Multi-component digital-based seismic landstreamer and boat-towed radio-magnetotelluric acquisition systems for improved subsurface characterization in the urban environment

Bojan Brodic[1*], Alireza Malehmir[1], Mehrdad Bastani[2], Suman Mehta[1], Christopher Juhlin[1], Emil Lundberg[1] and Shunguo Wang[1] introduce the two systems and present two case studies illustrating their potential.

Introduction

It is estimated that urban life will be the norm for around 60% of the total world's population by 2040, leading to a more centralized distribution of people and making the city as the main place of residence (Whiteley, 2009). This population centralization inherently implies rapidly expanding cities and imposes the need for more infrastructure within, around and between the present city boundaries. However, infrastructure projects nowadays have to follow strict civil engineering standards that require detailed knowledge of subsurface conditions during different stages of the construction processes. Since direct methods conventionally used for site characterization (e.g., drilling and/or core testing) are still relatively expensive the focus in the last two decades has been on non-invasive, geophysical methods. However, geophysical site characterization in urban areas is not an easy task owing to numerous challenges and various types of noise sources. Challenges such as electric/electromagnetic (EM) noise, pipelines and other subsurface objects (sometimes even unknown or undocumented), the inability to properly couple sensors because of pavement, traffic noises and limited space are common in urban environment. Since geophysical surveys need to be done with the least amount of disturbances to the environment, residents and traffic, new geophysical techniques for fast, non-invasive and high-resolution site characterization are needed.

To overcome some of these challenges, a nationwide joint industry-academia project was launched in 2012 (TUST GeoInfra, www.trust-geoinfra.se). As a component in the project, Uppsala University developed two new data acquisition systems. These are a fully digital MEMS-based (Micro-machined Electro-Mechanical Sensor) three component (3C) seismic landstreamer and a boat-towed radio-magnetotelluric (RMT) acquisition system. Both systems were specifically designed to address urban environments with the RMT system particularly aiming at efficient and cost-effective geophysical surveying on shallow-water bodies, which constitute 7% of Scandinavia. In this article, we will describe the two systems and present two case studies illustrating their potential. A number of published accounts are now available from the two systems showing what type of problems they can address (e.g., Bastani et al., 2015; Brodic et al., 2015; Malehmir et al., 2015a, 2015b, 2016a, 2016b, 2017; Dehghannejad et al., 2017; Maries et al., 2017; Mehta et al., 2017; Brodic et al., 2017).

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 (Eiken et al., 1989) 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 a recent case even single 3C accelerometers (see Brodic et al., 2015 and references therein). In contrast to the mentioned studies, the Uppsala University landstreamer 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). 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 (Brodic et al., 2017). 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

[1] Department of Earth Sciences, Uppsala University, Sweden | [2] Geological Survey of Sweden
[*] Corresponding author, E-mail: bojan.brodic@geo.uu.se

Figure 1 Sensor-sled assembly mounted on a non-stretchable woven belt with internal co-ordinate system of the sensor (a). Note here the wireless seismic recorders working in autonomous mode providing long offset data and a towing vehicle far in the back. (b) Different segments of the seismic landstreamer connected by trolleys carrying line powering units towed by a vehicle. In the test shown, the towing vehicle was also used as the recording vehicle.

Parameters	UU 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: 4 segments 1 segment	100 sensors on 5 segments each 20 units and spaced 2 m 20 units and 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

Table 1 Technical details of the system developed in this study

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 cover inaccessible areas
8. Can be towed in series (2D surveys) or parallel (3D surveys)
9. Can be used for both passive (ReMi, MASW) and active data acquisition

Table 2 Summary of the important characteristics of the developed landstreamer

woven belt used in the aircraft industry (Figure 1a). 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 1a). Technical details of the developed system can be found in Table 1.

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 1b). 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.

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 2). 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

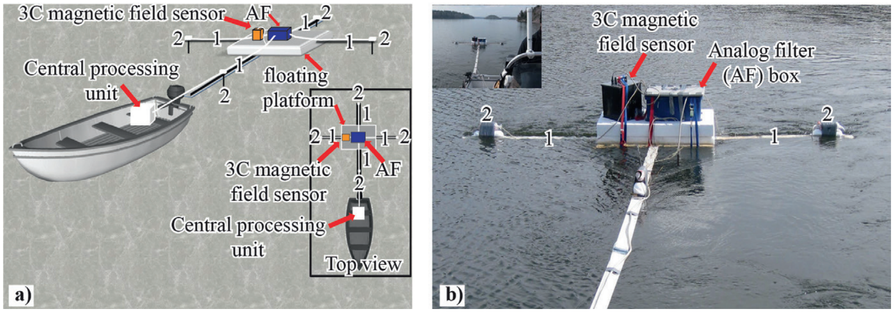

Figure 2 Boat-towed RMT acquisition system schematic (a) and a photo of the actual look of the system with inset showing it dragged behind the boat (b). Arms and cables for electric field measurements are marked with '1', while '2' marks 4 steel electrodes with buffer amplifiers. Modified after Bastani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

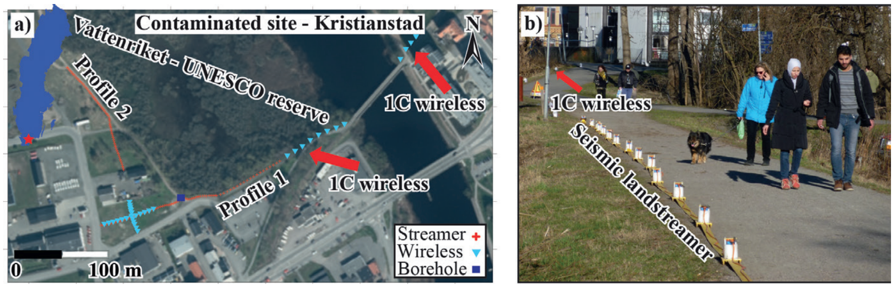

Figure 3 Location of the site and seismic lines acquired in Kristianstad (a) and a photo showing the streamer at one of the lines during data acquisition (b).

leakage in the cables) fixed on a pair of 2.5-metre-long arms (Figure 2, 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 2a, 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.

Landstreamer seismic survey at a contaminated site

During the early stage of the development of the streamer (in 2014) its potential was tested at a site contaminated by chlorinated hydrocarbons in Kristianstad, southern Sweden (Figure 3). The main goals of the survey were to characterize the depth to bedrock and possible fracture zones within, that could provide potential migration pathways of pollutants to the river and groundwater. The seismic data were acquired in an urban part of the city (Figure 3a) at a site where an old chemical-cleaning facility was located in the past. Soil analysis at the site shows high concentrations of chlorinated hydrocarbons, known as tetrachloroethylenes (PCE), that were used for the chemical-cleaning process and have leaked into the subsurface. The tetrachloroethylenes are highly harmful and carcinogenic (Guha et al., 2012) and could possibly have spread from the site through groundwater. Geologically, the site consists of 5-20 m thick glacial tills and clays overlaying an 80 m average thick limestone layer sitting on top of a regional glauconite aquifer. A great concern exists that the PCEs might infiltrate into the deep glauconite aquifer, used for the regional water supply, or migrate towards a nearby Unesco biosphere reserve called Vattenriket (Johansson et al., 2017).

At the Kristianstad site, two seismic profiles were acquired using a combination of the seismic landstreamer and single component (1C) wireless seismic recorders connected to 10 Hz vertical-component geophones (Figure 3). To generate a seismic signal, a source with the same principle as the 'Betsy seismic gun' charged with 12 mm blank cartridges was used (Miller et al., 1986). Shots were fired every 4 m and coincident with the nearest receiver. Along both profiles, ground conditions varied from asphalt bicycle roads to grass fields. The wireless recorders were used as an extension of the landstreamer and to overcome the problems associated with existing infrastructure and the river crossing the site. At the time of acquisition the landstreamer consisted of four segments with 20 3C-MEMS-based units in each segment. Three segments had sensor spacings of 2 m, while the 4th one had sensors spaced at 4 m. In addition, a short segment consisting of five units spaced at 2 m was also used, making the total length of the spread 210 m. Profile 1 is approximately 400 m long, extending from the western part of the site and east over the river. The eastern part of the profile (from 210-400 m) was covered with eight 1C wireless seismic recorders deployed at a distance of 10 m, while 4 wireless units with 10 m spacing were deployed west of the river. Profile 2 was acquired with the landstreamer on the northern part and 12 1C wireless recorders spaced at 4 m located further away. The sample rate used along both profiles was 1 ms and for every shot 5 s of data were recorded. The acquisition system used to acquire the data, Sercel Lite, operates using GPS time and stores the GPS timestamp of every shot in the trace headers. This provided a common reference time for every shot to download the data from the wireless units operating in autonomous mode and allowing the two data sets to be merged.

Here we focus on the vertical component of the 3C seismic landstreamer using both refraction tomography and reflection seismic imaging. P-wave first arrival tomography was done using the ps_tomo code (Tryggvason et al., 2002) with 2 m cell size in inline and depth, while a wide cell in the crossline direction was used to obtain a 2D velocity distribution. After 8 iterations no more changes in the models were observed and RMS errors of 3.2 ms (Profile 1) and 3.1 ms (Profile 2) were obtained. Both tomography models suggest bedrock dipping towards the river.

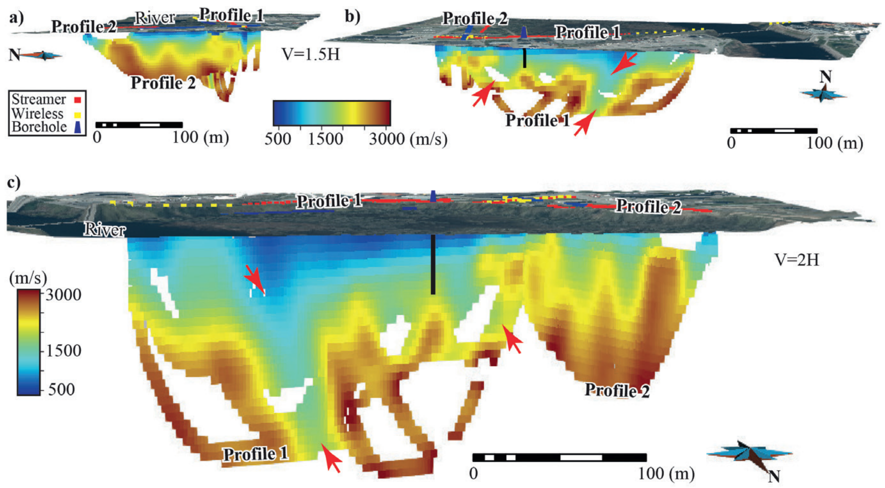

Figure 4 (a) Tomography model along Profile 2 with aerial photo projected on elevation surface. (b) Tomography model along Profile 1 with aerial photo projected on elevation surface, red arrows pointing at possible fractures in the bedrock and black line showing drilled depth to bedrock. (c) Both tomography models of Profile 1 and Profile 2 with elevation surface shown together.

Bedrock depth is well delineated on all results shown in Figure 4 and correlate well with borehole information. Along Profile 2, no major low-velocity zone in the tomography model can be noted that could indicate possible fracture zones. Significant velocity decreases can be seen in at least two zones in the tomography model of Profile 1 (red arrows in Figure 4b), indicating weak zones or fractured bedrock.

In addition to the refraction tomography, reflection seismic processing was performed with the processing steps shown in Table 3 and the results shown in Figure 5. The reflection seismic section along Profile 2 indicates that the bedrock is well delineated and dips towards the river, supporting the tomography result. Certain discontinuities of the reflections along Profile 2 can be seen, but with no clear evidence in the tomography models to support their interpretation as weak zones or fractures. An interruption of the reflection continuity, coinciding with a major low velocity zone seen on the tomography model of Profile 1, can be seen in Figure 5b,c (shown by the red arrows), which may additionally indicate fractured bedrock.

Boat-towed RMT survey in the city of Stockholm

To illustrate the potential of the boat-towed RMT system, an RMT survey was conducted close to 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 inferred by geotechnical investigations. 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 6a,b). 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 (Figure 6a). Compared

Parameter	Profile 1	Profile 2
Remove all but vertical component	Yes	Yes
Merge streamer and wireless	Yes	Yes
Add geometry	Yes	Yes
Trace edit	Yes	Yes
Pick first arrivals	Yes	Yes
Spectral balancing	15-25-90-120 Hz	15-25-90-120 Hz
FK mute – remove wind noise	Yes	Yes
Refraction static correction	Yes	Yes
Datum correction	0 m, 1200 m/s	0 m, 1200 m/s
Automatic gain control	100 ms	100 ms
Velocity analysis	Yes	Yes
NMO correction	70 % stretch mute	70 % stretch mute
Stack	Yes	Yes
Bandpass filtering	20-30-80-90 Hz	20-30-110-120 Hz
f-x deconvolution	Yes	Yes
Trace balance	Entire trace	Entire trace
Phase-shift migration	Yes	Yes

Table 3 Processing parameters applied for both lines

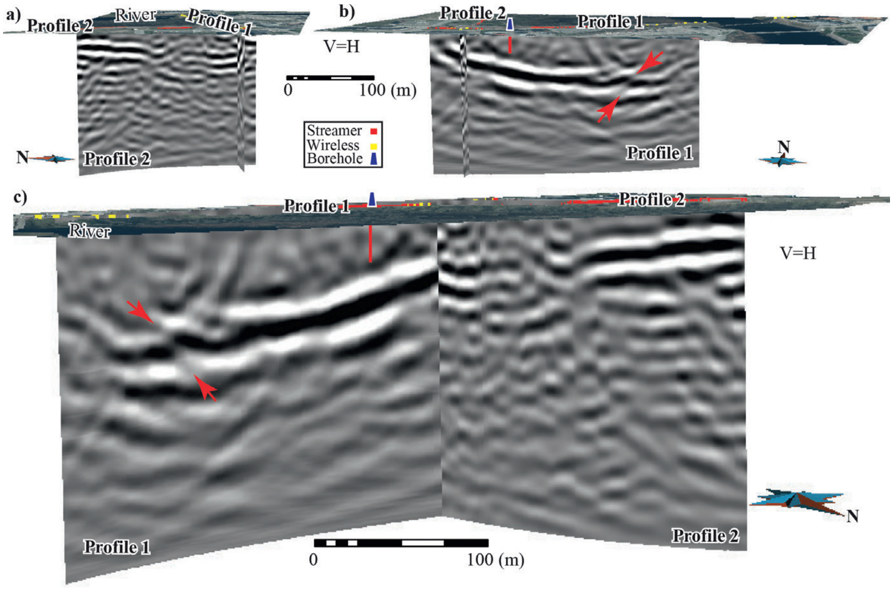

Figure 5 (a) Migrated reflection section of Profile 2 and Profile 1 (b) with aerial photo projected on elevation surface and red line showing drilled depth to bedrock. Note the discontinuity in the reflection shown by the red arrows indicating possibility of a fracture zone in the bedrock. (e) Both migrated reflection sections of Profile 1 and Profile 2 are shown together.

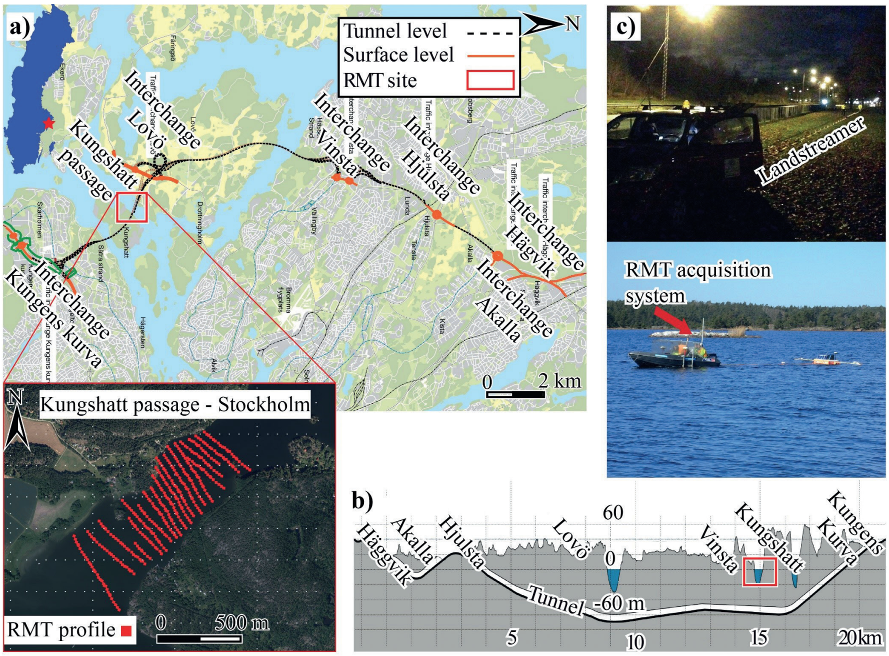

Figure 6 Location of the Stockholm Bypass (a) and an overview of the planned excavation depth along different segments of the tunnel (b). (c) Photos showing the two developed systems (seismic landstreamer and boat-towed RMT) side by side, (up) landstreamer towed by a vehicle, (down) boat-towed RMT system. (a) and (b) modified from the Swedish Transport Administration (Trfikverket; http://www.trafikverket.se/).

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. Details of the data acquisition and processing can be found in Bastani et al. (2015) and Mehta et al. (2017). Certain issues associated with the urban environment, such as cultural noise, can be seen on the raw data. Furthermore, the power cable underlying the water column also had adverse effects on data quality at some stations. These noises had to be identified and filtered before the inversion.

The data inversion was carried out with the code EMILIA based on damped Occam algorithm (Kalscheuer et al., 2008). Figure 7a,b shows 3D views from the 2D modelling of the RMT data together with information from an inclined well, B4, along with the model of the planned tunnel track. Fracture systems found during the core analyses are marked as K1-K5. Some cores analysed 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 7b, particularly note the resistive fresh water, with conductive sediments and a 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 are planned in the future. Details concerning resolution and a sensitivity analysis can be found in Mehta et al., (2017).

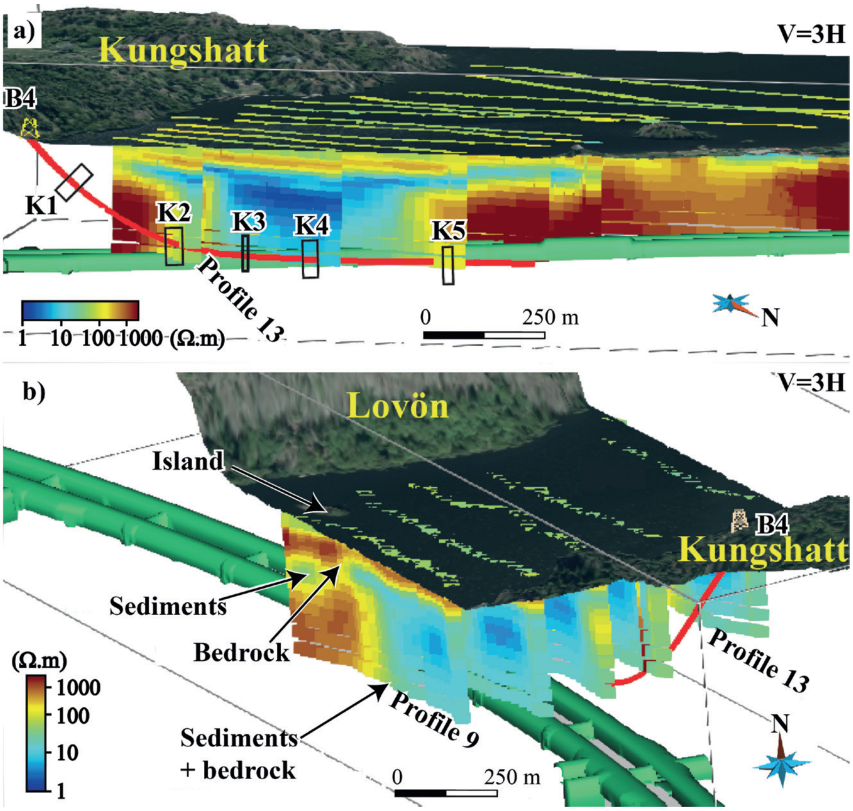

Figure 7 3D views showing (a) the directional borehole, B4, along with the RMT resistivity models and tunnel model shown in green. Five major fracture systems and their widths were mapped in the cores from B4, four (K2–K5) are likely to be contributing to the conductivity zone in the middle of the water 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.

Discussion and conclusions

Two modern geophysical systems have been developed with a particular focus on urban underground infrastructure planning projects and that can also 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 room for improvements based on the feedback from their applications. 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 system can also be enhanced using additional lower frequency controlled source (control source RMT).

Here, we presented a case study of the seismic landstreamer at a site contaminated with chlorinated hydrocarbons to image the bedrock and possible fracture zones that can be used as pathways for contaminant migration. Tomographic results along both profiles show that the bedrock depth is well determined and indicate the existence of at least two fracture zones in the bedrock. The reflection seismic section along Profile 1 shows a clear interruption of the interpreted bedrock reflection, indicating a potential fracture zone and supporting the tomography results. The boat-towed RMT case study from the Förbifart Stockholm also shows the potential of this method for mapping purposes 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 so far been used in several related studies in Sweden, Finland, Norway and Denmark, which encourages us to improve them further.

Acknowledgments

This study was conducted within the framework of Trust 2.2 (Trust-GeoInfra; http://www.trust-geoinfra.se,) sponsored by Formas (project number: 252-2012-1907), SGU (363-26512013), BeFo (BeFo 340), SBUF, Skanska, FQM and NGI. B. Brodic, S. Mehta and S. Wang PhD studies are supported by Trust 2.2 project. We thank Marcus Wennermark and Kristofer Hellman from Lund University for their help during the seismic acquisition in Kristianstad. We would like to thank Kristianstad municipality for permitting us to do the survey. Lund University (and their partners) through the Trust 4.2 project provided the seismic source used in the seismic study for which we are thankful. GLOBE Claritas under licence from the Institute of Geological and Nuclear Sciences Limited (GNS), Lower Hutt, New Zealand was used to prepare and process the seismic data. We thank A. Tryggvason for providing the ps_tomo tomography code. gOcad from Paradigm was used for 3D visualization and viewing of the data and results.

References

Bastani, M. [2001]. *EnviroMT: A new controlled source/radio magnetotelluric system*, Uppsala University, Department of Geophysics.

Bastani, M., L. Persson, S. Mehta, and A. Malehmir [2015]. Boat-towed radio-magnetotellurics — A new technique and case study from the city of Stockholm. *Geophysics*, **80** (6), B193–B10, doi:10.1190/geo2014-0527.1.

Brodic, B., A. Malehmir, C. Juhlin, L. Dynesius, M. Bastani, and H. Palm [2015]. Multicomponent broadband digital-based seismic landstreamer for near-surface applications. *J. Appl. Geophys.*, **123**, 227–241, doi:10.1016/j.jappgeo.2015.10.009.

Brodic, B., A. Malehmir and C. Juhlin [2017]. Delineating fracture zones using surface-tunnel-surface seismic data, P-S and S-P mode conversions. *J. Geophys. Res. Solid Earth*, n/a–n/a, doi:10.1002/2017JB014304.

Dehghannejad, M., A. Malehmir, M. Svensson, M. Lindén, and H. Möller [2017]. High-resolution reflection seismic imaging for the planning of a double-train-track tunnel in the city of Varberg, southwest Sweden. *Surf. Geophys.*, **1** (1), 226–240, doi:10.3997/1873-0604.2017011.

Eiken, O., M. Degutsch, P. Riste, and K. Rød [1989]. Snowstreamer: an efficient tool in seismic acquisition. *First Break*, **7** (1223), doi:10.3997/1365-2397.1989021.

Guha, N., D. Loomis, Y. Grosse, B. Lauby-Secretan, F. E. Ghissassi, V. Bouvard, L. Benbrahim-Tallaa, R. Baan, H. Mattock, and K. Straif [2012]. Carcinogenicity of trichloroethylene, tetrachloroethylene, some other chlorinated solvents, and their metabolites. *Lancet Oncol.*, **13** (12), 1192–1193, doi:10.1016/S1470-2045(12)70485-0.

Johansson, S., C. Sparrenbom, G. Fiandaca, A. Lindskog, P.-I. Olsson, T. Dahlin, and H. Rosqvist [2017]. Investigations of a Cretaceous limestone with spectral induced polarization and scanning electron microscopy. *Geophys. J. Int.*, **208** (2), 954–972, doi:10.1093/gji/ggw432.

Kalscheuer, T., L.B. Pedersen, and W. Siripunvaraporn [2008]. Radiomagnetotelluric two-dimensional forward and inverse modelling accounting for displacement currents. *Geophys. J. Int.*, **175** (2), 486-514, doi: 10.1111/j.1365-246X.2008.03902.x.

Malehmir, A., S. Wang, J. Lamminen, B. Brodic, M. Bastani, K. Vaittinen, C. Juhlin, and J. Place [2015a]. Delineating structures controlling sandstone-hosted base-metal deposits using high-resolution multicomponent seismic and radio-magnetotelluric methods: a case study from Northern Sweden. *Geophys. Prospect.*, **63** (4), 774–797, doi:10.1111/1365-2478.12238.

Malehmir, A., F. Zhang, M. Dehghannejad, E. Lundberg, C. Döse, O. Friberg, B. Brodic, J. Place, M. Svensson, and H. Möller [2015b]. Planning of urban underground infrastructure using a broadband seismic landstreamer — Tomography results and uncertainty quantifications from a case study in southwestern Sweden. *Geophysics*, **80** (6), B177–B192, doi:10.1190/geo2015-0052.1.

Malehmir, A., L. V. Socco, M. Bastani, C. M. Krawczyk, A. A. Pfaffhuber, R. D. Miller, H. Maurer, R. Frauenfelder, K. Suto, S. Bazin, K. Merz, and T. Dahlin [2016a]. Near-Surface Geophysical Characterization of Areas Prone to Natural Hazards: A Review of the Current and Perspective on the Future. *Adv. Geophys.*, **57** (1), 51–146, doi:http://dx.doi.org/10.1016/bs.agph.2016.08.001.

Malehmir, A., M. Andersson, S. Mehta, B. Brodic, R. Munier, J. Place, G. Maries, C. Smith, J. Kamm, M. Bastani, and H. Mikko [2016b]. Post-glacial reactivation of the Bollnäs fault, central Sweden; a multidisciplinary geophysical investigation. *Solid Earth*, **7** (2), 509–527, doi:10.5194/se-7-509-2016.

Malehmir, A., S. Heinonen, M. Dehghannejad, P. Heino, G. Maries, F. Karell, M. Suikkanen, and A. Salo [2017]. Landstreamer seismics and physical property measurements in the Siilinjärvi open-pit apatite (phosphate) mine, central Finland. *Geophysics*, **82** (2), B29–B48, doi:10.1190/geo2016-0443.1.

Maries, G., E. Ahokangas, J. Mäkinen, A. Pasanen, and A. Malehmir [2017]. Interlobate esker architecture and related hydrogeological features derived from a combination of high-resolution reflection seismics and refraction tomography, Virttaankangas, southwest Finland. *Hydrogeol. J.*, **25** (3), 829–845, doi:10.1007/s10040-016-1513-9.

Mehta, S., M. Bastani, A. Malehmir, and L. B. Pedersen [2017]. Resolution and sensitivity of boat-towed RMT data to delineate fracture zones – Example of the Stockholm bypass multi-lane tunnel. *J. Appl. Geophys.*, **139**, 131–143, doi:10.1016/j.jappgeo.2017.02.012.

Miller, R., S. Pullan, J. Waldner, and F. Haeni [1986]. Field comparison of shallow seismic sources. *Geophysics*, **51** (11), 2067–2092, doi:10.1190/1.1442061.

Tryggvason, A., S. ður T. Rögnvaldsson, and Ó. G. Flóvenz [2002]. Three-dimensional imaging of the P- and S-wave velocity structure and earthquake locations beneath Southwest Iceland. *Geophys. J. Int.*, **151** (3), 848–866, doi:10.1046/j.1365-246X.2002.01812.x.

Whiteley, R. [2009]. Application of geophysics to underground space development for improvement of urban environments. *20th Geophysical Conference*, Extended Abstracts.