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Multicomponent digital-based seismic landstreamer and boat-towed RMT systems for urban underground infrastructure planning

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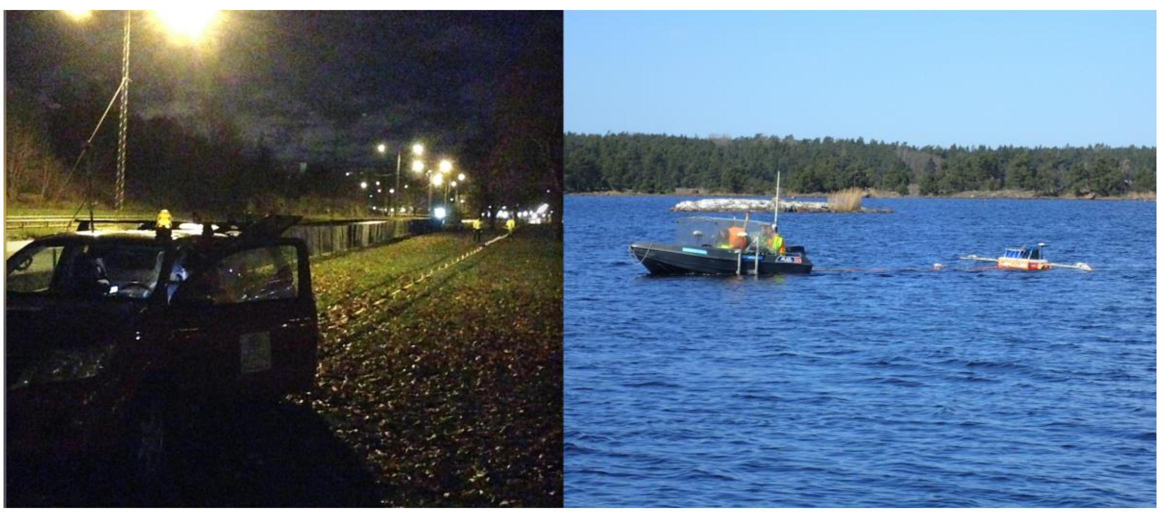

PREFACE

Urban environment poses by far a different challenge to most geophysical surveys than those of other places. Given the logistic challenges, space limitation, mixed land and water bodies, various type of noise, source and receiver coupling, and urban underground complexities, new and refined ways to better tackle these issues are necessary. In the frame of an industry-academia consortium (TRUST: TRansparent Underground STructures), we, TRUST 2.2, have developed a digital, MEMS-based, 3C seismic landstreamer and a boat-towed radio-magnetotelluric (RMT) system that can partly overcome some of these challenges in the urban environment. We have tested them at several sites and studied them for their applications for urban underground infrastructure planning projects. We, for example, illustrate that the seismic streamer is free of electromagnetic-electric noise; it allows high-resolution broadband data recording and it is by far superior to its geophone-type predecessors when it comes to its full spectrum of applications. The boat-towed RMT system combined with additional low-frequency controlled sources makes the method quite cost-effective, e.g., 1 km line data per hour, and is reliable for bedrock mapping and fracture delineation.

More than 15 relevant sites in Sweden, Norway, Finland and Denmark were surveyed during the course of the project illustrating the innovative aspect of the systems and their sustainability beyond TRUST 2.2 project. As an example, in a dedicated test at the Äspö Hard Rock Laboratory we targeted a fracture system using surface-tunnel-surface seismic data acquisition. Low-velocity zones related to steeply dipping fracture systems were delineated and their dynamic mechanical properties such as Poisson's ratio and seismic quality factor studied. Changes in these parameters for different fracture sub-sets were related to the degree of fluid conductivity and fracture aperture and orientations.

TRUST 2.2 was sponsored mainly by Formas and co-financed by BeFo, SBUF-Skanska, SGU, FQM and NGI. Several case studies were carried out using external funding provided for example by Tyréns for the Varberg double-track underground train-planning project, Turku water management company, Yara, SKB, Nova FoU-Oskarshamn, NGI-Oslo, among others.

The project supported three PhD students, one post-doc and several short-term researchers and has so far resulted over 15 peer-reviewed publications and more than 40 conference publications. Several popular science Swedish and English publications and short videos were also produced to outreach the activities.

FÖRORD

Urbana stadsmiljöer utgör i många aspekter större utmaningar för geofysiska mätningar än de flesta andra miljöer. Det är därför nödvändigt att utveckla nya och förbättrade metoder för att kunna hantera logistiska utmaningar, bristen på utrymme, kombinationen av både land- och vattenytor, olika typer av brus, sensorernas och källans koppling till marken, samt komplexa förhållanden i underjorden. Inom ramarna för ett samarbete mellan industrin och akademin (TRUST: Transparent Underground STructures) har vi inom TRUST 2.2 utvecklat en seismisk landstreamer med digitala MEMS-baserade 3-komponentsensorer och ett system för radiomagnetotelluriska (RMT) mätningar som bogseras efter en båt. Dessa system kan i viss utsträckning övervinna flera av utmaningarna i urbana miljöer. Vi har genomfört ett flertal tester vid olika platser och för varierande ändamål och utvärderat resultateten och teknikens användbarhet för planeringen av underjordiska infrastrukturprojekt. Vi har bland annat demonstrerat att den seismiska landstreamern möjliggör insamling av högupplöst bredbandsdata utan att påverkas av elektromagnetiskt brus och att den är, när det gäller hela dess breda spektrum av användningsområde, helt överlägsen de sensorer av geofon-typ som länge varit standard. Det båt-bogserade RMT systemet i kombination med en kontrollerad källa för lågfrekventa signaler har visat sig vara både jämförelsevis snabbt (med exempelvis 5 km profilmätningar per dag) och pålitligt vid kartläggning av berggrunden och sprickzoner.

Fler än 15 relevanta platser i Sverige, Norge, Finland och Danmark har undersökts som en del i projektet och påvisar de innovativa aspekter som gör systemet flexibelt och användbart långt bortom TRUST 2.2. Som ett exempel undersöktes ett spricksystem genom ett specialanpassat experiment vid Äspö Hard Rock Laboratory med hjälp av seismisk datainsamling mellan markytan och ett tunnelsystem. Låghastighetszoner relaterade till kraftigt stupande spricksystem kunde kartläggas och dess dynamiska och mekaniska egenskaper, såsom Poisson’s faktor och den seismiska kvalitetsfaktorn, kunde studeras. Förändringar i dessa egenskaper mellan de olika spricksystemen kan relateras till variationer i sprickornas storlek, orientering och hydrauliska konduktivetet.

TRUST 2.2 har i huvudsak finansierats av Formas tillsammans med BeFo, SBUF-Skanska, SGU, FQM och NGI. Ett flertal fallstudier kunde utföras genom extern finansiering från olika partner, såsom exempelvis Tyréns när undersökningar gjordes för den planerade dubbelspåriga tågtunneln i Varberg.

Hittills har tre doktorander, en postdoktor och ett flertal korttidsanställda forskare finansierats genom projektet och resulterat i publikationen av mer än 15 vetenskapligt granskade artiklar och 40 konferensbidrag. Dessutom har ett flertal populärvetenskapliga artiklar på både svenska och engelska samt videoklipp producerats för att informera och involvera allmänheten.

SUMMARY

Over the past few years, the demand for urban infrastructures has continuously increased worldwide and in particular, in Sweden. However, there is a lack of knowledge about subsurface geology and structures in the urban environment. Occasionally, information about former or hidden outcrops exists or is available from, for example, municipalities, consultants, and construction companies. Accurate knowledge about the bedrock depth and condition is important for planning a trench or a tunnel because it may imply what kind of excavation and rock reinforcement methods should be used. The urban environment is, however, challenging for most geophysical methods due to the multiple sources of noise (e.g., ground vibrations caused by vehicles and electromagnetic noise from power lines) and spatial and temporal restrictions imposed on geophysical surveys by infrastructure. The geophysical survey equipment used needs to be flexible and versatile, and highly insensitive to electromagnetic noise. In this project, we have developed a multicomponent broadband seismic landstreamer system based on digital sensors and particularly suitable for noisy environments and areas in which high-resolution images of the subsurface are desired. We have evaluated results, interpretations, and approaches using the streamer in the planning of several underground infrastructure projects in Sweden, Norway and Finland. We have also developed a new data acquisition system and technique to measure the radio magnetotelluric (RMT) signals from distant radio transmitters with the objective of mapping and modeling electric resistivity structures below a river or lake. A boat tows the acquisition system; therefore, we refer to it as boat-towed RMT. The data acquisition is fast with a production rate of approximately 1 km⁄hr using a nominal sampling spacing of 10–15 m. Owing to the ample number of radio transmitters available in most parts of the world, the method can be used for near-surface studies of various targets. We have developed boat-towed RMT measurements on Lake Mälaren near the city of Stockholm in Sweden and at the Äspö Hard Rock Laboratory to determine the feasibility of the method. The boat-towed RMT technique is well suited for water bodies with moderate electric resistivity such as in brackish and freshwater environments. The project has served research materials for three PhD students (two defended in fall 2017 and one during February 2018), one post-doc and several short-term researches.

SAMMANFATTNING

Under de senaste åren har efterfrågan och krav på urban infrastruktur ökat över hela världen och då inte minst i Sverige. Även om viss information om berggrunden från platser som idag inte är tillgängliga ibland kan ha bevarats av t.ex. kommuner, konsult- och byggföretag, så saknas dock oftast kunskap och förståelse om rådande geologi och strukturer under ytan i stadsmiljöer. En detaljerad kunskap om förhållanden i berggrunden är väldigt viktig vid planeringen av till exempel diken, kulvertar och tunnlar eftersom det kan avgöra vilka metoder som bör användas vid när man gräver eller förstärker.

Geofysiska mätningar i en dynamisk stadsmiljö är däremot i de flesta fall förknippat med en mängd svårigheter relaterat till begränsningar i utrymme och tid samt den stora mängden av signalstörningar (t.ex. markvibrationer från fordon eller elektromagnetiska störningar från kraftledningar). Därför ställs det höga krav på att den geofysiska mätutrustningen måste vara flexibel och anpassningsbar för en mängd olika situationer med minimal påverkan på omgivningen. Men samtidigt får den inte heller påverkas av t.ex. elektromagnetiskt brus.

Som en första del i detta projekt har vi utvecklat ett seismiskt landstreamer-system med digitala multikomponent-sensorer som är känsliga över ett brett frekvensspektrum. Detta har visat sig särskilt lämpligt när man är i behov av högupplöst information i omgivningar med starkt störande miljöer. Både tekniken och metoder för datainsamling med den seismiska landstreamern, samt resultat och tolkningar av insamlad data har utvärderats vid ett flertal planeringsprojekt för underjordisk infrastruktur i både Sverige, Finland och Norge.

För att möjliggöra kartläggning och modellering av elektriskt resistiva strukturer i berggrund som täcks av sjöar eller vattendrag har vi dessutom utvecklat helt ny utrustning och en ny metod för mätning av radiomagnetotelluriska (RMT) signaler från avlägsna radiosändare. Detta system bogseras på vattenytan av en båt och metoden har därför getts namnet båt-bogserad RMT. Datainsamlingen har visat sig kunna göras förhållandevis snabbt vid till exempel profilmätningar med en hastighet på ungefär 1 km per timme om mätvärden tas med 10 – 15 meters mellanrum. Tack vare det stora antalet aktiva radiosändare som finns över hela världen så kan metoden användas för många olika typer av studier. Den båt-bogserade RMT metoden har testats och utvärderats genom mätningar vid Mälaren i närheten av Stockholm och vid det underjordiska Äspö Hard Rock Laboratory. Den båt-bogserade RMT metoden lämpar sig särskilt bra på vatten med måttlig resistivitet, såsom bräckt vatten eller färskvatten. Hittills har forskningen inom projektet sysselsatt tre doktorander (som förväntas disputera mot slutet av 2017), en post-doktor och ett flertal korttidsanställda forskare.

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1. INTRODUCTION

Over the past few years, the demand for urban infrastructures has continuously increased worldwide and in particular, in Sweden. However, there is a lack of knowledge about subsurface geology and structures in the urban environment. Occasionally, information about former or hidden outcrops exists or is available from, for example, municipalities, consultants, and construction companies. Accurate knowledge about near-surface geology and rock quality is important for planning of underground infrastructures because it implies what kind of excavation and rock reinforcement methods should be used. The urban environment, however, is challenging for most geophysical methods due to the multiple sources of noise (e.g., ground vibrations caused by vehicles and electromagnetic noise from power lines) and spatial and temporal restrictions imposed on geophysical surveys by infrastructure. The geophysical survey equipment used needs to be flexible and versatile, and highly insensitive to electromagnetic noise. Geophysical systems and methods have to also be developed top tackle water-bodies covering 7-8% of Swedish land where the need to develop infrastructures in these areas is highly.

1.1 Scope and objectives

To overcome issues with the electromagnetic noise and also to provide sensors that are of higher amplitude dynamic compared with common geophones, we developed a multicomponent broadband seismic landstreamer (Figure 1). We based it on the micro-electromechanical systems (MEMS) sensors and tested and employed it during the course of the project for planning of several major urban underground infrastructures inside and outside Sweden. A boat-towed RMT system (Figure 1) was also developed and used at several test sites in Sweden to show case its potential for delineating structures that are crucial for planning of under-water tunnels or facilities. Along the equipment developments, several methods and algorithms were developed to extract rock quality information and proxies that can be directly linked to tunneling design or compared with parameters obtained using static tests.

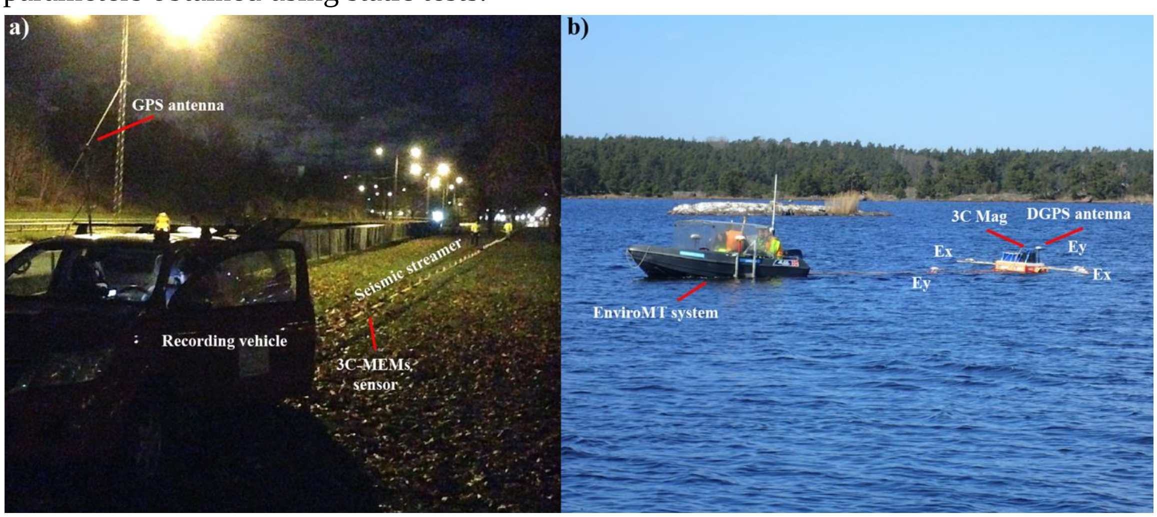


Figure 1. *(left) Seismic landstreamer when tested at the Vinsta access ramp (Förbifart Stockholm) during its early stage of development (the first test in 2013) and (right) the boat-towed RTM when tested over the Äspö HRL facility (2015).*

The project comprised of 4 main steps:

- Brainstorming and backyard tests on instrumentations
- Small-scale tests and quality control against known targets
- Larger-scale surveys and becoming involved in major running urban underground infrastructure projects
- Developing algorithms and methodologies to maximize the results and their impacts with a particular focus on either extracting dynamic mechanical properties or quantifying uncertainty in the results.

The working team had two separate objectives: (i) development of the seismic landstreamer and boat-towed RMT and also (ii) met, discussed and provided ways to integrate the two methods with each other also other type of data. TRUST 2.2 (*Development of modern seismic and electromagnetic methods for pre-investigation for underground infrastructure facilities in urban environment*) also provided support and input to other projects; for example collaborated with TRUST 2.1 (*Geoelectric mapping as a tool for pre-investigation for underground infrastructure facilities in urban environment*), TRUST 3.3 (*Real time monitoring of grouting need using the RTGC-method*) and TRUST 4.2 (*Integrated use and interpretation of geophysical and non-geophysical data in pre-investigations for underground infrastructure facilities*).

1.1.1 Project structure and advisory board

The core institutions worked actively on the project were Uppsala University and the Geological Survey of Sweden. The project however benefited from additional experts and advisors who provided feedbacks and supports but also organized sites and knowledge to improve data acquisition and methods used in the project. The core research team consisted of:

Uppsala University: Alireza Malehmir, Christopher Juhlin, Laust B. Pedersen, Lars Dynesius, Bojan Brodic (PhD student), Suman Mehta (PhD student), Shunguo Wang (PhD student), Joachim Place (post-doc), Mahdieh Dehghannejad (short-term researcher), Magnus Andersson (short-term researcher), Emil Lundberg (short-term researcher).

SGU: Mehrdad Bastani, Lena Persson, Philip Curtis, Sverker Olsson.

Support and advisory team: Robert Sturk (Skanska), Per Tengborg (BeFo)
Andre Pugin (Geological Survey of Canada), Mats Svensson (Tyréns), Chris Wijns (FQM, Australia), Andreas Aspmo Pfaffhuber and Sara Bazin (NGI), Roger Wisén and Christer Andersson (Ramboll), Nils Rydén (PEAB), Antti Pasanen (GTK), Ulrich Polom (LIAG), Cecilia Montelius (NCC).

1.1.2 Sponsors and industry participants

These organizations provided direct funding to TRUST 2.2:
Formas: The main funding sponsor of the project.
Uppsala University: A major in-kind supporter of the project.
Geological Survey of Sweden (SGU): Co-financed the project through sponsoring their staff and funding for boat-towed RMT surveys.
BeFo: Co-financed the project for 4 years through the support of the PhD students and their field activities.

SBUF-Skanska: Co-financed the project for 4 years through the support of the PhD students and their field activities. Skanska was also providing advice and support to the activities of TRUST 2.2.
Norwegian Geotechnical Institute (NGI): Co-financed the project through sponsoring their staff and provided funding to employ the streamer for the planning of E18-Oslo underground tunnel.
First Quantum Minerals Ltd. (FQM): A small co-financing through their staff and consulting during the course of the project.
Boliden: A small co-financing through a test site at Laisvall. Boliden pulled out during the second year of the project.
Tyréns: Became a major supporter of the project by providing test sites at Varberg and Kristianstad.
Nova FoU-SKB: Sponsored the tunnel-surface-tunnel seismic experiment and the boat-towed RMT at Äspö HRL. SKB also sponsored the Bollnäs geophysical investigations.

Project progress and example case studies were presented at two major Swedish related conferences:

- Malehmir, A., Lundberg, E., Dehgahnnejad, M., Zhang, F., Friberg, O., Brodic, B., Döse, C., Place, J., Svensson, M., and Möller, H., 2015. Varberg: Developing urban geophysical instruments and methods – Pushing the boundaries. **Grundläggningsdag** (Foundation Day), Stockholm, Sweden, 15 pages.
- Malehmir, A., Lundberg, E., Dehgahnnejad, M., Zhang, F., Friberg, O., Brodic, B., Döse, C., Place, J., Svensson, M., and Möller, H., 2015. Seismic landstreamer for planning of infrastructure projects – A case study from Varberg. **Bergmekanikdagen** (Rock Mechanic Day), Stockholm, Sweden, 15 pages.

1.1.3 Educational aspects and cross collaborations

TRUST 2.2 had a major component in supporting three PhD studies. Two licentiates by Bojan Brodic and Suman Mehta were produced during December 2015. Three PhD theses were defended in September 2017 (Shunguo Wang), October 2017 (Suman Mehta) and February 2018 (Bojan Brodic) at which the project formally finalized.

- Licentiate thesis of Bojan Brodic can be found here:

http://uu.diva-portal.org/smash/get/diva2:873173/FULLTEXT01.pdf

- PhD thesis of Bojan Brodic can be found here:

http://uu.diva-portal.org/smash/get/diva2:1164138/FULLTEXT01.pdf

- Licentiate thesis of Suman Mehta can be found here:

http://uu.diva-portal.org/smash/get/diva2:875252/FULLTEXT01.pdf

- PhD thesis of Suman Mehta can be found here:

https://uu.diva-portal.org/smash/get/diva2:1135290/FULLTEXT01.pdf

- PhD thesis of Shunguo Wang can be found here:

http://uu.diva-portal.org/smash/get/diva2:1129430/FULLTEXT01.pdf

During the course of the project we also collaborated with TRUST 3.3 to monitor grouting in artificial fractures using ultrasonic waves and sensors (Place et al., 2016).

The collaboration has also been fruitful with TRUSTs 2.1 and 4.2 at Äspö HRL, Lake Mälaren, Varberg and Dalby.

1.2 State-of-the-art and success measures

TRUST 2.2 had a late start due to missing co-financing issues but quickly managed to recover when the potentials of the instrumentations and ideas became clear to several partners inside and outside of the project team. The landstreamer system for example has been and is being used in various projects hence meeting the main objective of the call by Formas on being truly innovative. The application fields are enormous as listed in the following where we have contributed with the instrumentations and methods:

Sweden:

- Laisvall (October 2014): Mineral exploration and geological mapping
- Stockholm (November 2013): Förbifart Stockholm, site characterization and equipment quality control
- Kristianstad (April 2014): Contaminated site and test work
- Varberg (May 2014): Planning of a double-track train tunnel
- Bollnäs (October 2014): Post-glacial fault imaging
- Äspö (April 2015): Tunnel-surface-tunnel seismics and boat-towed RMT for fracture mapping and rock quality estimations
- Ludvika (October 2015): Mineral exploration and geological mapping
- Mora (October 2015): Geological mapping
- Malmberget (Nov 2015): Mine planning
- Varberg (June 2017): Contaminated site prior in the planning of the tunneling project

Norway:

- Oslo (June 2015): Planning of E18-Oslo tunnel

Finland:

- Turku (July 2014): Esker structures and water management
- Siilinjärvi (July 2014): Mineral exploration/mine planning

Denmark:

- Stevns chalk group May 2016, PhD school

More than 15 peer-reviewed publications, 30 conference abstracts, 30 oral presentations (including keynotes) nationally and internationally, contribution to popular science publications and promotional videos, two-licentiate theses and several reports have come out of TRUST 2.2 project. Examples are provided in the publication list.

1.2.1 Beyond TRUST 2.2-GeoInfra project

TRUST 2.2 will continue employing the methods and instruments developed within the project beyond the TRUST project. Examples include:

- High-resolution landstreamer seismic studies prior to the COSC2 deep drilling (sponsored by SGU to Peter Hedin et al.): planned for August 2017.
- High-resolution in-mine landstreamer seismics similar to the Äspö HRL surface-tunnel-surface test sponsored by EIT KIC Raw Materials to be used at Garpenberg mine: planned for 2018.
- Planned activities and further developments in an up-coming H2020 project.

2 INSTRUMENT SET-UP

2.1 Seismic landstreamer

Similar to marine seismic surveys, the idea of having a portable receiver array that can be towed along the surface has been intriguing researchers working on shallow subsurface characterization using seismic methods on land as well. In the 1970s, this led to the development of the concept of a seismic landstreamer. Landstreamer is defined as an array of seismic receivers that can be dragged along the surface without the need for 'planting'. The concept was first applied in the form of a snow-streamer and since this pioneering work, seismic landstreamers of various kinds have proven their value and potential. This is particularly true for near-surface mapping and characterization in urban areas, especially on asphalt and/or paved surfaces (see Brodic et al., 2015 and references therein). Published studies involving landstreamers for acquiring seismic data have used various types of geophones, mostly single geophones on a sled (vertical or horizontal), two geophones per sled (one vertical and one horizontal), or in our case even single 3C accelerometers (see Brodic et al., 2015 and references therein). In contrast to the mentioned studies, the Uppsala University landstreamer (Figure 2) is built with digital 3C, MEMS-based sensors, making this landstreamer a unique system to date. Compared to geophones that are widespread and conventionally used, the MEMS-based sensors are digital accelerometers designed to work below their resonance frequency (e.g., 1 kHz).

Figure 2. *Photos showing details of the landstreamer versus planted geophones tested at the early stage of the development of the streamer. (a) Landstreamer was located in the middle of two planted geophone-type (10 Hz on the right-hand and 28 Hz on the left-hand side) lines. Note the difference in cabling involved for the planted lines and the streamer-mounted units. A sledgehammer was used as the seismic source in this study. (b) Side-by-side comparison between planted and streamer mounted 3C (DSU3, MEMS-based) sensors. This test was done to study different characteristics of the seismic wavefield registered on the streamer mounted sensors and if the sleds have some noticeable effects on the wavefield especially the horizontal components.*

Advantages of MEMS over geophones include their broadband linear amplitude and phase response (0-800 Hz), tilt angle measurements up to high angles and insensitivity to contamination from electric or EM noise sources (Figure 3). The landstreamer is based on Sercel Lite technology and Sercel DSU3 (MEMS-based) sensors. The sensors are mounted on sleds (receiver holders), and the sleds fixed firmly to a non-stretchable woven belt used in the aircraft industry (Figure 2). The system was designed to support both DSU3 sensors and geophones and can be combined with wireless units for complementary acquisition if longer offsets are necessary (Figure 2). Technical details of the developed system can be found in Table 1.

Table 1. *Technical details of the system developed in this study.*

Parameters	**UU Seismic Landstreamer**
Sensors	3C MEMS
Frequency bandwidth	0 - 800 Hz
Tilt angle	Recorded in the header
Acquisition system	Sercel Lite (MEMS + geophones)
Max number of channels	2000
Present configuration	100 sensors on 5 segments each 20 units and spaced 2 m, 20 units spaced 4 m
Cable connection	Sensors on a single cable
Data transmission	Digital
Data format	SEGD
GPS time of the record	Recorded in the header

The present-day configuration of the streamer consists of five segments with each of the segments having 20 sensors mounted. The segments are interconnected by small carriages carrying line-powering units (Figure 2). Four of the segments contain 20 units spaced 2 m, while the fifth one has 20 units spaced at 4 m. The spacing can be reduced to 25 cm, if required. The entire five segments long spread connected by small trolleys was designed to be as light as possible and easily pulled by a 2WD or 4WD vehicle. With a team of 3 to 4 persons for the set-up, data acquisition rates vary from 600 m to 1200 m of seismic line in a day using a source spacing of 2 m to 4 m. A summary of the key landstreamer properties can be found in Table 2.

Table 2. *Summary of the important characteristics of the developed landstreamer.*

Technical advantages of the developed seismic landstreamer
1. Less sensitivity to tilting or can be easily estimated and corrected for it using built in tilt test
2. Full digital data transmission avoids any pick-up noise, crosstalk and sensitivity to leakage
3. It is lighter and requires less number of batteries compared to the existing and comparable technology available on the market
4. No need for sensor planting, an issue in big cities, mines, etc.
5. High-resolution imaging using densely spaced sensors
6. Covering large areas relatively fast
7. Easily combined with wireless units to extend the line or extending offset
8. It can be towed in series (2D surveys) or parallel (3D surveys)
9. It can be used for both passive (ReMi, MASW) and active data recording

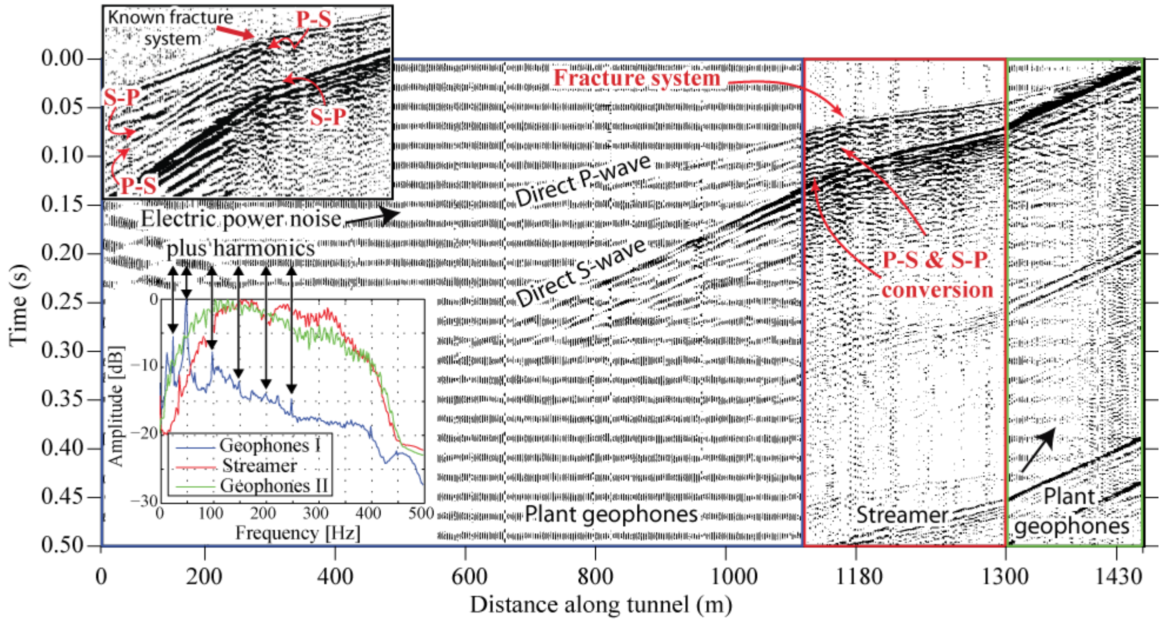


Figure 3. *Example shot gather acquired from the tunnel experiment at Äspö HRL showing the quality of streamer data in comparison with the plant geophones. Note the 50 Hz noise contaminations and its harmonic sequence in the geophone data that are totally absent in the streamer data. A major fracture system inside the tunnel was the target of this study producing strong wave-mode conversions (P-S and S-P) that are better noticeable in the streamer data (see the inset on the top).*

2.2 Boat-towed RMT

The boat-towed RMT system is developed for shallow fresh water surveys to support the planning phase of underground infrastructure developments in the city of Stockholm (Bastani et al., 2015) and evolved from the EnviroMT acquisition system (Bastani, 2001) that has been traditionally used for land surveying. The RMT method uses distant radio-transmitters in the very low frequency range (VLF, 15–30 kHz) and low-frequency range (30-300 kHz) as the EM source. Compared with traditional VLF measurements, RMT covers a wider frequency range and the data are used to model the variations of the electrical resistivity in the subsurface.

The boat-towed RMT system remains the same as for the land surveys, with the difference of the analog part of the equipment being mounted on a floating platform made of wood and Styrofoam and towed by a boat (Figure 4). The analog parts include a 3C magnetic field sensor (MFS), steel electrodes, analog filter (AF) box and other electronics. Three components of the Earth's magnetic field are measured by the MFS on the platform. Measurement of the two components of the electric field is enabled by two pairs of steel electrodes (with buffer amplifiers used to minimize capacitive leakage in the cables) fixed on a pair of five-meter-long arms (Figure 4, marked by '1' and '2'). The floating platform is towed at a distance of 10 m behind the boat and connected to an additional arm carrying the cable used to transfer the analog signal to the digital part of the system that is positioned inside the boat (Figure 4, central processing unit). The measurements with the boat-towed RMT system are carried out while the boat is moving, making the data acquisition much more efficient and faster compared to the land surveys.

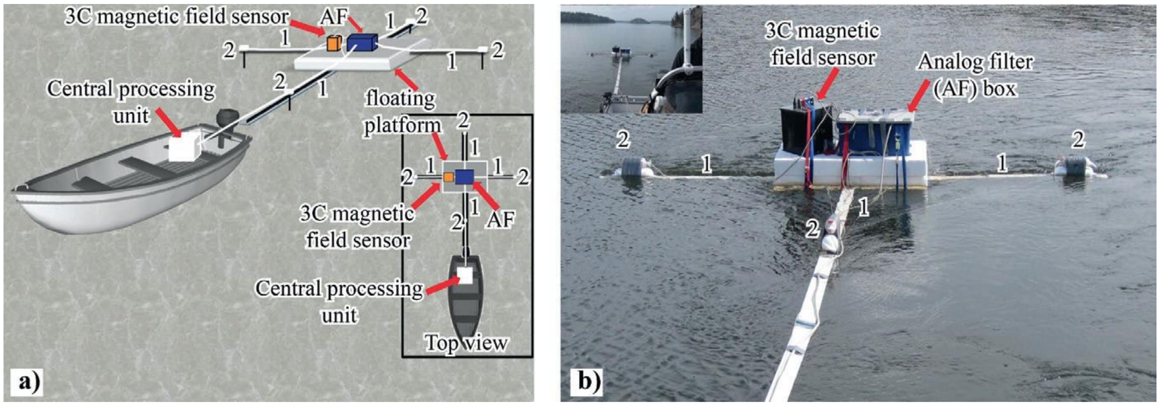


Figure 4. *Boat-towed RMT acquisition system schematic (a) and a photo of the actual look of the system with inset showing it dragged behind the boat (b). Arms and cables for electric field measurements are marked with '1', while '2' marks 4 steel electrodes with buffer amplifiers. From Bastani et al. (2015).*

3. EXAMPLES OF FIELD DATA AND RESULTS

3.1 Vinsta Stockholm Bypass access ramp (Förbifart)

This survey was carried out at the early stage of the system development and for checking the potential of the landstreamer system in urban environment. Stockholm Bypass (also known as Förbifart Stockholm) was chosen, which is a planned underground highway (8 lanes) approximately 21 km long of which more than 17 km is to be tunnel through crystalline bedrock (www.trafikverket.se/forbifartstockholm). It will pass under 3 water bodies, with the deepest point reaching approximately 85 m below sea level. A test site where an access ramp for the tunneling will start, "Vinsta", located in the northern part of Stockholm city was chosen for the streamer test (Figure 5).

Motivation to carry out the test at this site was a priori knowledge about a potential weak zone identified by a number of geotechnical boreholes suggesting poor rock quality (geotechnical Q-value below one) close to where the two seismic lines were designed to intersect each other (Figure 5). The geophysical objectives of the study were to evaluate the potential of the landstreamer in such a noisy environment, combination of the streamer with wireless units, obtaining information about depth to the bedrock and velocity information that may be linked to the rock quality, especially where the poor quality rocks were inferred to be present.

During November 2013, we acquired two seismic lines (Lines 1 and 2; Figure 5) at the site. Due to the urban nature of the site, after a reconnaissance, a decision was made to conduct the whole survey at night to avoid heavy traffic and, most importantly, trams passing next to one of the seismic lines (Line 2). Although we managed to avoid "rush hours", there was still significant traffic during the whole survey time, including trams passing every few minutes up until midnight and heavy trucks passing due to accessibility to the city during the night hours. The trams stopped for four hours during the nights for maintenance between 1 a.m. and 5 a.m., thus allowing a time slot to conduct the survey.

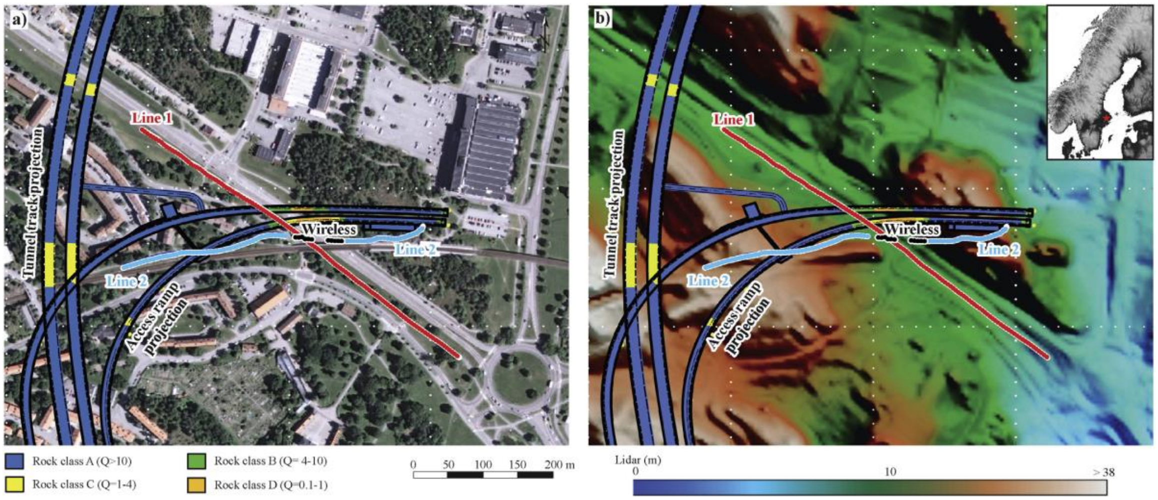


Figure 5. *Location of seismic lines (Lines 1 and 2) with respect to the planned access ramp and the main tunnel projected to the surface (a) aerial photo and (b) LiDAR (elevation) map. Colors on the tunnel track and access ramps show different rock classes identified from geotechnical boreholes. Twelve MEMS-based wireless recorders, six on each side of the road, are marked with the black points. Geotechnical data were kindly provided by the Swedish Transport Administration (Trafikverket). From Brodic et al. (2015).*

Tomography results along Line 1 (Figure 6) suggest that the bedrock deepens towards the southeastern side of the line, but with sharp changes in elevation where the poor quality rocks are observed. The sudden change in the bedrock topography may be an indication of fracturing or faulting, hence the poor quality of rocks at this location. Bedrock in the northwestern side of the line is as shallow as a couple of meters. The tomography results along Line 2 suggest an undulating bedrock surface with its deepest point where the road is located (Figure 6). At almost every location where velocities more than 5000 m/s are observed near the surface there is bedrock outcropping (our observations), supporting the tomography results and further showing the potential of the streamer for this type of application. This test survey was encouraging to use the streamer for more real applications with no known or little known subsurface geology.

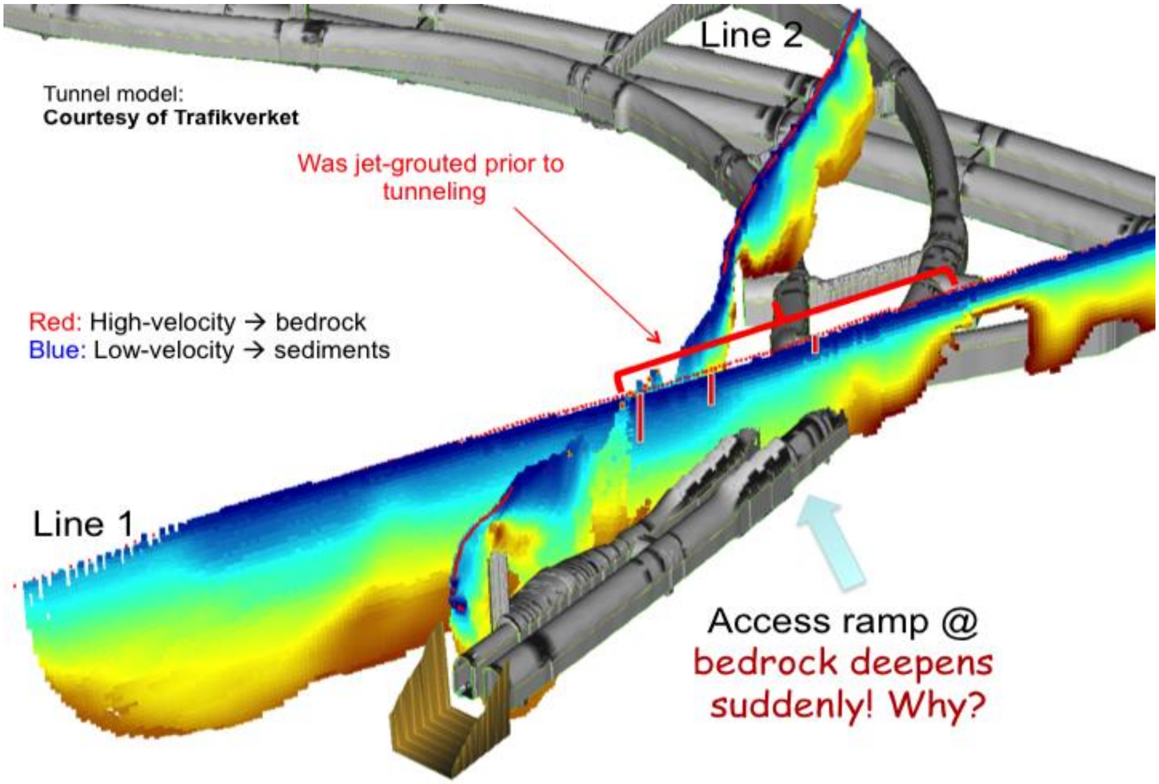


Figure 6. *3D view showing visualization of the first-break traveltime tomography results with the model of the planned tunnel and the access ramp. It indicates a low-velocity zone where the bedrock deepens and where rocks have poor quality. This area was jet grouted prior to the excavation. The tunnel model was kindly provided by the Swedish Transport Administration (Trafikverket). Modified from Brodic et al. (2015).*

This study showing the development of the landstreamer was published by Brodic et al. (2015) for the Journal of Applied Geophysics.

3.2 Varberg double-track train tunnel

As an example, the streamer was used for the planning of an underground double-track train tunnel in the city of Varberg in southwest Sweden during May 2014. Targets were depth to bedrock and weakness zones (e.g., fracture zones) in it. More than 7 km of high-resolution seismic data, 25 profiles, were acquired using 2-4 m source and receiver spacing and an accelerated weight-drop (ESS100) source. At places where placing the streamer was not possible (e.g., at road crossings), wireless recorders were deployed (Figure 7); these data were later merged with the streamer data using the GPS time of the active shots recorded on the streamer data. Details of the data acquisition and results can be found in Malehmir et al. (2015).

Figure 7. Field photos showing the acquisition conditions in the city of Varberg. (a) Combined seismic streamer and wireless recorders (often about 4 m apart) were used to acquire the data (along line 2 and parts of line 3; see Figure 1). (b and c) Ground conditions and (d) use of a sledgehammer for some of the lines in downtown Varberg. From Dehghannejad et al. (2017).

As an example we present first-break tomography results (Figure 8) from the city center area and their correlations with borehole data (bedrock depth) provided to us for this study. A good correspondence can be observed in most places illustrating the success of the streamer in this project.

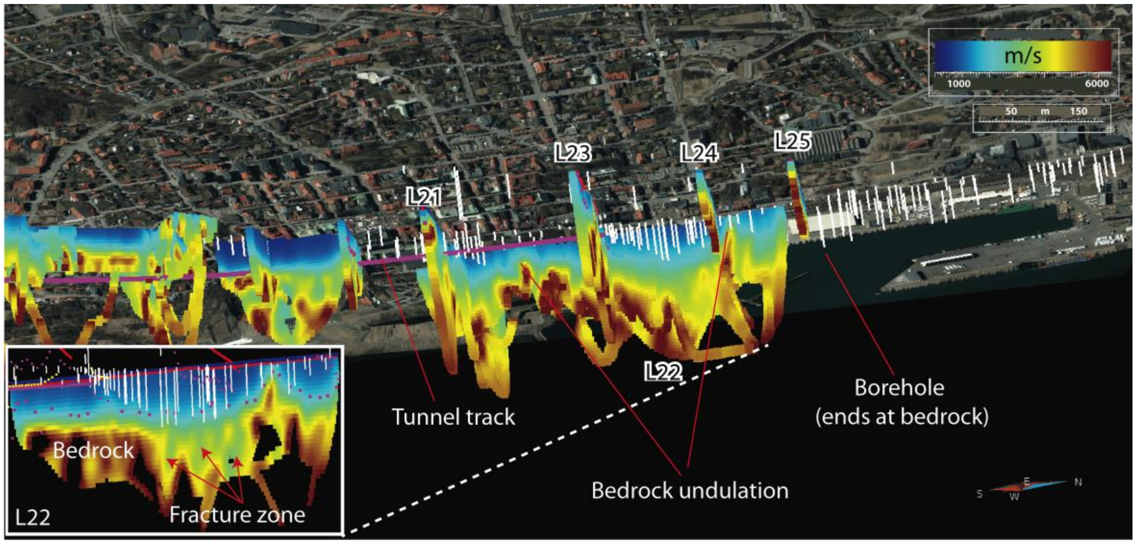


Figure 8. *3D view (from below) showing first-break tomography results in the city center (about 12 profiles are shown) and available borehole data (until May 2016). The planned tunnel is shown using purple line. A close up of the results along profile 22 where several fracture systems are speculated is shown as an inset. Modified from Malehmir et al. (2015) and Dehghannejad et al. (2017).*

Varberg seismic studies were published in Geophysics by Malehmir et al. (2015) and Near Surface Geophysics by Dehghannejad et al. (2017).

3.3 Bollnäs post-glacial fault

We were asked by SKB if we could use our newly developed systems for delineating a speculated post-glacial fault near the city of Bollnäs, central Sweden. Glacially induced intraplate faults are conspicuous in Fennoscandia where they reach trace lengths of up to 155 km with estimated magnitudes up to 8 for the associated earthquakes. While they are typically found in northern parts of Fennoscandia, there are a number of published accounts claiming their existence further south and even in northern central Europe. This study focused on a prominent scarp discovered recently in LiDAR (light detection and ranging) imagery hypothesized to be from a post-glacial fault and located about 250 km north of Stockholm near the town of Bollnäs. The Bollnäs scarp strikes approximately north–south for about 12 km. The maximum vertical offset in the sediments across the scarp is 4–5 m with the western block being elevated relative to the eastern block. To investigate potential displacement in the bedrock and identify structures in it that are related to the scarp, we conducted a multidisciplinary geophysical investigation that included gravity and magnetic measurements, high-resolution landstreamer seismics, land RMT, electrical resistivity tomography (ERT) and ground-penetrating radar (GPR).

Results of the investigations (Figure 9) suggest a zone of low-velocity and high-conductivity in the bedrock associated with a magnetic lineament that is offset horizontally about 50 m to the west of the scarp. The top of the bedrock is found 10 m below the surface on the eastern side of the scarp and about 20 m below on its western side. This difference is due to the different thicknesses of the overlying sediments accounting for the surface topography, while the bedrock surface is likely to be more or less at the same topographic level on both sides of the scarp; else the difference is not resolvable by the methods used. To explain the difference in the sediment covers, we suggest that the Bollnäs scarp is associated with an earlier deformation zone, within a wide (> 150 m), highly fractured, water-bearing zone that became active as a reverse fault after the latest Weichselian deglaciation.

This work was published in the journal of Solid Earth by Malehmir et al. (2016).

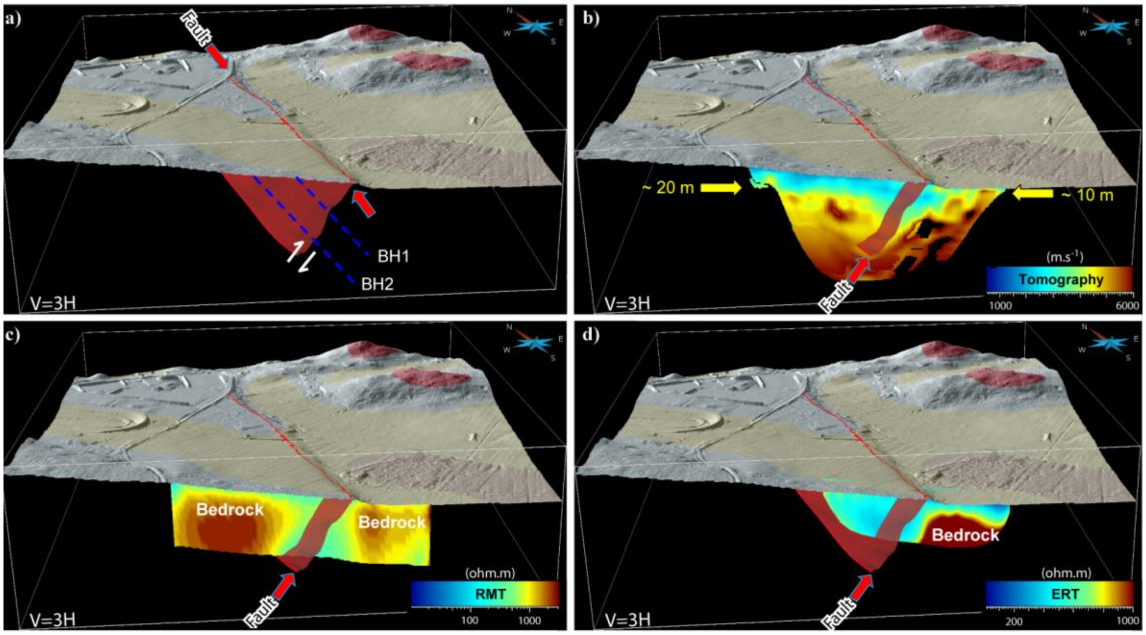


Figure 9. *Boat 3-D visualization of the geophysical results along profile 1. (a) Surface geology projected onto the lidar data with a hypothetical shape of the Bollnäs fault plane (assumed to be reversed) generated using the magnetic lineament observed in our own data, (b) travel time tomography, (c) RMT and (d) ERT models. Future plans should aim at drilling (e.g. BH1 and BH2) the weak zone that is interpreted to be a deformation zone hosting the Bollnäs postglacial fault and defining the bedrock level along profile 1. A better estimation of the throw may be then estimated and downhole logging would be conducted to verify the geophysical results presented here. From Malehmir et al. (2016).*

3.4 Äspö Hard Rock Laboratory

TRUST 2.2 employed both landstreamer and boat-towed RMT at the Äspö HRL site. It also combined with other works carried out by TRUSTs 2.1 and 4.2.

3.4.1 Tunnel-surface-tunnel seismics

A surface-tunnel-surface seismic experiment was conducted at the Äspö Hard Rock Laboratory to study the seismic response of major fracture systems intersecting the tunnel. A newly developed three-component micro-electro-mechanical sensor-based seismic landstreamer was deployed inside the noisy tunnel (Figure 10) along with conventional seismic receivers. In addition to these, wireless recorders were placed on the surface. This combination enabled simultaneous recording of the seismic wavefield both inside the tunnel and on the surface. The landstreamer was positioned between two geophone-based line segments, along the interval where known fracture systems intersect the tunnel.

Figure 10. *Photo showing the deployment of the landstreamer in the Äspö tunnel intersecting the NE1 fracture system. The experiment was done using a tunnel-surface-tunnel seismic experiment.*

First arrival tomography produced a velocity model of the rock mass between the tunnel and the surface with anomalous low-velocity zones correlating well with locations of known fracture systems (Figure 11). Prominent wave mode converted direct and reflected signals, P-S and S-P waves, were observed in numerous source gathers recorded inside the tunnel. Forward travel time and 2-D finite difference elastic modeling, based on the known geometry of the fracture systems, show that the converted waves are generated at these systems.

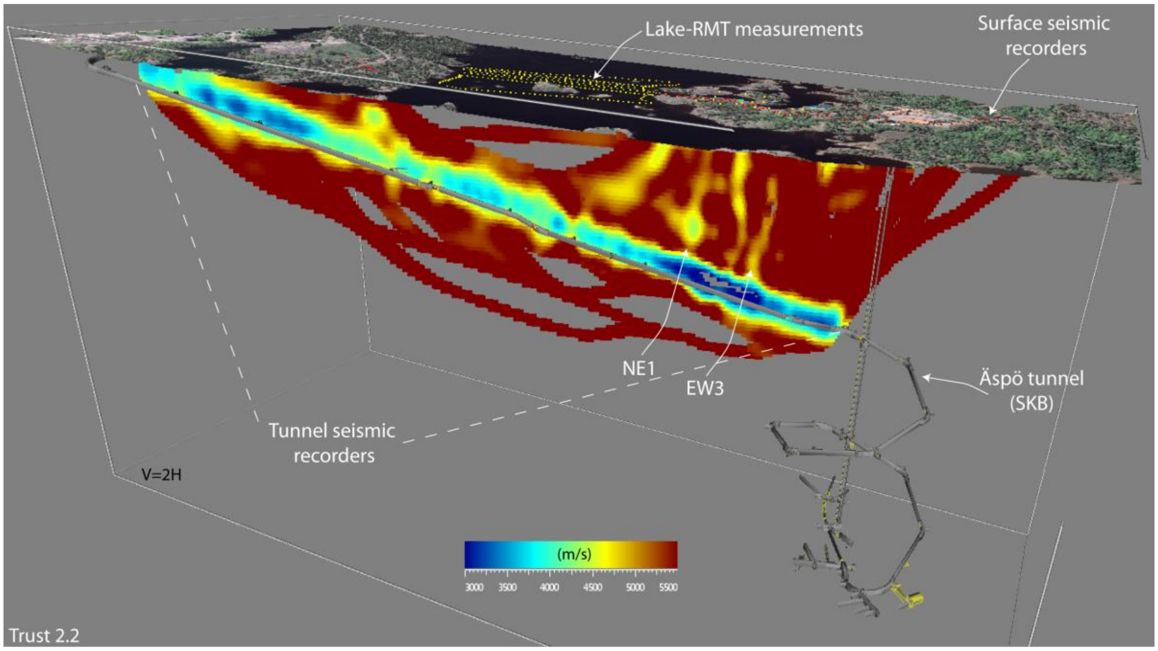


Figure 11. *The 3D of the final P-wave velocity model obtained from joint P- and S-wave tomography inversion. P-wave velocity model with aerial photo projected on top of the LiDAR surface, tunnel model, surface projections of the fracture systems, and their intersection with the tunnel, along with location of seismic receivers both in the tunnel and on the surface shown by red dots. Note how NE1 and EW3 are clearly delineated in this study. From Brodic et al. (2017).*

Additionally, the landstreamer data were used to estimate Vp/Vs, Poisson's ratio, and seismic attenuation factors (Qp and Qs) over fracture sets that have different hydraulic conductivities (Figure 12). The low-conductivity fracture sets have greater reductions in P wave velocities and Poisson's ratio and are more attenuating than the highly hydraulically conductive fracture set. Our investigations contribute to fracture zone characterization on a scale corresponding to seismic exploration wavelengths.

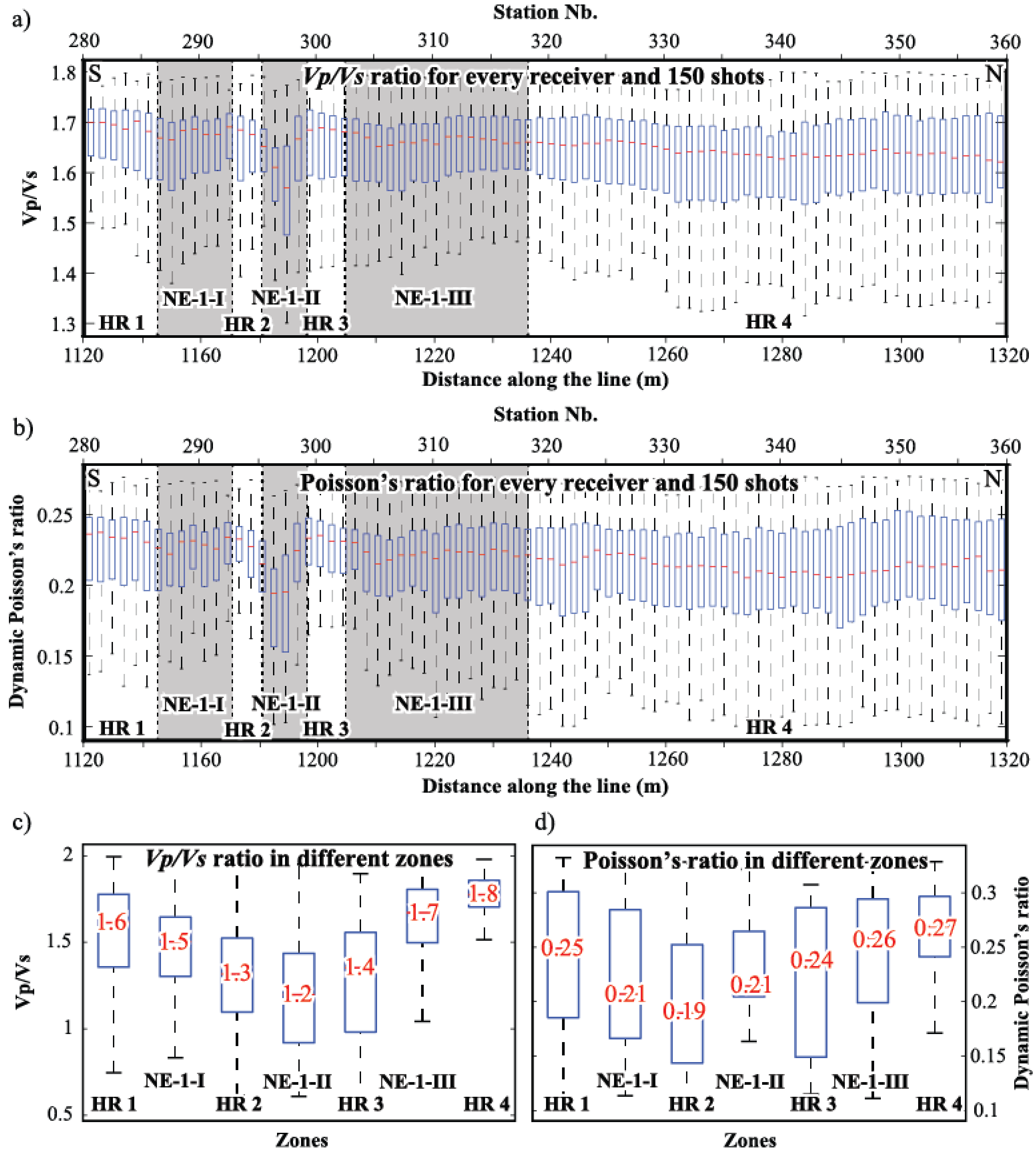


Figure 12. *Variations of dynamic elastic properties in the zone of the NE-1 fracture system calculated using two different approaches. (a) Vp/Vs ratio variation and (b) Poisson's ratio variation based on the ratio of picked first arrivals of the S- and P-waves from 150 sources along a portion of the seismic line in the tunnel. (c) Vp/Vs ratio variation and (d) Poisson's ratio variation within seven different zones as shown in Figure 9 and velocities obtained from regression analysis. HR represents host rock before and after NE-1 (HR 1 and 4) and between its different sets (HR 2 and 3). From Brodic et al. (2017).*

This study was published in the Journal of Geophysical Research-Solid Earth by Brodic et al. (2017).

3.4.2 boat-towed RMT

The ERT method provides moderately good constraints for both conductive and resistive structures while the RMT method is well suited to constrain conductive structures. Additionally, RMT and ERT data may have different target coverage and are differently affected by various type of noise. Thus, joint inversion of RMT and ERT datasets may better constrain the resultant model compared with single inversion. In this study, joint inversion of boat-towed RMT (TRUST 2.2) and lake-floor ERT (TRUST 2.1) data was for the first time formulated and implemented. A synthetic test together with a case study from the Äspö HRL was used to illustrate the implementation of the joint inversion approach. A 790-m-long profile comprising lake-floor ERT, boat-towed RMT data, and partial land RMT data was used in the field application (Figure 13).

Figure 13. *Photos showing the deployment of the boat-towed RMT system during the Äspö experiment.*

With or without weighting (applied to different datasets, vertical and horizontal model smoothness) and constraint of bathymetry data and water resistivity measurements, joint inversion were performed and compared. A major north-easterly directed fracture system, NE-1, observed in the HRL facility and boreholes together with a previously uncertain weak zone EW-5 are inferred in this study (Figure 14).

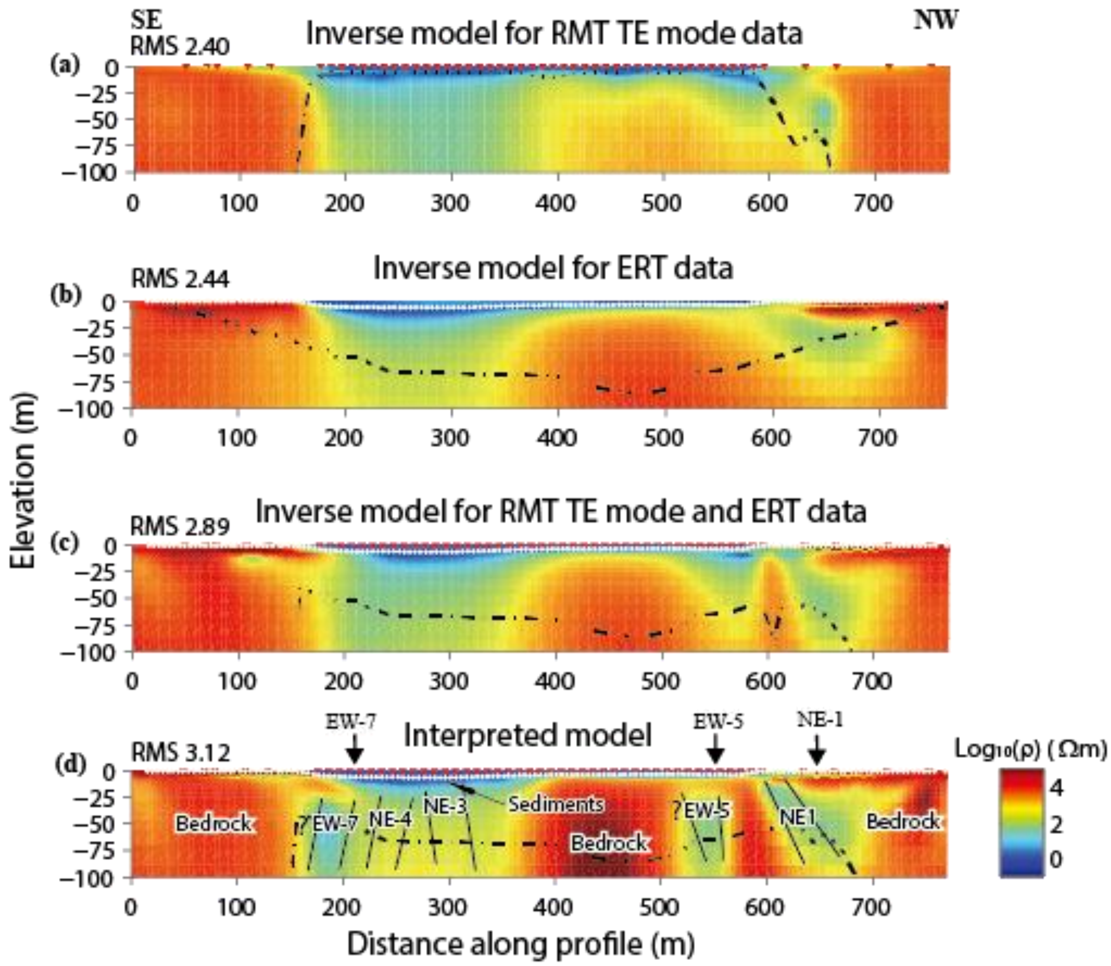


Figure 14. *(a) Inversion model for RMT TE-mode data. (b) Inversion model for ERT data. (c) Joint inversion model for RMT TE-mode and ERT data. Total RMS is 2.89 (RMS of RMT is 3.36 and RMS of ERT is 2.69). (d) Joint inversion model constrained with bathymetrical data and water resistivity measurement. Total RMS is 3.12 (RMS of RMT is 4.28 and RMS of ERT is 2.56). Separate RMS values from joint inversion are slightly higher than those of the single inversions. However, the model fits both datasets with an acceptable RMS. From Wang et al. (2017).*

This study is accepted for the Geophysical Journal International by Wang et al. (2017).

3.5 Lake Mälaren (Förbifart Stockholm)

To illustrate the potential of the boat-towed RMT system, an RMT survey was conducted in the city of Stockholm where one of the largest underground infrastructures in Sweden is being built, a 21-km-long multi-lane bypass-tunnel (Förbifart Stockholm).
Several RMT profiles were acquired in the lake Mälaren to determine the depth to bedrock and investigate possible fracture zones that were geotechnically inferred at one location. The tunnel will pass beneath three water passages and the deepest point will reach about -80 m (or 65 m below sea level). Here, we will focus on one of the three water passages, Kungshatt-Löven (Figure 15).

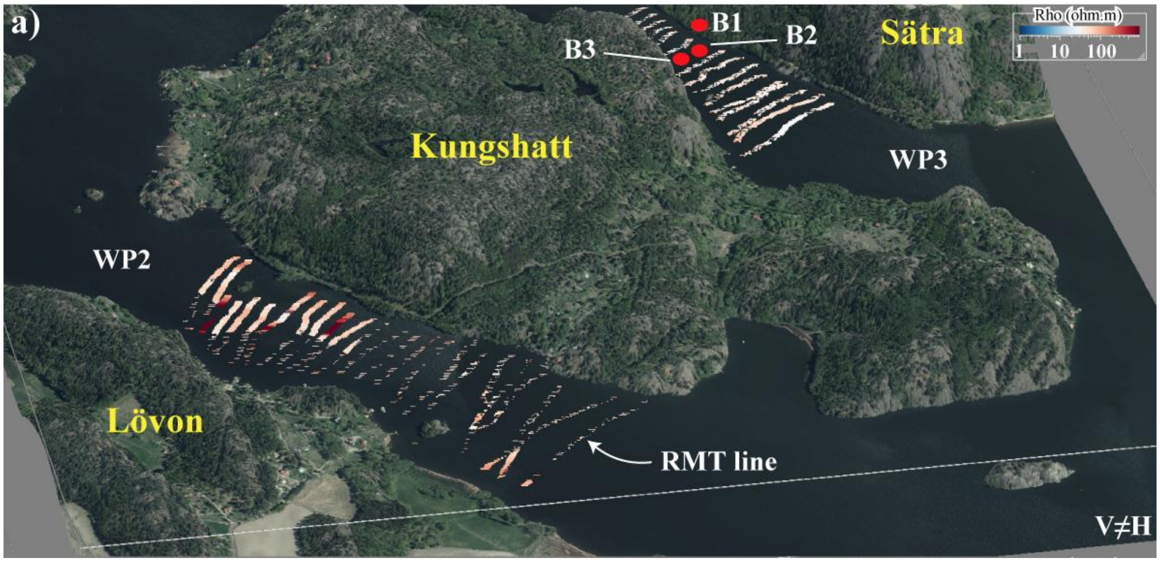
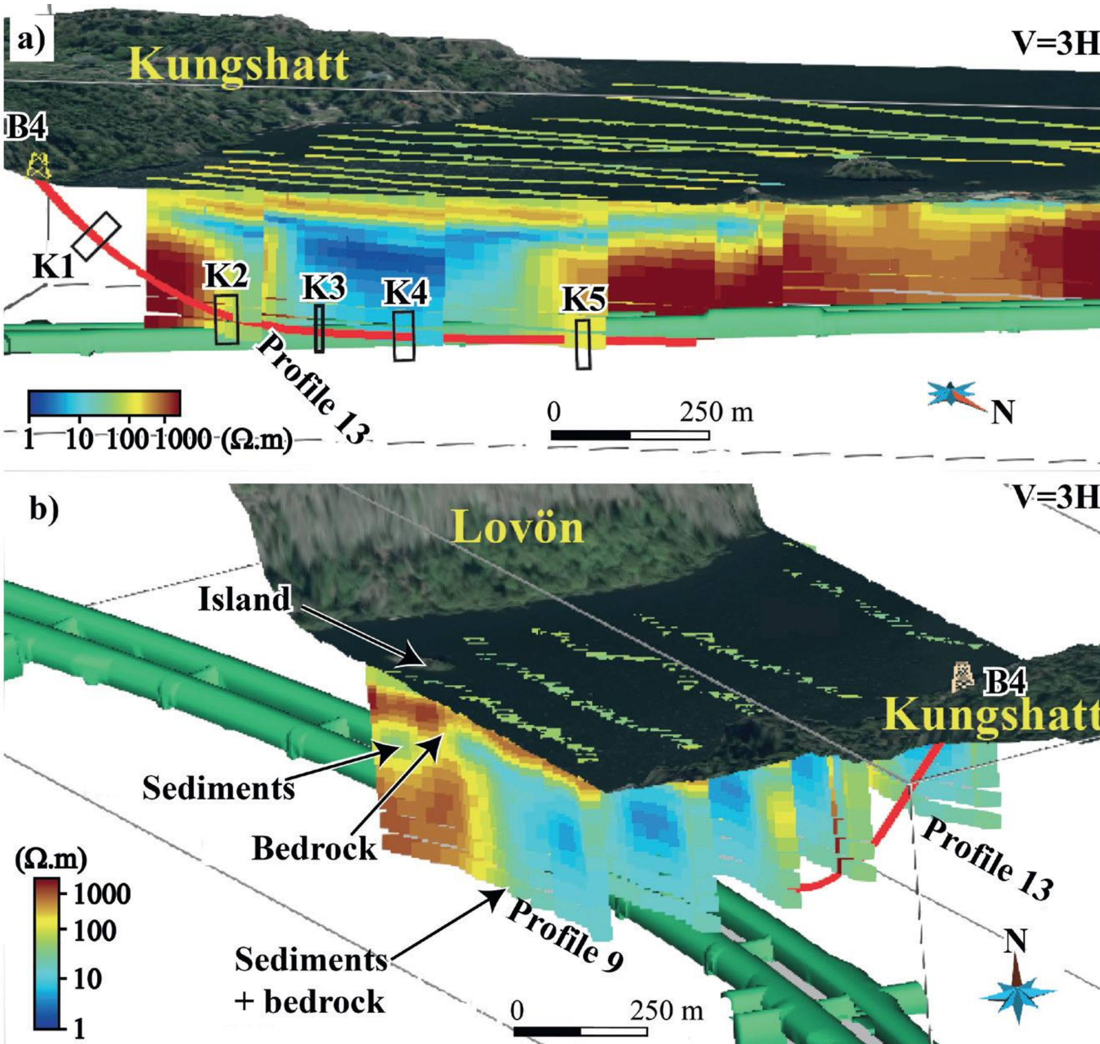


Figure 15. *3D views showing (a) RMT lines from the two of the three water passages where measurements were conducted, and (b) resistivity models and interpretations of features observed. From Mehta et al. (2017).*

The tunneling is planned with two separate tunnels, each with three lanes. The longest part of the tunnel is 16.5 km between the Kungens kurva and Lunda access ramps. Construction began in early 2015 and is expected to take ten years to complete. When up and running, 140,000 vehicles per day are expected to use the bypass. Approximately 15 km of RMT profiles, with 15 m average spacing, were surveyed during three days, 3-5 hours each day between Löven and Kungshatt islands (Figure 15). Compared to traditional RMT land surveys, under normal field conditions (0.5 km long profile per day with 10 m station spacing), the new system is around 10 times faster.

Figure 16 shows 3D views from the 2D modeling of the RMT data together with information from an inclined well, B4, along with the model of the planned tunnel trace. Fracture systems found during the core analyses are marked as K1-K5. Some cores analyzed showed clays, graphite, salt and sulphide minerals within them likely contributing to the low-resistivity features seen in the models. The top of the bedrock is well resolved near the shorelines, but not as clearly in the middle of the water passages owing to the diffusive behavior of EM signals, making the direct interpretation of the fractured bedrock ambiguous. A small island visible on the aerial photo is clearly resolved by the RMT models. The top resistive layer is interpreted to be the fresh water in Figure 16b, particularly note the resistive fresh water, with conductive sediments and resistive bedrock near the small island on the Löven side of the profiles. These models show the reliability and potential of this prototype boat-towed RMT system in shallow water conditions with it being both cost effective and efficient. Thus, it has encouraged us to build a more robust and sophisticated acquisition system for future use. One of the drawbacks of RMT is the limited depth of penetration. Acquisition of lower frequencies using a controlled source is planned in the future.



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directional borehole, B4, along with the RMT inverted models and tunnel model shown in green. Five major fracture systems and their widths were mapped in the cores from B4; four (K2–K5) are likely to be contributing to the conductivity zone in the middle of the water passage. (b) A small island at the site and its response observed in the RMT model. Note that the RMT data resolve the water column, lake sediments and the underlying bedrock clearly in this part of the model. From Mehta et al. (2017).

Details of the data acquisition and processing work can be found in Bastani et al. (2015). Details concerning resolution and a sensitivity analysis can be found in Mehta et al. (2017).

4. EXAMPLES OF SPIN-OFF PROJECTS

We provide short summary for a selection of spin-off projects here where the seismic landstreamer or methods developed in the project were used for relevant projects.

4.1 Dalby energy storage site

This study was conducted in collaboration with Skanska, Sweco and Lund University:

Three high-resolution refraction and reflection seismic profiles for the planning of a major underground thermal-energy-storage site within the Tornquist suture zone of Scania in southwest of Sweden were acquired during August 2015. Combined cabled- and wireless recorders were used to provide continuity on both side of a major road running in the middle of the study area. First arrivals are clear in most shot gathers allowing them to be used for traditional refraction seismic data analysis and also for more advanced traveltime tomography. Bedrock depressions are clearly observed in the tomograms suggesting the possibility of weakness zones, highly fractured and/or weathered, in the bedrock and confirmed in several places by boreholes. Signs of reflections in raw shot gathers were encouraging and motivated to process the reflection component of the data. Several steeply dipping reflections were imaged down to 400 m depth. The origins of the reflections are unclear right now ranging from amphibolite sheets to diabase dykes as well as faults within the gneissic rocks, and each of this implies a different geological scenario at where the site will be developed. This study however illustrates the potential of the combined refraction and reflection imaging for underground energy-storage-site characterizations.

An extended abstract presentation was given at the EAGE-NSG 2017, Malmö.

4.2 Oslo E18 underground tunnel planning

This study was conducted in collaboration with NGI:

Oslo municipality is presently planning bus and car tunnels to facilitate its accessibility and increase traffic efficiency. Urban environment is usually a challenge for geophysical pre-investigations because of the various sources of noise, vibrations and restriction both in time and space. These technical challenges were overcome with the use of a newly developed seismic streamer specifically designed for noisy urban areas, from an industry-academia partnership. A total of 3.5 km long seismic data along 14 profiles were acquired for the tunnels pre-investigation with the main goals of (1) obtaining information about depth to bedrock, (2) detecting potential weakness zones, and (3) optimizing the number of drillings and their locations for a follow-up study. In addition, six electrical resistivity tomography profiles were acquired near the planned tunnel alignments. Inversion of first breaks and electrical resistivity data provides a seamless depth to bedrock interface that is in most places in good agreement with the nearby geotechnical soundings. In addition, the geophysical sections reveal the bedrock undulation character and provide some indication of weakness zones. This case study also illustrates that if the pre-investigation had been based only on boreholes, it would have overseen a potential difficulty during excavation.

An extended abstract presentation was given at the EAGE-NSG 2016, Barcelona.

4.3 Turku esker water management

This study was conducted in collaboration with GTK, Turku Water Management Company and University of Turku:

A novel high-resolution (2–4 m source and receiver spacing) reflection and refraction seismic survey was carried out for aquifer characterization and to confirm the existing depositional model of the interlobate esker of Virttaankangas, which is part of the Säkylänharju-Virttaankangas glaciofluvial esker-chain complex in southwest Finland. The interlobate esker complex hosting the managed aquifer recharge (MAR) plant is the source of the entire water supply for the city of Turku and its surrounding municipalities. An accurate delineation of the aquifer is therefore critical for long-term MAR planning and sustainable use of the esker resources. Moreover, an additional target was to resolve the poorly known stratigraphy of the 70–100-m-thick glacial deposits overlying a zone of fractured bedrock. Bedrock surface as well as fracture zones were confirmed through combined reflection seismic and refraction tomography results and further validated against existing borehole information. The high-resolution seismic data proved successful in accurately delineating the esker cores and revealing complex stratigraphy from fan lobes to kettle holes, providing valuable information for potential new pumping wells. This study illustrates the potential of geophysical methods for fast and cost-effective esker studies, in particular the digital-based landstreamer and its combination with geophone-based wireless recorders, where the cover sediments are reasonably thick.

A follow-up RMT survey was also conducted at one of the two sites surveyed in Turku area, however, results are not yet ready for presentations.

A peer-reviewed article is already published by Maries et al. (2017). Several extended abstract presentations given at for example the EAGE-NSG 2016, Barcelona.

4.4 Siilinjärvi open-pit apatite mine

This study was conducted within ERA-MIN1 StartGeoDelineation (sponsored by Vinnova, SGU, Tekes, Yara and NIO) and in collaboration with GTK and Yara for open-pit mine planning purposes:

We tested the applicability of a newly developed broadband (0–800 Hz) digital-based seismic landstreamer for open-pit mine planning in the apatite-bearing Siilinjärvi mine in central Finland. Four seismic profiles, in total approximately 2.5 km long (2–4 m source and landstreamer receiver spacing), two inside the pit and two on its margins, were acquired in combination with wireless recorders connected to 10 Hz geophones and fixed at every 10 m spacing along the seismic profiles while the streamer data were being acquired. Downhole logging and laboratory physical property measurements on core and rock samples were carried out to not only support the seismic interpretations but also to provide information about the possible geophysical signature of these unique types of deposits. In spite of a highly noisy mining environment, seismic data of high quality were acquired; however, reflection processing and interpretations were challenged by the geologic complexities of several generations of basic and carbonatite dikes. To complement the reflection data imaging and to account for the steep elevation changes and crookedness of some of the seismic profiles, 3D first-arrival traveltime tomography and 3D swath reflection imaging were also carried out. Clear refracted arrivals from the open-pit profiles suggest the possibility of low-velocity zones associated with either blasting or several shear zones intersecting the seismic profiles. In terms of reflectivity, reflections have a different appearance from short and flat to longer and steep ones. The downhole- and borehole logging data suggest that some of these reflections are associated with diabase dikes and some are likely from zones of weaknesses in the alkaline-carbonatite complex. We determine the potential of using seismic streamers for cost- and time-effective open-pit mine planning and encourage further testing in simpler geologic settings to be established.

A peer-reviewed article is already published by Malehmir et al. (2017).

4.5 Blötberget mining area

This study was conducted within ERA-MIN1 StartGeoDelineation project (sponsored by Vinnova, SGU, Tekes, Yara and NIO) and in collaboration with Nordic Iron Ore where the potential of the streamer for deep mineral exploration was tested.

To be fully embraced into mineral exploration, seismic data require to be acquired fast, cheaper and with minimum environmental impacts addressing also the often brown-field highly noisy environment where these surveys are employed. Since 2013 and through a number of case studies, we have been testing a newly developed for urban environment, digital-based 240 m long, seismic landstreamer for mine planning and mineral exploration purposes. Here, we present a pilot study examining the potential of the streamer for deep targeting a known, down to approximately 850 m depth, iron-oxide mineralization in the historical Blötberget-Ludvika mining area of Bergslagen mineral district of central Sweden. Combined streamer (100-3C-MEMS (micro-electromechanical system), 2-4 m spacing) and 75 wireless recorders (mixed 10 Hz and MEMS, 10 m spacing) were used. A Bobcat-mounted drophammer, 500 kg, was used to generate the seismic signal. Within 4 days, approximately 3.5 km of seismic data using 2-10 m source and receiver spacing were acquired. Reflection data processing results clearly image the mineralization as a set of strong high-amplitude reflections and likely slightly extending beyond the known 850 m depth. This is encouraging and suggests such a cost-effective exploration method can be used in the area and elsewhere to delineate similar depth range iron-oxide deposits.

A peer-reviewed article is published by Malehmir et al. (2017) in Nature Scientific Reports.

5. OUTREACH

TRUST 2.2 took part or even contributed to several outreach activities. Participated actively in all the workshops organized by the management team, those by Trafikverket, SGU, Boliden, GTK, SBUF and Skanska. Figure 17 shows an example popular science article published by NyTeknik where our developments have a clear presence in the article.

16 NY TEKNIK · 20 JANUARI 2016 · NR 3

Fokus • Underjordens hemligheter synas

Fler metoder samtidigt ger billigare tunnel

Det gäller att veta hur berggrunden ser ut när stora tunnlar ska byggas. Därför utvärderar svenska experter elektriska och seismiska mätmetoder för att kunna se under markytan.

Inför ett stort infrastrukturbygge brukar man alltid göra provborrningar och ta djupa jordprover, så kallade jordsonderingar, för att ta reda på vad som döljer sig under markytan.

Men det är inte alltid som seismiska eller elektriska mätningar görs.

– Vi tycker att sådana här undersökningar ska göras som standard i ett tidigt stadium i komplicerade projekt, säger Maria Ask, professor i tillämpad geologi vid Luleå tekniska universitet.

Maria Ask.

Hon leder det svenska projektet Trust, Transparent Underground Structure, som förenar forskare, företag och myndigheter. Syftet är bland annat att utveckla metoder som ska ge ett bättre underlag för tunnelbyggen.

– Det som är unikt med vårt projekt är att vi använder flera mätmetoder. När du lägger ihop dem ökas kunskapen, du får säkrare tolkning och bättre kvalitet på dina undersökningar, säger Maria Ask.

Till exempel kan sprickzoner i berget och förorenade jordlager upptäckas, som kan skapa kostsamma problem i bygget om de dyker upp som överraskningar.

Elektriska, elektromagnetiska och seismiska mätningar har hittills gjorts på flera ställen i landet, främst vid Äspölaboratoriet i Oskarshamn, Varbergstunneln och Förbifart Stockholm.

Den seismiska mätmetoden innebär att sensorer mäter hur snabbt vågor rör sig genom marken efter ett hammarslag eller en dynamitladdning. Inom Trustprojektet utvärderas nya sensorer som kan känna av markens rörelser i flera olika riktningar.

– Resultatet är en snabb mätmetod där man ser allt tydligare och med bättre upplösning. Det är som när man får på sig nya glasögon, säger Maria Ask.

Genom att sätta sensorerna på en 240 meter lång kabel har forskarna utvecklat ett nytt mätinstrument. Det kallas för landstreamer och innebär att man slipper det tidsödande arbetet att gräva ner sensorerna i marken.

– Vi har utvecklat ett unikt seismiskt mätsystem, som inte är så känsligt för elektriskt brus, för att kunna utföra seismiska mätningar i städer där det finns mycket som stör, säger Alireza Malehmir, lektor i geofysik vid Uppsala universitet och ledare för ett av delprojekten i Trust.

Även radiovågor används inom Trustprojektet för att ta reda på hur berggrunden ser ut. Via mätningar från båt har forskarna också kunnat avgöra hur berget ser ut under grunda vattendrag.

– De har till exempel sett en sprickzon i Mälaren, det är viktigt när man ska dra tunneln till Förbifart Stockholm där, säger Maria Ask.

LINDA NOHRSTEDT

Uppsalaforskare med den nya landstreamern, som består av en ny typ av sensorer (i vita plastboxar med gult band). Resultatet jämförs med traditionella sensorer (till höger i bild, sammanbundna av en orange sladd) som grävs ned i marken. I mitten är Peter Hedin redo att slå till metallplattan som ska generera seismiska vågor.

Seismiska mätningar i Varberg. Forskaren Joachim Place med hammaren som genererar vågor i marken.

Radiovågor används för att undersöka hur berggrunden ser ut under vattendrag. Här görs så kallade RMT-mätningar vid Oskarshamn. Längst fram i båten syns Lundaforskaren Roger Wisén.

Så ser Trustforskarna under markytan

- **Resistivitetsmätning:** En elektrisk ström sänds genom två elektroder för att mäta markens elektriska motstånd, resistiviteten. Metoden kan användas för att se jordlager, bergkvalitet och förorenade områden.
- **Inducerad polarisation:** Elektrisk ström skickas ned i marken och sedan mäts hur fort den uppladdade spänningen avtar med tiden. Metoden används för att skilja bergområden med olika typer av mineraler från varandra.
- **Seismiska mätningar:** Sensorer mäter hur snabbt seismiska vågor rör sig i marken efter ett hammarslag eller dynamitladdning. På så sätt kan man upptäcka sprickor och olika typer av material i marken.
- **Radiomagnetotellurik:** Mäter hur elektromagnetiska signaler i frekvensbandet 10–250 kHz påverkas av att passera genom marken. Metoden kan användas för att avgöra hur djup berggrunden är och se om berget har sprickor.

Figure 17. *A scan copy of the Ny Teknik article published in the January of 2016 dedicated to the activities of the TRUST with clear presence of our development as illustrated in the pictures.*

Other outreach activities included short videos and here a couple of links to some of the short videos produced during the course of the project:

- TRUST 2.2 general ideas and Varberg seismic survey:
https://www.youtube.com/watch?v=xjK8EhkGpEc
- Our advisory member, Maria Ask and PhD student Bojan Brodic:
https://www.youtube.com/watch?v=yOTkbqzXWco
- TRUST – GeoBIM-metodik och nyutvecklade geofysiska metoder:
https://www.youtube.com/watch?v=NmXicev0coQ
- Pilot tests at Laisvall and Förbifart Stockholm using the seismic landstreamer:
https://www.youtube.com/watch?v=TClV3ie8FVY
- Äspö HRL surveys:
https://www.youtube.com/watch?v=X3YE2A0RDFA

Several short news and information activities were also produced by various organizations. Figure 18 shows an example from SKB in connection with the Bollnäs surveys.

Geofysiker med fokus på jordens ytskikt

Hur kan geofysiker göra världen till en bättre plats? Efter att ha förfinat metoder, algoritmer och mätutrustning i över hundra år är det dags att göra skillnad på riktigt, tycker professor Alireza Malehmir, som installerades som ny professor i november.

– Geofysiker studerar jordens inre med hjälp av fysikens lagar och matematiska tricks. Vi använder oss av vibrationer, magnetism, seismik, gravitation och elektromagnetiska vågor, som hjälper oss att avläsa innehållet i marken, säger Alireza Malehmir, en av alla nya professorer som installerades i november.

Tack vare geofysiken så vet vi i dag ungefär hur planeten ser ut ända ned till jordens mittpunkt, trots att det fortfarande är praktiskt taget omöjligt att borra djupare än tre kilometer ned i jordskorpan.

FOTO: LASSE MODIN, SKB

Alireza Malehmir avläser innehållet i marken under våra fötter. Här undersöker han en så kallad förkastningslinje i Bollnäs.

ALIREZA MALEHMIRS FORSKARGRUPP HAR de senaste åren jobbat med att undersöka mer marknära fenomen.

– Utan geofysiken skulle vi bokstavligen talat bara skrapa på ytan i vår förståelse av planeten. Den "djupa" geofysiken är viktigt, men vi får inte glömma bort att det som händer i det översta skiktet har störst betydelse för oss människor. Det är där vi gräver våra tunnlar, bygger hus och vägar och hittar våra naturresurser. Det är helt enkelt i jordens ytskikt som vi geofysiker har möjlighet att göra störst skillnad, förklarar Alireza Malehmir.

– Jag ser det som vår uppgift att bli mer aktiva i samhället och samhällsbyggandet. I över hundra år har vi förfinat våra metoder och vår mätutrustning, och nu har vi verkligen möjligheter att vara till hjälp.

Dessa nya mätmetoder har forskargruppen använt i planeringen av projektet Förbifart Stockholm, där forskarna kunde peka ut den bästa och säkraste placeringen av vägtunnlar. De undersöker också marken för att se om det finns risk för till exempel jordskred.

– Nu är det dags för oss geofysiker att visa att vi kan göra världen till en bättre plats, säger Alireza Malehmir.

Börje Dahrén

Figure 18. *Promotion news by SKB in connection with the Bollnäs surveys. Seismic landstreamer is shown in the background.*

6. DISCUSSION

Two modern geophysical systems have been developed and employed for various near-surface applications with a particular focus on urban underground infrastructure planning projects. Data acquired by the systems show excellent quality allowing high-resolution imaging of the subsurface structures. While there are rooms for improvements, they are currently being used in several infrastructure-planning projects inside and outside Sweden illustrating their potentials.

Future developments will include exploiting the broadband frequency nature of the streamer data and development of a 3C source that can generate broad frequency data that the streamer sensors are capable of recording. Boat-towed RMT system will require new hardware and software developments. A DGPS system was recently linked to the system to provide high-precision geodetic surveying of the acquisition points, which proved to be important for this type of survey.

7. CONCLUSIONS

Two modern geophysical systems have been developed with a particular focus on urban underground infrastructure planning projects and that can be used for various near-surface applications. Data acquired by the two systems show excellent quality, allowing high-resolution imaging of the subsurface structures in urban environments. The two systems are currently being used in several infrastructure-planning projects and there is still space for improvements based on the feedback from their application. Future developments will include exploiting the broadband frequency nature of the streamer data and development of a 3C source that can generate broad frequency range signals that the streamer sensors are capable of recording. The boat-towed RMT system will require new hardware and software developments. A DGPS system was recently linked to the system to provide high-precision geodetic surveying of the acquisition points, which is essential for this type of survey. The boat-towed RMT works quite efficiently, e.g., 5 km line-data per day, and shows high reliability for bedrock mapping and fracture zone delineation, particularly over shallow water bodies. The signal penetration depth of the boat-towed RMT system can also be enhanced using additional lower frequency controlled source (controlled-source RMT).

The boat-towed RMT case study from the Förbifart Stockholm also shows the potential of this method for bedrock topography and fracture zone mapping in a time- and cost-effective manner on fresh or brackish water bodies. This is particularly important and can provide important information for where detailed drilling and geotechnical investigations should be carried out. The two systems have been used in several related studies in Sweden, Finland, Norway and Denmark, which encourages us to improve them further.

8. ACKNOWLEDGMENTS

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9. PEER-REVIEWED JOURNAL PUBLICATIONS

Here we list in a chronological order peer-reviewed journal publications where TRUST 2.2 was involved:

Malehmir, A., Maries, G., Bäckström, E., Schön, M., and Marsden, P., 2017. Developing cost-effective seismic mineral exploration methods using a landstreamer and a drophammer. *Scientific Reports*, 7, 10325.

Mehta, S., Pedersen, L.B., Kamm, J., Bastani, M., and Malehmir, A., 2017. Enhanced model resolution from inversion of RMT data by preserving the identity of radio transmitters. *In revision.*

Wang, S., Kalscheuer, T., Bastani, M., Malehmir, A., Pedersen, L.B., Dahlin, T., and Meqbel, N., 2017. Joint inversion of lake-floor electrical resistivity tomography and boat-towed radio-magnetotelluric data illustrated on synthetic data and an application from the Äspö Hard Rock Laboratory site, Sweden. *Geophysical Journal International*, in press. https://doi.org/10.1093/gji/ggx414

Brodic, B., Malehmir, A., and Juhlin, C., 2017. Delineating fracture zones using surface-tunnel-surface seismic data, P-S and S-P mode conversions. *Journal of Geophysical Research-Solid Earth*, 122. http://dx.doi.org/10.1002/2017JB014304.

Brodic, B., Malehmir, A., Bastani, M., Mehta, S., Juhlin, C., Lundberg, E., and Wang, S., 2017. Multi-component digital-based seismic landstreamer and boat-towed radio-magnetotelluric acquisition systems for improved subsurface characterization in the urban environment. *First Break*, 35(8), 41–47.

Dehgahnnejad, M., Malehmir, A., Svensson, M., Lindén, M., and Möller, H., 2017. High-resolution reflection seismic imaging for the planning of a double-train-track tunnel in the city of Varberg, southwest Sweden. *Near Surface Geophysics*, 15(3), 226–240.

Malehmir, A., Heinonen, S., Dehgahnnejad, M., Heino, P., Maries, G., Karell, F., Suikkanen, M., and Salo, A., 2017. Landstreamer seismics and physical property measurements in the Siilinjärvi open-pit apatite (phosphate) mine, central Finland. *Geophysics*, 82, B29–B48.

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Maries, G., Ahokangas, E., Mäkinen, J., Pasanen, A., and Malehmir, A., 2017. Interlobate esker architecture and related hydrogeological features derived from a combination of high-resolution reflection seismics and refraction tomography, Virttaankangas, SW-Finland. *Hydrogeology Journal*, 25, 829–845.

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Place, J.A.P., Nejad Ghafar, A., Malehmir, A., Draganovic, A., Larsson, S., 2016. On using the thin fluid-layer approach at ultrasonic frequencies for characterising grout propagation in an artificial fracture. *International Journal of Rock Mechanics & Mining Sciences*, 89, 68–74.

Wang, S., Malehmir, A., and Bastani, M., 2016. Geophysical characterization of areas prone to quick-clay landslides using radio-magnetotelluric and seismic methods. *Tectonophysics*, 677-678, 248–260.

Malehmir, A., Andersson, M., Mehta, S., Brodic, B., Munier, R., Place, J., Maries, G., Smith, C., Kamm, J., Bastani, M., Mikko, H., and Lund, B., 2016. Post-glacial reactivation of the

Bollnäs fault, central Sweden - a multidisciplinary geophysical investigation. *Solid Earth*, 7, 509–527.

Brodic, B., Malehmir, A., Juhlin, C., Dynesius, L., Bastani, M., and Palm, H., 2015. Multicomponent broadband digital-based seismic landstreamer for near surface applications. *Journal of Applied Geophysics*, 123, 227–241.

Malehmir, A., Zhang, F., Dehgahnnejad, M., Lundberg, E., Döse, C., Friberg, O., Brodic, B., Place, J., Svensson, M., and Möller, H., 2015. Planning of urban underground infrastructure using a broadband seismic landstreamer—Tomography results and uncertainty quantifications from a case study in southwest of Sweden. *Geophysics*, 80, B177–B192.

Bastani, M., Persson, L., Mehta, S., and Malehmir, A., 2015. Boat-towed radio-magnetotellurics (RMT)—a new technique and case study from the city of Stockholm. *Geophysics*, 80, B193–B202.

Abbaszadeh Shahri, A., Malehmir, A., and Juhlin, C., 2015. Soil classification analysis based on piezocone penetration test data — A case study from a quick-clay landslide site in southwestern of Sweden. *Engineering Geology*, 189, 32–47.

Malehmir, A., Wang, S., Lamminen, J., Brodic, B., Bastani, M., Vaittinen, K., Juhlin, C., and Place, J., 2015. Delineating structures controlling sandstone-hosted base-metal deposits using high-resolution multicomponent seismic and radio-magnetotelluric methods: a case study from Northern Sweden. *Geophysical Prospecting*, 63, 774–797.

10. PEER-REVIEWED CONFERNCE PUBLICATIONS

Brodic, B., Malehmir, A., Maries, G., 2017. SH- and surface-wave imaging potential of a 3C-digital-based seismic landstreamer illustrated at an esker site in SW Finland. EAGE Near Surface Geoscience, workshop on Geophysics in infrastructure planning, Malmö-Sweden, September 2017.

Malehmir, A., 2017. Geohazards and how geophysics can help. Geosciences applied to solve humanitarian problems all over the world, Belgrade-Serbia, May 2017.

Brodic, B., Lundberg, E., and Malehmir, A., 2017. Subsurface characterization of a cancerogenic contaminated site seismic methods in an urban setting in southwest Sweden. Geosciences applied to solve humanitarian problems all over the world, Belgrade-Serbia, May 2017.

Ronczk, M., Olsson, P.-I., Rossi, M., Malehmir, A., and Dahlin, T., 2017. Geophysical site investigation at Dalby-Önneslov using joint inversion. EAGE Near Surface Geoscience, Malmö-Sweden, September 2017.

Malehmir, A., Bergman, B., Andersson, B., Sturk, R., and Johansson, M., 2017. High-resolution seismic investigations of a geological energy-storage site: Dalby (Tornquist Zone), southwest Sweden. EAGE Near Surface Geoscience, Malmö-Sweden, September 2017.

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Lähivaara, T., Pasanen, A., Malehmir, A., and Kaipio, J.P., 2017. Full-waveform seismic inversion for estimating aquifer dimensions and hydrologic parameters. EAGE Near Surface Geoscience, Malmö-Sweden, September 2017.

Brodic, B., and Malehmir, A., and Juhlin, C., 2017. Bedrock and fracture zone delineation using different near-surface seismic sources. EAGE Near Surface Geoscience, Malmö-Sweden, September 2017.

Mehta, S., Bastani, M., Malehmir, A., and Pedersen, L.B., 2017. CSRMT survey on frozen lake – A new technique with an example from the Stockholm bypass tunnel. EAGE Near Surface Geoscience, Malmö-Sweden, September 2017.

Malehmir, A., Maries, G., Bäckström, E., Schon, M., and Marsden, P., 2017. Deep targeting an iron-oxide ore body using a seismic landstreamer and a 500-kg drop hammer source. EAGE annual conference, Paris-France, June 2017.

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Brodic, B., Malehmir, A., and Juhlin, C., 2016. Rock mass and fracture characterization at Äspö HRL using tunnel-surface seismics. The underground space challenge, Kalmar, Sweden, October 2016.

Malehmir, A., Bastani, M., Brodic, B., Mehta, S., and Wang, S., 2016. Development and applications of a MEMs-based seismic landstreamer and a boat-towed radio-magnetotelluric system–tackling the urban environment. EAGE workshop on Urban Geophysics, Barcelona, Spain, September 2016.

Wang, S., Kalscheuer, T., Bastani, M., Malehmir, A., Pedersen, L.B., Dahlin, T., and Meqbel, N., 2016. Joint inversion of on-lake radio-magnetotelluric and lake-floor direct current

resistivity data and its applications. 23rd Electromagnetic Induction in the Earth Workshop, Chiang Mai, Thailand, August 2016.

Dehghannejad, M., Malehmir, A., Lundberg, E., Möller, H., and Svensson, M., 2016. High-resolution reflection imaging for the planning of a double train-track tunnel in the city of Varberg, Sweden. EAGE workshop on Near Surface Seismology, Vienna, Austria, May 2016.

Bazin, S., Sauvin, G., Dehghannejad, M., Lundberg, E., Lysdahl, A.K., Malehmir, A., Kveldsvik, V., Boge, K., and Pfaffhuber, A.A., 2016. Seismic and electrical resistivity investigations for the planning of a tunnel in Oslo outskirts. EAGE Near Surface Geoscience, Barcelona, Spain, September 2016.

Malehmir, A., Tryggvason, A., Wijns, C., Lindqvist, T., Skyttä, P., Koivisto, E., and Montonen, M., 2016. 3D traveltime tomography and reflection imaging for mine planning and exploration in the Kevitsa Ni-Cu-PGE mine, Finland. EAGE Near Surface Geoscience, Geophysics on Mineral Exploration and Mining, Barcelona, Spain, September 2016.

Salas-Romero, S., Malehmir, A., and Snowball I., 2016. Combined land and river high-resolution reflection seismic imaging of an area prone to quick-clay landslides in Sweden. EAGE Near Surface Geoscience, Barcelona, Spain, September 2016.

Ahokangas, E., Maries, G., Mäkinen, J., Pasanen, A., and Malehmir, A., 2016. Seismic imaging of esker sediments within the Satakunta sandstone depression in Köyliö, SW Finland. EAGE Near Surface Geoscience, Barcelona, Spain, September 2016.

Bastani, M., Wang, S., and Malehmir, A., 2016. Boat-towed RMT measurements on the water surface over the Äspö Hard Rock Tunnel in Sweden. EAGE Near Surface Geoscience, Barcelona, Spain, September 2016.

Brodic, B., and Malehmir, A., and Juhlin, C., 2016. Fracture system characterization using wave-mode conversions and tunnel-surface seismics. EAGE Near Surface Geoscience, Geophysics on Mineral Exploration and Mining, Barcelona, Spain, September 2016.

Malehmir, A., Brodic, B., Dehgahnnejad, M., Juhlin, C., and Lundberg, E., 2016. A state-of-the-art MEMs-based 3C seismic landstreamer for various near-surface applications. EAGE workshop on Near Surface Seismology, Vienna, Austria, May 2016.

Place, J., and Malehmir, A., 2016. Using Super-virtual First Arrivals for Improving the Seismic Imaging of Deep Deposits - Well Worth the Effort. DGG-EAGE workshop on Deep Mineral exploration: chasing both land and sea deposits, Münster, Germany, March 2016.

Malehmir, A., Lundberg, E., Dehgahnnejad, M., Zhang, F., Friberg, O., Brodic, B., Döse, C., Place, J., Svensson, M., and Möller, H., 2015. Varberg: Developing urban geophysical instruments and methods – Pushing the boundaries. Grundläggningsdag (Foundation Day), Stockholm, Sweden, 15 pages.

Malehmir, A., Lundberg, E., Dehgahnnejad, M., Zhang, F., Friberg, O., Brodic, B., Döse, C., Place, J., Svensson, M., and Möller, H., 2015. Seismic landstreamer for planning of infrastructure projects – A case study from Varberg. Bergmekanikdagen (Rock Mechanic Day), Stockholm, Sweden, 15 pages.

Bastani, M., Malehmir, A., Saavaidis, 2015. Combined use of controlled-source and radio-magnetotelluric methods for near surface studies. Expanded abstract, 4 pages, ASEG 2015. Perth, Australia.

Wang, S., Bastani, M., Malehmir, A., 2014. Integrated use of Radio-Magnetotelluric and High-Resolution Reflection Seismic data to delineate near surface structures – two case studies from Sweden. 22nd EM Induction workshop, Weimar, Germany.

Malehmir, A., Wang, S., Lamminen, J., Bastani, M., Juhlin, C., Vaittinen, K., Dynesius, L., and Palm, H., 2014. High-resolution multicomponent hardrock seismic imaging of mineral deposits and their host rock structures. Expanded abstract, 3 pages, *EAGE 2014*, Amsterdam, Netherlands.

11. Appendixes

All the publications are available upon request. Write your requests for the publications and data sharing to alireza.malehmir@geo.uu.se. These publications are attached to this report:

- SBUF flyer (mid-project), NR 16:24.
- Brodic, B., Malehmir, A., and Juhlin, C., 2017. Delineating fracture zones using surface-tunnel-surface seismic data, P-S and S-P mode conversions. *Journal of Geophysical Research Solid Earth*, 122. http://dx.doi.org/10.1002/2017JB014304.
- Brodic, B., Malehmir, A., Bastani, M., Mehta, S., Juhlin, C., Lundberg, E., and Wang, S., 2017. Multi-component digital-based seismic landstreamer and boat-towed radio-magnetotelluric acquisition systems for improved subsurface characterization in the urban environment. *First Break*, 35(8), 41–47.
- Brodic, B., Malehmir, A., Juhlin, C., Dynesius, L., Bastani, M., and Palm, H., 2015. Multicomponent broadband digital-based seismic landstreamer for near surface applications. *Journal of Applied Geophysics*, 123, 227–241.

Complied by Alireza Malehmir
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