. The reconstructions clearly show the increase of the electrical conductivity due to the infiltration of salt water. The reconstructions are presented as two-dimensional cross-sections of three-dimensional EIT reconstructions. The duration of the experiment was only 45 minutes totalling six data sets. The measurement system shut down after 45 minutes of measuring due to the cold weather. The cold weather might also have effected the reconstructions by causing some error.

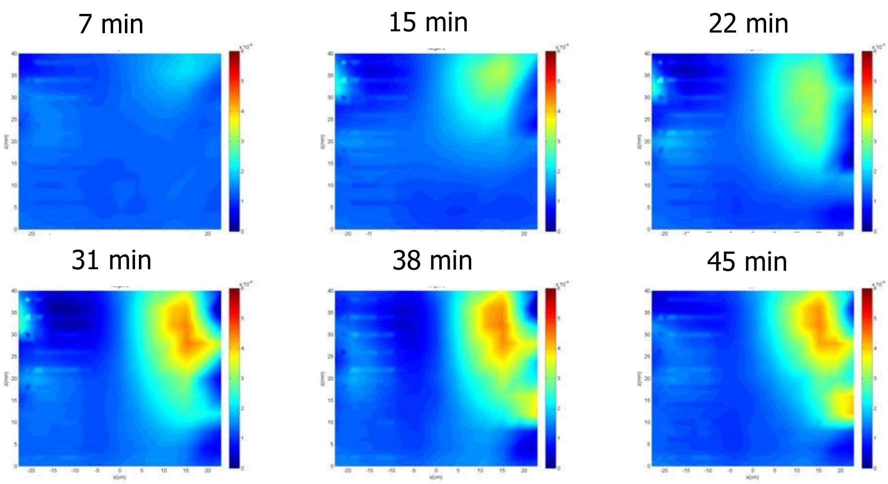

FIGURE 23 EIT reconstructions of the first field experiment (2012)

6.3 Field measurement August 2013

The second field experiment was carried out in August 2013. The experiment was carried out by the same ridge in Noro as the previous experiment (Figure 24). As a difference to the previous measurement, the soil in the second one was finer and more packed sand. Another significant difference between this and the previous field study was that some water was sprayed on the electrodes of the poles to make better contact impedance. These changes had been made in order to improve the results from the first measurement in the field. In addition, this experiment was carried out in warmer weather in order to improve the operability of the measurement system.

FIGURE 24 Photograph of field set-up (2013) (Photograph Paula Kaipio 2013)

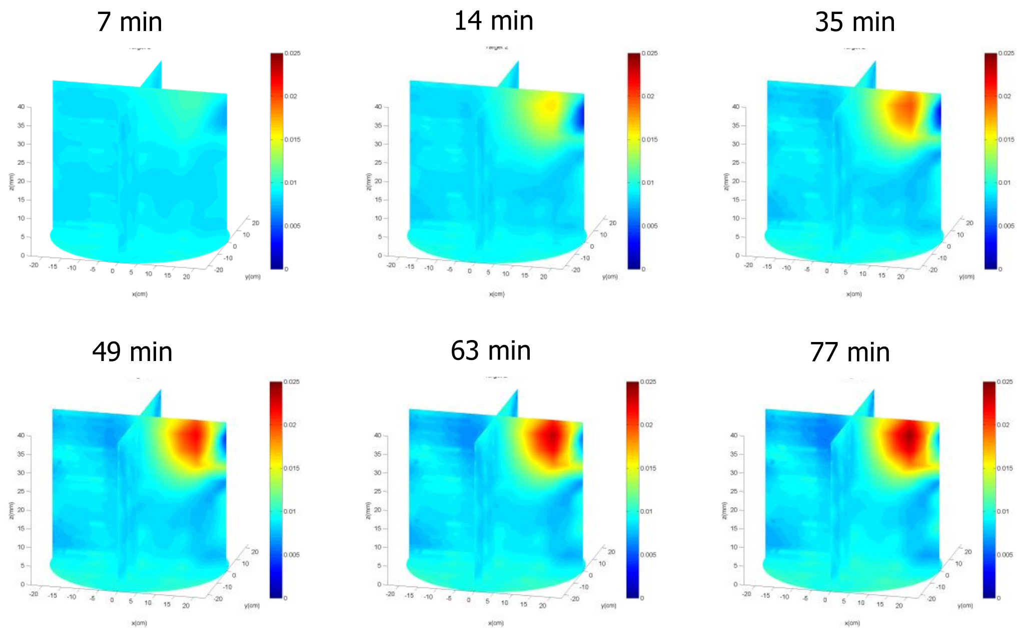

FIGURE 25 EIT reconstructions of the second field experiment (2013)

Salt water was injected into the soil during the whole experiment. Figure 25 represents the EIT reconstructions corresponding to times 7 min, 14 min,…, 77 min. Again, the EIT reconstructions clearly show the increase of the electrical conductivity due to the infiltration of salt water. It is clearly shown how the water flow is slower in comparison with the previous experiment. It was expected due to selecting finer and more packed soil for measuring. In comparison with the first field measurement, there were also a lot more frames of this experiment. Only six of these are presented in Figure 25 since the last frames were extremely similar to the sixth reconstruction (77 min). This suggests that the moisture distribution did not majorly change towards the end of measuring.

6.4 Discussion of field experiments

There are many uncertainties in the field experiments. The results are surprisingly good taking into account especially the geometrical modeling errors made in cases of field studies.

As for the first measurement (October 2012) the temperature during actual measurement was just above 10 degrees which affected the measuring devices and computer. Measuring took more time than normally in laboratory, which makes the reconstructions more inaccurate. The less time measuring one data set takes (of which one reconstruction represents), the better it indicates situation under surface in real time. Now there is only one EIT image per every 7-8 minutes, even though in that time naturally there has been changes in the water movement.

Set-up for field experiment was done imitating the laboratory scale when it comes to the boundaries of the soil between the electrodes. Measured area was set to match the size of the laboratory tank. Also the amount of water poured into the ground, and the size of the tube were same in general in comparition with the laboratory experiments. These arrangements were put up for the ability of using the same Matlab-codes for computing the results, as well as for comparability with the previous results.

Reconstructions of the second experiment (August 2013), are even better in comparison with the first one. The set-up is theoretically equally as prone to the amount of errors, both in measuring and modeling as for the first experiment. However, better results were obtained, perhaps because of warmer weather and better functuability of devices. In addition, finer soil is better choice when it comes to the temporal resolution: water flow is slower. It corresponds better to the 7-8 minutes time lapse of one frame. Otherwise the same factors affected the second field experiment. Overall the set-up was similar in both.

7 CONCLUSIONS

The aim of this thesis was to investigate the suitability of electrical impedance tomography (EIT) for monitoring unsaturated water flow in different soils. Experiments were set up in which EIT measurements were performed during water was added in soil samples. Laboratory and field experiments were carried out to analyse, whether EIT could be used for receiving accurate and feasible three-dimensional reconstructions of water flow in soil.

In both laboratory and field experiments feasible information of moisture distribution was received. The reconstructions of water movement show approximately the position and amount of water in the soil sample. Some faults occurred in part of the results, possibly due to measurement or modeling errors. However, the majority of the results strongly support the usability of EIT for monitoring water flow in soil.

The results indicate that EIT could be used for detecting water flow and saline contaminants in vadose zone, and even the structure of soil. Further feasibility still requires imrovements and more testing, as image reconstruction problem in EIT is very sensitive to measurement and modeling errors. For further testing of EIT, the practical suitability and target for measuring needs to be carefully considered. Measuring water flow in for example silty sand is extremely slow and for example measuring possible leaks in landfills might need reference data before leaking occurs.

The results in this thesis strongly support the possibility of a competitive method for measuring water flow in soil. With more research and testing of EIT, the method could in the future provide even more accurate and reliable information of water movement in soil. The method would at its best enable investigating and predicting water resources even globally. In general, it would possibly be a tool for preventing groundwater contamination, and even for example the causes of frost heaving and spring flooding of extreme snowmelt. Preventing these causes would save resources and support the health of humans and nature.

REFERENCES

AKINYEMI, O. D. OGUNGBE, A.S. OLOWOFELA, J.A. 2012 Imaging and Detecting Underground Contaminants in Landfill Sites Using Electrical Impedance Tomography (EIT): A Case Study of Lagos, Southwestern, Nigeria. Avano.

ALLEY, W.M. REILLY, T.E. and FRANKE, O.L. 1999. Sustainability of ground-water resources. Circular 1186. Denver, CO: U.S. Geological Survey.

ARISTODEMOU, E. and THOMAS-BETTS, A. 2000. DC resistivity and induced polarisation investigations at a waste disposal site and its environments. Journal of Applied Geophysics. 44 (2-3) 275-302

BACKMAN, Birgitta. LUOMA, Samrit. SCHMIDT-THOME, Philipp and LAITINEN, Jukka 2007. Potential risks for shallow groundwater aquifers in coastal areas of the Baltic Sea, a case study in the Hanko area in Southern Finland, 2007. [reference made 2014-4-13] Available at: http://www.helsinki.fi/aleksanteri/civpro/publications/WP2.pdf

BAEHR, Arthur and CORAPCIOGLU, M. Yavuz 1984. A Predictive Model for Pollution from Gasoline in Soils and Groundwater. Virginia: U.S. Geological Survey.

BEAR, Jacob 2007. Hydraulics of Groundwater, McGraw-Hill Book Co., London 567 p. 1979, re-published by Dover Publications, 2007.

BEAR, Jacob 1972. Dynamics of Fluids in Porous Media. Dover

BEAR, J. ZASLAVSKY, D. and IRMAY, S. 1968 Physical Principles of Water Percolation and Seepage. Arid Zone Research. (29) p. 465

BEDIENT, P.B. RIFAI, H.S. and NEWELL, C.J. 1994. Ground water contamination: transport and remediation. New Jersey: Prentice-Hall Publishing Co., Englewood Cliffs, NJ

BEFF, L. GUNTER, T. VANDOORNE, B. COUVREUR, V. and JAVAUX, M. 2013. Three-dimensional monitoring of soil water content in a maize field using electrical resistivity tomography. Hydrology and Earth System Sciences, 17(2), 595-609. http://www.gembloux.ulg.ac.be/agricultureislife/?page_id=121

BELCHER, D. J. CUYKENDALL, T. R. and SACK, H. S. 1950. The measurements of soil moisture and density by neutron and gamma-ray scattering, U.S. Civil Aeronautics Admin. Tech. Devel. Rept. 127, pp. 20, 1950

BERGERON, M. P. and BUGLIOSI, E. F. 1988. Ground-water flow near two radioactive-waste-disposal areas at the Western New York Nuclear Service Center, Cattaraugus County, New York; results of flow simulation. USGS Water-Resources Investigations Report. Available at: http://pubs.er.usgs.gov/publication/wri864351

BORCEA, Liliana 2002. Electrical impedance tomography. Inverse Problems.

BRITSCHGI, Ritva. ANTIKAINEN, Merja. EKHOLM-PELTONEN, Maria. HYVÄRINEN, Vesa. NYLANDER, Esko. SIIRO, Petri and SUOMELA, Tapani 2009. Ympäristöopas, Suomen ympäristökeskus [manual]. [reference made 2014-5-12] Available at: https://helda.helsinki.fi/bitstream/handle/10138/38830/YO_2009_Pohjavesi_11_5_09.pdf?sequence=1

CHAMBERS, J.E. LOKE, M.H. OGILVY, R.D. and MELRDRUM, P.I. 2004. Noninvasive monitoring of DNAPL migration through a saturated porous medium using electrical impedance tomography. 68(1-2) 1-22.

COLUCCI, P. DARILEK, G.T. LAINE, D.L. and BINLEY, A. 199 Locating landfill leaks covered with waste. Proceedings Sardinia 99, 4-8 October 1999 [Conference paper] [reference made 2014-5-5] Available at: http://landect.com/pdf/5Colucci.pdf

DALTON, Russell J. BECK, Paul Allen and FLANAGAN, Scott C. 1984. Electoral Change in Advanced Industrial Democracies. Princeton: Princeton University Press. 3-22.

DEIANA, R. CASSIANI, G. KEMNA, A. VILLA, A. BRUNO, V. and BAGLIANI, A. 2007. An experiment of non-invasive characterization of the vadose zone via water injection and cross-hole time-lapse geophysical monitoring. Near Surface Geophysics 5 (3) 183-194

DOMENICO, P.A. SCHWARTZ, F.W. 1998. Physical and chemical hydrogeology. Publisher: Wiley

EARTH MANUAL, U. S. Department of the Interior Bureau Of Reclamation, 1998. Geotechnical Research, Technical Service Center, Denver: Colorado [Manual] [reference made 2013-4-4] Available at: http://www.usbr.gov/pmts/materials_lab/pubs/earth.pdf

EEP, European Environment Agency. Progress in management of contaminated sites (LSI 003/CSI 015) - Assessment published Aug 2007 [reference made 2013-4-4] Available at: http://www.eea.europa.eu/data-and-maps/indicators/progress-in-management-of-contaminated-sites/progress-in-management-of-contaminated-1

EUROPEAN COMMISSION, Sustainable agriculture and soil conservation, 3-2009, [reference made 2014-5-20]. Available at http://eusoils.jrc.ec.europa.eu/projects/SOCO/FactSheets/ENFactSheet-04.pdf

EUROPEAN PARLIAMENT AND THE COUNCIL 2004. Directive 2004/35/CE, Environmental Liability. 2004-4-21 Reference made [2013-26-3] Available at http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2004:143:0056:0075:en:PDF

FALKENMARK, M. WIDSTRAND, C. 2-1992. Population and water resources: a delicate balance. Population bulletin.

FATTA D., PAPADOPOULOS, A. and LOIZIDOU, M. 1999. A study on the landfill leachate and its impact on the groundwater quality of the greater area, Environmental Geochemistry and Health.

FRENCH, H.K. HARDBATTLE, C. BINLEY, A. WINSHIP, P and JAKOBSEN, L. 2002. Monitoring snowmelt induced unsaturated flow and transport using electrical resistivity tomography. Journal of Hydrology.

FRTR, Soil Remediation Technology; [reference made 2014-3-3] Available at: http://www.frtr.gov/matrix2/section4/4-29.html

GRISSO, Robert. WYSOR, Mark Alley W.G. HOLSHOUSER, David and THOMASON, Wade. Precision Farming Tools: Soil Electrical Conductivity. Available at: http://pubs.ext.vt.edu/442/442-508/442-508_pdf.pdf

GUNTER, Thomas and RUCKER, Carsten 2001. Electrical Resistivity Tomography (ERT) in geophysical applications – state of the art and future challenges. In proceeding of: Schlumberger Symposium - 100 years of electrical imaging, Paris. France.

HAUKSBEE, Francis 1712. An account of an experiment touching the ascent of water between two glass planes, in a hyperbolick figure. Philosophical Transactions of the Royal Society of London, 27 539–540.

HOEKSTRA, A.Y. (Edited) 2003-2. IHE DELFT. Proceedings of the International Expert Meeting on Virtual Water Trade. Researh Report Series No. 12. [reference made 2014-5-11] Available at: http://www.waterfootprint.org/Reports/Report12.pdf

HOLDER, David 1993. Clinical and physiological applications of electrical impedance tomography. London: UCL Press.

INTERNATIONAL ATOMIC ENERGY AGENCY. 2001. Characterization of groundwater flow for near surface disposal facilities. [reference made 2012-4-16]. Available at http://www-pub.iaea.org/MTCD/publications/PDF/te_1199_prn.pdf

KAIPIO, J. and SOMERSALO E. 2005 Statistical and Computational Inverse Problems, Springer New York.

KANSAS GEOLOGICAL SURVEY. 1954-3 Geologic History of Kansas. [reference made 2014-4-24] Available at: http://www.kgs.ku.edu/General/Geology/Marshall/05_gw.html

KARHUNEN, Kimmo. SEPPÄNEN, Aku. LEHIKOINEN, Anssi. MONTEIRO, Paulo J. M. and KAIPIO, Jari P. 2010. Electrical Resistance Tomography imaging of concrete. Cement and Concrete Research.

KOESTEL, J. KEMNA, A. JAVAUX, M. BINLEY, A and VEREECKEN, H. 2008. Quantitative imaging of solute transport in an unsaturated and undisturbed soil monolith with 3-D ERT and TDR. Water Resources Research 44 (12)

KOH, C. S. KIM, M-K. JUNG, H-K. HAHN, S-Y. and SUH, B-S. 1997 Electric Resistivity Tomography for Geophysical Inverse Problems, Magnetics IEEE Transactions 33(2), 1852-1855

KONIKOW, Leonard. GREEN, Timothy R. CHEN, Jianyao. TANIGUCHI, Makoto. BIERKENS, Marc F. P. MCDONALD, Alan. FAN, Ying. MAXWELL, Reed M. YECHIELI, Yossi. GURDAK, Jason J. ALLEN Diana M. SHAMSUDDUHA, Mohammad. HISCOCK, Kevin. YEH, Pat J.-F. HOLMAN, Ian and TREIDEL, Holger. 2012 Groundwater and climate change. Natural Climate Change. Nature Publishing Group: Macmillan Publishers Limited.

KOLEHMAINEN, Ville. VAUHKONEN, Marko. KARJALAINEN, Pasi A. KAIPIO, Jari P. 1997. Assessment of errors in static electrical impedance tomography with adjacent and trigonomtric current patterns. Physiological Measurement 18 (4)

KOWALSKI Kathiann M. 2013. Study Supports Nuclear Waste Disposal near Great Lakes (Midwest Energy News on 2013-9-9). [reference made 2013-12-12]. Available at: http://www.midwestenergynews.com/2013/09/09/study-supports-nuclear-waste-disposal-near-great-lakes/

KRAUSKOPF, K.B. 1988. Geology of High-Level Nuclear Waste Disposal. Annual Review of Earth and Planetary Sciences 16, p. 173.

KRAUTBLATTER, Michael. VERLEYSDONK, Sarah. FLORES-OROZCO, Adrian and KEMNA, Andreas. 2010-1 Temperature-calibrated imaging of seasonal canges in permafrost rock walls by quantitative electrical resistivity tomography (Zugspitze, German/Austrian Alps). Journal of Geophysical Research: Earth Surface (2003-2012) 155(F2) American Geophysical Union.

LAVAPURO, Maarit. LIPPONEN, Annukka. ARTIMO, Aki. KATKO, 2008-10-31. Tapio S. Groundwater sustainability indicators: testing with Finnish data. Boreal Environment Research 13, 381-402. Helsinki. [reference made 2014-2-3] Available at: http://www.borenv.net/BER/pdfs/ber13/ber13-381.pdf

LEHTINEN, Martti. NURMI, Pekka and RÄMÖ, Tapani 1998 (toim.): Suomen kallioperä: 3000 vuosimiljoonaa. Helsinki: Suomen geologinen seura. [reference made 2014-5-15] Available at: http://www.geologinenseura.fi/suomenkalliopera/index.html

LIN, Hsin-Chi J. RICHARDS, David R. YEH, Gour-Tsyh, CHENG, Jing-Ru and CHENG, Hwai-Ping. FEMWATER: A Three-Dimensional Finite Element Computer Model for Simulating Density-Dependent Flow and Transport in Variably Saturated Media. U.S. Army Corps of Engineers and Pennsylvania State University Technical Report CHL-97-12. 1997

MOORE, R.D. RICHARDS, G. and STORY, A. 2008. Electrical Conductivity as an Indicator of Water Chemistry and Hydrologic Process. Streamline: Watershed Management Bulletin 11(2) [reference made 2014-2-24] Alaivalbe at: http://www.siferp.org/sites/default/files/publications/articles/streamline_vol11_no2_art5.pdf

MOR, Suman. RAVINDA, Khaiwal. DAHIYA, R.P. and A. CHANDRA. 2006 Leachate Characterization and Assessment of Groundwater Pollution near Municipal Solid Waste Landfill Site. Environmental Monitoring and Assessment.

MURRAY, James P. ROUSE, Jim V. and CARPENTER, Alden B. 1981. Grounwater contamination by sanitary landfill leachate and domestic wastewater in carbonate terrain: Principle source diagnosis, chemical transport characteristics and design implications. Water Research 15(6) 745-757. Elsevier.

MYYRÄ, Karoliina, 2006. Pilaantuneiden maiden puhdistus rakennuskohteissa [reference made 2013-8-17] Available at: http://www.theseus.fi/bitstream/handle/10024/11146/2006-08-21-18.pdf?sequence=1

NIMMO, J. R. Unsaturated zone Flow Process, 2005 [reference made 2014-5-12] Available at: http://wwwrcamnl.wr.usgs.gov/uzf/abs_pubs/papers/nimmo.05.uzflowproc.ehs.hsa161.pdf

NUTTALL, Mark 2012-11-12. Encyclopedia of the Arctic. Routledge (imprint of Taylor and Francis)

O'GEEN, Anthony Toby 2012 (Soil Resource Specialist in Cooperative Extension Dept. of Land, Air and Water Resources, UC Davis) Nature Education [Reference made 2014-5-20] Available at: http://www.nature.com/scitable/knowledge/library/soil-water-dynamics-59718900

ORAM, HALSOR, REDMONT 2013-4-4 Water Quality [Booklet] [reference made 2013-4-4] Available at: http://wilkes.edu/Include/WaterResearch/PDFs/Waterbooklet070610.pdf

PARK, S. K. 1998. Fluid migration in the vadoze zone from 3-d inversion of resistivity monitoring data. Geophysics.

PHYSICAL GEOGRAPHY, Chapter 8: Introduction to the Hydrosphere. Infiltration and Soil Water Storage. 2009-7-5 [Reference made 2014-5-12] Available at http://www.physicalgeography.net/fundamentals/8l.html

PLANT AND SOIL SCIENCES. 1999. Chapter 4, Measuring Soil Water [reference made 2014-5-4] Available at: http://croptechnology.unl.edu/pages/informationmodule.php?idinformationmodule=1130447123&topicorder=4&maxto=13&minto=1

QUAILS, Russell J. SCOTT, Joshua M. and DEOREO William B. 2007-6-8 SOIL MOISTURE SENSORS FOR URBAN LANDSCAPE IRRIGATION: EFFECTWENESS AND RELIABILITY JAWRA Journal of the American Water Resources Association 37 (3) 547-559

RADIC RESEARCH, Germany, SIP256-flyer [refered on 2014-5-2] Germany. Available at: http://www.radic-research.homepage.t-online.de/Flyer_SIP256C_161104.pdf

RAMAKRISHNA, Devikarani M. and THIRUVENKATACHARI, Viraraghavan. 2005. Environmental Impact of Chemical Deicers – A Review. Water, Air and Soil Pollution 166 (1-4) 49-63

REMPEL, A.W. 2007-6-21. Formation of ice lenses and frost heave. Journal Geophysical Research: Earth Surface (2003-2010) 112(F2). American Geophysical Union. [Open access article] [reference made 2014-5-16] Available at: http://pages.uoregon.edu/rempel/15_jgr07.pdf

RICHARDS, L.A. 1931. Capillary Conduction of Liquids Through Porous Mediums. Journal of Applied Physics 1(5): AIP Publishing.

ROTH, K. 2012: Soil Physics Lecture Notes, V2.2 Soil Water Flow Institute of Environmental Physics, Heidelberg University, Germany [Lecture Notes] [Reference made 2014-3-25] Available at: http://www.iup.uni-heidelberg.de/institut/forschung/groups/ts/soil_physics/students/lecture_notes05/sp-v2.2-ch6.pdf

RUSANEN, Kaisa. FINER, Leena. ANTIKAINEN, Merja. KORKKA-NIEMI, Kirsti. BACKMAN, Birgitta and BRITSCHGI, Ritva 2004. The effect of forest cutting on the quality of groundwater in large aquifers in Finland. [Open access publication] [reference made 2014-4-23] Available at: http://www.borenv.net/BER/pdfs/ber9/ber9-253.pdf

SAVOLAINEN, Tuomo. Inverse Problems & Mathematical Modelling: Process Tomography Laboratory (Introduction). [reference made 2014-5-22] Available at: http://venda.uef.fi/inverse/FrontPage/LaboratoryFacilities/ProcessTomo

SCOTT, D and McCANN, H. 2005. Handbook of Process Imaging for Automatic Control. CRC Press.

SINNOTT BLACKTOP, LLC. Frost Action and Frost Heaving [reference made 2013-4-4] Available at: http://www.sinnottblacktop.com/frostactionandheaving.htm

SLATER, L. BINLEY, A. VERSTEEG, R. CASSIANI, G. BIRKEN, R. and SANDBERG. S 2002. A 3D ERT Study of Solute Transport in a Large Experimental Tank. Journal of Applied Geophysics, 49 (4) pp. 211-229.

SPRING HILL GROUNDWATER SUPPLY PROTECTION AREA CONSULTATIVE COMMITTEE, Australia. 2001. Groundwater management plan 2001 [reference made 2012-4-16] http://www.g-mwater.com.au/downloads/Groundwater/Springhill_Groundwater_Mgt_Plan.pdf

TABER, Stephen. 1929. Frost Heaving. The Journal of Geology. Chicago: The University of Chicago Press.

TAYLOR, Richard G. SCANLON, Bridget. DÖLL, Petra. RODELL, Matt. VAN BEEK, Rens. WADA, Yoshihide. LONGUEVERGNE, Laurent. LEBLANC, Marc. FAMIGLIETTI, James S. EDMUNDS, Mike.

ULRICH, C. and SLATER, L. 2004. Induced polarization measurements on unsaturated, unconsolidated sands. Geophysics 69(3), 762-771

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY (EPA), 2011. Groundwater [reference made 2012-2-3]. Available at: http://cfpub.epa.gov/eroe/index.cfm?fuseaction=list.listBySubTopic&ch=47&s=201

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY (EPA), 2011. Soil Contamination [reference made 2012-3-15]. Available at: http://www.epa.gov/oswer/international/factsheets/200906_eu_soils_contamination.htm

VALTIONEUVOSTON ASETUS KAATOPAIKOISTA: 331/2013. FINLEX 2013. [Law decree] [reference made 2014-2-1] Available at: http://www.finlex.fi/fi/laki/alkup/2013/20130331

VAUHKONEN, P.J. VAUHKONEN M. SAVOLAINEN, T. AND KAIPIO, J.P. 1999. Three-dimensional electrical impedance tomography based on the complete electrode model. IEEE Trans. Biomed. Engineering. 46, 1150-1160

VOUTILAINEN, A. LEHIKOINEN, A. VAUHKONEN, M. and KAIPIO, J. P. 2011 A reduced-order filtering approach for 3D dynamical electrical impedance tomography Measurement Science and Technology 22 (2)

WALTERS FORENSIC ENGINEERING. Frost Heave (Civil Engineering vol.1 No.11) [reference 2014-3-4] Available at: http://www.waltersforensic.com/articles/civil_engineering/vol1-no11.htm

WHITE, C. C. and BAKER, R. D. Summer, 1997. Electrical leak detection system for landfill liners: a case history.” Ground Water Monitor Remediation, v.17, n.3, p.153-159ALLOWAY, Brian J. 2013. Heavy Metals in Soils, Trace Metals and Metalloids in Soils and their Bioavailability. Environmental Pollution 22

YERWORTH, R. J. BAYFORD, R. H. CUSICK, G. CONWAY, M. and HOLDER, D. S. 2002. Design and performance of the UCLH Mark 1b 64 channel electrical impedance tomography (EIT) system, optimized for imaging brain function. Physiological Measurement.

APPENDIX 1 MEASUREMENT RECORDING SHEET

EXPERIMENT #   , DATE

ARRANGEMENTS

1. Injections:
2. Soil type:
3. Humidity:
4. Weight (DRY/WET):

MEASURING

1. Obstacle Y/N
   a. Size/Shape:
   b. In front of electrode:
   c. Depth from surface:
   d. Distance from inner side:
2. Amount of water added:
3. Permitting

Time	Amount (ml)

4. Tube
   a. Size/Shape:
   b. In front of electrode:
   c. Depth from surface:
   d. Distance from inner side:

DATA

1. Voltage:
2. Shunt:
3. Other parameters:
4. Homogeneous:
   a. 2012_ _homog V.txt
   b. 2012_ _homog V.txt
   c. Voltage/…
5. Data names:
   a. 2012_ .txt – 2012_ .txt

OTHER INFORMATION