Multicomponent digital-based seismic landstreamer for urban underground infrastructure planning

Licentiate thesis

Bojan Brodic



Abstract

In the field of urban seismics, challenges such as difficulty to plant seismic receivers, electric or electromagnetic (EM) noise pickup, along with many others are encountered on a daily basis. To overcome them, as a part of this study, a 3C MEMS-based seismic landstreamer was developed at Uppsala University. A landstreamer is an array of seismic sensors that can be pulled along the ground without planting. To date, the 3C MEMS-based seismic sensors make the developed landstreamer a unique system. Compared to geophones, MEMS sensors are digital accelerometers designed to work below their resonance frequency (1 kHz), with a broadband linear amplitude and phase response (0-800 Hz). Other advantages of MEMS over geophones include insensitivity to electric and EM noise contamination and tilt angle measurements. The landstreamer is based on Sercel Lite technology and Sercel DSU3 (MEMS-based) sensors. The sensors are mounted on receiver holders (sleds), and the sleds connected by a non-stretchable belt used in the aircraft industry. The system supports both geophones and DSU3 sensors and can be combined with wireless units supporting either of the two. It currently consists of 5 segments of 20 sensors that are connected by small trollevs carrying line-powering units. Four segments are of 20 units with 2 m spacing each, and the fifth consists of 20 units 4 m apart. With a team of 3 to 4 persons for the setup, data acquisition rates vary from 600 m to 1200 m/day of seismic line, with a source to receiver spacings of 2 to 4 m.

The landstreamer was tested against planted 10 Hz and 28 Hz geophones, where even with the sensors mounted on the sleds, better data quality could be seen on the landstreamer datasets. No negative effects like time delays phase or particle polarization changes due to overall streamer assembly were noted, comparing the planted DSU3 sensors versus the streamer mounted ones. At the Stockholm Bypass site, no electric or EM noise pickup has been noted in the data, and wireless seismic recorders combined with the streamer were essential to image the poor quality rock zones under major road, without influencing the traffic. Results from an ongoing study to test the landstreamer inside a tunnel at a depth of -160 to -200 m below sea level, intersecting known fracture systems, further support that no electric noise pickup is seen. On the shot gathers from this site, we can note P-S mode converted energy, interpreted as being generated at fracture zones. Here, using a tunnel-surface seismic setup, the rocks between the tunnel and the surface were tomographyically imaged.



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Supervisor

Associate professor Alireza Malehmir Department of Earth Sciences - Geophysics Uppsala University

Co-supervisor

Professor Christopher Juhlin Department of Earth Sciences - Geophysics Uppsala University

Reviewer

Dr André Pugin Geological Survey of Canada, GSC

List of Papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.

- I Brodic, B., Malehmir, A., Juhlin, C., Dynesius, L., Bastani, M., Palm, H. (2015) Multicomponent broadband digital-based seismic landstreamer for near-surface applications. *Journal of Applied Geophysics*, 123: 227–241
- II Brodic, B., Malehmir, A., Juhlin, C. (2015) All wave-modes converted and reflected from fracture systems: A tunnel-surface seismic experiment. *Manuscript*

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Abbreviations

2D	Two-dimensional	
3D	Three-dimensional	
1C	single component	
3C	three component	
HRL	Hard Rock Laboratory	
UU	Uppsala University	
TRUST	Transparent Underground Structures	
km	kilometer	
m	meter	
Hz	Hertz	
kg	kilogram	
m^3	meter cubic	
CDP	Common Depth Point	
VSP	Vertical Seismic Profiling	
Vs	Shear wave velocity	
Vp	Compressional wave velocity	
Ga	billion years	
S	second	
ms	millisecond	
l/min	liters per minute	
dB	Decibel	
EM	Electromagnetic	
MEMS	Micro electro mechanical system	

1. Introduction

The possibility of recording seismic data at a relatively high speed, hence lower cost, has been intriguing researchers working on the shallow subsurface characterization using the seismic method for almost half a century (Eiken et al., 1989; Huggins, 2004; Inazaki, 1999; Kruppenbach and Bedenbender, 1975; Pugin et al., 2004; van der Veen and Green, 1998). The idea has gained even more attention recently due to population centralization with expanding cities, imposing the need for more infrastructure and opening the research field area of "urban geophysics" (Brodic et al., 2015; Krawczyk et al., 2013; Malehmir et al., 2015b; Pugin et al., 2013; Socco et al., 2010). Modern civil engineering standards (Eurocode - EC, International Building Code - IBC or others state specific ones) require the knowledge of the shallow subsurface properties, such as Vs_{30} (shear wave velocity in the top 30 m), depth to bedrock and/or water table, among others, in the preliminary planning stage (Kanlı et al., 2006; Nazarian and Stokoe, 1983; NEHRP, 2001). During the construction phase, monitoring of the surrounding structures, and the construction itself, using geophysical methods may give information about terrain subsidence, possible lateral water inflows, changes in water table regime, changes in the local stress field or increased vibration levels (Angioni et al., 2003; Brauchler et al., 2012; Dietrich and Tronicke, 2009; Hajduk and Adams, 2011; Maurer and Green, 1997). All possible information that may be obtained using geophysical measurements, along with mandatory pile testing, can help in building safer, more environmental friendly constructions and prevent disasters (Håkansson, 2000; Reynolds, 2002).

Urban environments, on the other hand, impose many challenges for geophysical exploration, problems from electric and electromagnetic (EM) noise or existing underground facilities and pipelines can be mentioned as examples. Most of the expanding cites nowadays have been settled in the past as well, and the historical and cultural heritage can't be neglected and should be preserved (Komatina and Timotijevic, 1999; Kydland Lysdahl et al., 2014). Moreover, the difficulty to properly couple the electrodes or receivers used to record the investigated geophysical signals on paved surfaces is not uncommon.

To tackle the challenges encountered in application of geophysical methods in urban areas Uppsala University (UU), as a part of an industryacademia consortium, has developed a seismic landstreamer system. A landstreamer can be defined as an array of seismic receivers that can be dragged along the surface without the need for "planting" (Brodic et al., 2015; Inazaki, 1999; Malehmir et al., 2015b; Suarez and Stewart, 2007). The idea of having a receiver array that is coupled to the ground by the weight of the receivers or some sort of receiver holders (sleds) and receivers was patented in the 1970s, and first applied in the form of a snow-streamer (see Determann et al., 1988; Eiken et al., 1989 and references therein). Since these pioneering works, seismic landstreamer systems of various kinds have proven to be valuable for near surface mapping and characterization in urban areas, especially on asphalt and paved surfaces (Brodic et al., 2015; Deidda and Ranieri, 2001; Huggins, 2004; Inazaki, 2004; Krawczyk et al., 2012; Malehmir et al., 2015c; Pugin et al., 2013, 2009, 2004; Pullan et al., 2008; van der Veen et al., 2001).

To the best of my knowledge, published studies involving any kind of landstreamer for acquiring seismic data have been conducted using single (1C), two different component (2C) receivers mounted on a single sled or, in rare cases, single three component (3C) geophones (see Brodic et al., 2015 and references therein). Even though geophones have, and are, successfully serving the seismic industry for more than 70 years now (Salvatori, 1938), they suffer from many limitations. Some of them include electrical or EM noise pickup, limited bandwidth and no control and correction over their tilt angles (Alcudia et al., 2008; Hons, 2008; Hons et al., 2007). In contrast to the mentioned studies, the Uppsala University landstreamer is built with digital 3C, MEMS-based (Micro-machined Electro-Mechanical Sensor) units. Numerous case studies have proven their value and advantages in urban and other areas (Brodic et al., 2015; Malehmir et al., 2015a, 2015b, 2015c). A detailed discussion comparing geophones and MEMS-based units mounted on the UU landstreamer is given in Chapter 2 and, partly, in the papers attached to this thesis.

This thesis addresses and summarizes the experiences obtained working with the landstreamer for over two years and testing it in different environments. More specifically the articles included in the thesis address the following issues:

- Comparison of data recorded with planted different natural frequency geophones versus data recorded with the landstreamer;
- Urban site characterization using both the landstreamer and wireless recorders to obtain longer offset data and subsurface information at one of the planned access ramps of the Stockholm Bypass (Förbifart Stockholm) project;
- Characterization of rock masses between an existing tunnel and the surface (surface-tunnel seismics) using a combination of wire-less recorders, the seismic landstreamer and planted geophones;
- Fracture detection using mode-converted direct and reflected waves;

• Extraction of fracture zone dynamic mechanical properties, such as Vp/Vs and Poisson's ratio from seismic data.

The last two items are from an ongoing study conducted to test the possibility of using the seismic landstreamer, combined with wireless and planted units, to characterize fractures and rock masses between the tunnel and the surface and the potential of imaging deeper structures inside the rock volume space. This approach may be applied during the tunneling phase for characterization of rock masses surrounding tunnels, or to monitor changes in rock quality and stress regime due to the excavation. In the long-term, this may also open possibilities for deep in-mine studies.

Highlights of the main findings of the two papers that the thesis is based on are:

- The seismic landstreamer benefits from no electric or EM noise pickup;
- No need for planting and the dense receiver spacing enables high speed, high resolution seismic imaging as illustrated from various test environments;
- Good quality data can be obtained in extremely noisy urban environments;
- Signal quality is superior to the geophones used in the studies;
- 3C data recording is crucial in understanding and for correct interpretation of the data acquired in full 3D rock volume space, where particle motion plots enable discrimination of different types of seismic waves,
- Imaging of water bearing fracture systems and their characterization is possible using mode-converted waves, in particular when the near surface effect is avoided like inside tunnels or mining galleries.

2. Seismic Method

The seismic method is based on detecting differences in traveltimes of seismic waves propagating through an elastic medium and imaging reflections from impedance contrasts within the medium. Different traveltimes correspond to different seismic velocities, hence different seismic events are attributed to the waves reflected from an acoustic impedance contrast, or refracted through higher velocity structures (Sheriff, 2002). In the most fundamental form, an elastic medium¹ can be characterized by two parameters; bulk modulus (K) and shear modulus (μ) (Helbig, 2015; Mavko et al., 2009). In this type of media, seismic waves can propagate in the form of body (primary or compressional, P-wave or secondary or shear, S-wave) or surface waves. With surface waves, we can distinguish Rayleigh and Love waves that are commonly present in surface seismic surveys (free surface-half space contact). The equivalent of surface waves propagating in boreholes are called Stoneley (tube wave, borehole surroundings-borehole fluid contact) or in marine environments, named Scholte (bottom-water contact) waves (Shearer, 2009). Primary and secondary body waves travel at different velocities, and have distinct particle motions (Figure 2.1). Particle motions of the *P*-wave are perpendicular to the wave front in isotropic media, while the *S*wave is characterized by particle motions on the plane of wave front (Pujol, 2003). In an anisotropic media, a phenomena called shear-wave splitting² may occur, and an S-wave traveling in an anisotropic environment can be further decomposed into two distinct components As schematically shown on Figure 2.1, the SV wave particle motion is here defined to be on the wave front plane. The SH wave particle motion is here in the horizontal direction, perpendicular to the SV motion.

¹ The author here refers to a homogenous isotropic media requiring only two constants for generalized Hooke's law expressing the relationship between stresses and strains (Garotta, 1999).

² In an anisotropic media, shear waves split into fast and slow components, with the one faster generally vibrating parallel to the plane of foliation, fractures, tectonic stresses or mineral orientation, while the slower one vibrates perpendicular to it.



Figure 2.1. A schematic view of the *P*- and *S*-wave vectors, with *S*-wave further decomposed into vertical (*SV*) and horizontal (*SH*) components relative to the wave front shown in grey. Dashed arrows represent the direction of particle motion for each individual body wave and dashed ellipse and half ellipse schematically show planes and trajectories of the particle motions of two types of surface waves, Love (*L*) and Rayleigh (*R*).

Surface waves or "ground roll" are waves whose initiation and propagation is mainly confined to a layer just beneath the surface. Due to the high impedance contrast between the surface, overburden layer and bedrock, the energy stays trapped and travels near the free surface of the elastic media (Garotta, 1999; Knopoff, 1952). Depending on the plane of particle motion, we distinguish Rayleigh and Love waves (Figure 2.1). Both of them are guided and dispersive waves and the particle motion of the two follow a distinct pattern in different planes as shown in an illustrative way in Figure 2.1. In conventional seismic data processing, surface waves, are considered as noise and many different acquisition and processing approaches are used to remove them. Interestingly, in recent years, surface waves are getting a more important role and attention in the characterization of the shear velocity of near surface materials, where reflective structures are difficult to observe using reflection seismic processing (Bachrach and Nur, 1998; Garotta, 1999; Park et al., 1999; Socco and Strobbia, 2004; Steeples and Miller, 1998; Xia et al., 2003). As mentioned by Sirles et al. (2013), when everything else fails, surface waves and their analysis comes to play a role and this can be particularly important for urban geophysical applications.

To derive the relationship between elastic parameters and the P- and Swave velocities, Vp and Vs respectively, one needs to use the generalized Hooke's law expressing the relationship between stresses and strains in an elastic media. In three-dimensional (3D) space, according to the Voigt notation, and taking into account symmetry and summation over repeated indices, Hooke's law can be expressed as:

$$\begin{pmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \sigma_{xy} \\ \sigma_{yz} \\ \sigma_{yz} \\ \sigma_{zx} \end{pmatrix} = \begin{pmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} \\ C_{21} & C_{22} & C_{23} & C_{24} & C_{25} & C_{26} \\ C_{31} & C_{32} & C_{33} & C_{34} & C_{35} & C_{36} \\ C_{41} & C_{42} & C_{43} & C_{44} & C_{45} & C_{46} \\ C_{51} & C_{52} & C_{53} & C_{54} & C_{55} & C_{56} \\ C_{61} & C_{62} & C_{63} & C_{64} & C_{65} & C_{66} \end{pmatrix} = \begin{pmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \varepsilon_{zz} \\ \varepsilon_{yz} \\ \varepsilon_{zx} \end{pmatrix},$$

where σ and ε are direction dependent stress and strains, respectively, and C_{nn} represents one of the elements of the stiffness matrix. For the simplest media (homogenous and isotropic), $C_{13} = C_{21} = C_{13} = C_{23} = C_{31} = C_{32} = C_{12}$, $C_{22} = C_{33} = C_{11}$, $C_{55} = C_{66} = C_{44}$, with all the other stiffness matrix elements being equal to zero, and $C_{11} = K + 4/3\mu$, $C_{44} = \mu$ and $C_{12} = C_{11} - 2C_{44}$. To describe the elastic wave propagation in this media, we need to consider Newton's second law (F = ma), with the bulk density³ of the material (ρ) having the role of mass in the system (Sheriff and Geldart, 1995). The phase velocities⁴ of the seismic waves propagating in this media are:

$$Vp = \sqrt{\frac{C_{11}}{\rho}} = \sqrt{\frac{K + 4/3\mu}{\rho}}$$
$$Vs = \sqrt{\frac{C_{44}}{\rho}} = \sqrt{\frac{\mu}{\rho}}.$$

By knowing the elastic parameters of the media, we can obtain seismic velocities, or if the velocities are known, the elastic parameters may be inferred (Castagna et al., 1993; Gardner et al., 1974; Gebrande, 1982; Kearey et al., 2002; Lindseth, 1979; Ricker, 1944; Sheriff and Geldart, 1995; Waters, 1981).

In the course of my research, I have been involved in development and testing of the digital MEMS-based seismic landstreamer and different types

³ The bulk density of a material can be considered as a function of porosity, fluid type, water saturation, mineral composition and the matrix material (Helbig, 2015)

⁴ Phase velocity can be regarded as a velocity of a given phase (peak or trough velocity) and is different from the velocity of the envelope maximum, known as the group velocity. The term apparent velocity is sometimes used (Sheriff, 2002).

of *P*- and *S*-wave seismic sources. Most of the research concerning sources remains as unpublished material used for internal purposes and quality control of different stages of source development. The published results, however, go more into detail on the possible unwanted effects induced of the overall streamer assembly and the analysis of the landstreamer acquired data in different environments. Therefore, considering the contents of the two papers that the thesis is based on, in the following sections I will try to provide a concise overview on the seismic receivers and summarize the main results of the two.

2.1. Seismic receivers

All controlled-source seismic experiments include an active source, receivers and a recording system. Seismic signals initiated at a source location are convolved with the earth's materials (earth response) and detected at the receivers, from where they are transferred and saved in a recording unit. The output signal from a receiver can be proportional to displacement, ground velocity (velocimeters - geophones) or ground acceleration (accelerometers). The choice of a seismic receiver strongly depends on its specifications like:

- Physical characteristics (diameter, height, weight, operating temperature range),
- Frequency bandwidth,
- Sensitivity,
- Damping,
- Distortion,
- Coil resistance,
- Dynamic range,
- Power consumption,
- Available static and dynamic tests.

Frequency bandwidth of a receiver is directly connected with its natural and spurious frequencies. Natural frequency represents the resonance frequency of the spring-mass system and it is the lower frequency limit of a seismic receiver. Below the resonance frequency, the amplitude response of the receiver decreases typically by 12db/octave (Hons, 2008; Hons and Stewart, 2006). Spurious frequency represents the resonance of the system perpendicular to its working axis. It is a combination of multiple vibration modes and represents the upper frequency limit of the receiver (Faber and Maxwell, 1996).

The sensitivity of a receiver is the smallest change a receiver is capable of detecting. It is related to the strength of the magnetic field and the number of loops in the coil and is a value specified by the manufacturer (Hons, 2008;

Sheriff, 2002). It is measured in output volts per unit of velocity or acceleration.

Another manufacturer defined characteristic of seismic receivers is the damping or the damping factor⁵. It is related to the springs opposing the movement of the moving mass in the receiver and slowing down the oscillations to prevent dissipation of the oscillation energy. The damping factor is the ratio of friction of the system to the friction necessary to achieve critical damping (Sheriff, 2002).

Distortion is related to the nonlinear response of the seismic receiver and the changes of the wave-shapes of the recorded signal due to receiver construction.

Dynamic range represents the ratio of the highest and lowest detected or recorded seismic signal. It is commonly expressed in units of dB as:

dynamic range(dB) =
$$20\log\frac{S}{s}$$
,

where S is the highest and s the lowest signal detected (Dragašević, 1983). The units of S and s can be electrical (voltage, current, power) or mechanical (displacement, velocity or acceleration).

Coil resistance is another specification of the manufacturer and relates to the coil winding.

Power consumption is becoming a more important specification nowadays, since digital receivers require power for functioning, while the analog ones required power for the A/D conversion part. This conversion can be done in the geophone proximity (e.g. Sercel field digitizing units, FDUs) or at the recording unit itself (e.g. Geode recording system).

In the field of broadband seismic data acquisition, different receiver tests indicating the quality of the acquisition spread and quantifying factors influencing the sensor response (such as ground coupling, crosstalk, leakage, tilt) play an important role. The entire data enhancements that are applied are based on the assumption that good or reasonable quality data have been acquired, where different field tests become essential for these purposes.

⁵ The damping factor dictates whether the spring/mass system of a seismic receiver will oscillate or not, and here we can distinguish critical damping (1, minimal damping to prevent oscillations), underdamped (less then 1, oscillating) or overdamped (grater then 1, non-oscillating) systems.

2.1.1. Geophones

Geophones have been serving the seismic industry for more the 70 years (seismometer patent, Salvatori, 1938). In the most fundamental form, it can be thought of as an analog device⁶ used to convert ground motions into electric signals recorded on a recording device. Most commonly, they are based on a moving-coil design, where the coil is suspended by springs in the field of a permanent magnet attached to the geophone casing (Figure 2.2). The permanent magnet - suspended coil system is an oscillatory system, with the resonance frequency determined by the coil mass and the suspension spring stiffness. Output waveform of a geophone depends on how it converts the coil displacement into voltage, sensitivity and selection of the damping factor (Kearey et al., 2002). Typically, underdamped systems are common, with a damping factor ranging from 0.62 to 0.7 giving a flat frequency response above the resonant frequency (Hons, 2008; Kearey et al., 2002; Sheriff, 2002; Telford et al., 1990). Overdamping of the system leads to sensitivity reduction, hence distortion of the recorded waveform. Geophones sense the motion along the axis of the coil, and the number of coils and their orientation defines the number of components (1C, 2C or 3C; and even 4C when combined with hydrophones), along with the type of motions they are able to record (vertical and/or horizontal).

Generally speaking, for any geophone, the input to the oscillatory system and its output are related by the geophone transfer function. Without going into derivation⁷, a geophone transfer function (R_g) in the frequency domain can be given as (Hons, 2008; Juhlin, 2014):

$$R_g(\omega) = \frac{\omega^2 K_g}{\omega^2 - 2ih\omega\omega_0 - \omega_0^2},$$

with K_g as the sensitivity, *h* damping factor, ω angular frequency and $\omega_0=2\pi f_0$, with f_0 being the geophone resonance frequency. Real part of the equation represents the geophone amplitude spectrum, while the imaginary is the phase spectrum.

⁶ By analog, the author implies that an analog-to-digital (A/D) conversion of the recorded signal is mandatory for data to be stored using modern data types.

For a detailed derivation, the reader is referred to Hons, 2008.



Figure 2.2. Schematic for a typical geophone showing a closer look of the internal structure of the coil/spring system. Ground motion causes the movement of the inertial mass in the magnetic field of the stable magnet along the coil axis, producing the output signal. Figure modified from Linear Collider Consortium (www.linearcollider.org).

Even though geophones still dominate the field of seismic data acquisition, their design imposes certain limitation such as:

- Limited bandwidth; recorded seismic signal is confined to the frequency range between resonance and spurious frequency. This is becoming a problem in recent years, where the same seismic data sets may be used not just for reflection and refraction imaging, but also for full waveform imaging, surface wave inversion or other passive-type (like noise) studies (Adamczyk et al., 2014; Miller et al., 2014; Park et al., 1999; Socco and Strobbia, 2004; Todorovic-Marinic et al., 2005; Zhang et al., 2014).
- No information about the receiver tilt can be a problem, since the unit has to be planted within the specified tilt angle tolerance range. With a tilt angle reaching 40° from the vertical, the geophone output is about 70% of the maximum and is sinusoidally decreasing (Bertram et al., 1999).
- The greatest challenge facing urban seismic exploration is the electric or EM noise pickup. Analog signals received at the seismic receivers have to be transformed into digital form for data storage and further signal processing. Regardless of where the A/D conversion is performed (FDU's for transferring the analog signal to the recording unit where it is digitized), the geophone design, and the cablings involved always leave potential for electric and EM noise contaminations, if these noise sources are present. A common approach to suppress them is an application of a narrow stop-band filter (the so called Notch). This approach sometimes

may not work perfectly, as is exemplified in Paper II of this thesis, where not only the dominant current frequency, but also its harmonics are strongly contaminating parts of the data acquired using geophones. Even after application of several Notch filters, traces of current contamination may still be noted on geophone recorded signals, while the MEMS units are unaffected.

To overcome the previously mentioned limitations, along with the others summarized in Paper I, a decision was made to build a seismic landstreamer based on Sercel DSU3 (MEMS-based) sensors and technology. The choice was also justified by the availability of the recording system based on Sercel and earlier experiences working with the recording system, moreover, the possibility of combining both MEMS and geophone type sensors using identical acquisition system.

2.1.2. DSU3 MEMS-based technology and receivers

Compared to conventionally available geophones and accelerometers, Sercel DSU3 sensors are fully digital 3C units based on MEMS technology (Figure. 3). MEMS sensors are based on the same mass/spring system as the geophones, implying that the casing moves with respect to inertial mass, when subjected to displacement. Here, the displacement of the casing of the MEMS is canceled by a force feedback system and the residual mass displacement measured by an accompanying ASIC (application specific integrated circuit) chip weighting less than 1 gram and ~1 cm long (Mougenot, 2004). The proof mass of the MEMS is a micro-machined thin piece of silicon covered by metal plating on both sides acting as mobile electrodes, while the frame itself acts as the transducer part (Hons, 2008). The frame and the proof mass together form a capacitor, where the ASIC chip is used to transfer the capacitance change resulting from the mass displacement into output voltage induced by acceleration (Laine and Mougenot, 2014). The mechanical idea of springs is here represented by very thin regions of silicon by which the moving mass is suspended from the outer frame, allowing a small amount of elastic motion (Hons, 2008). The resonant frequency of the springs is close or above 1 kHz (Hons, 2008). The whole frame-spring-mass system is sealed in a vacuum ceramic package to prevent Brownian-motion⁸ noise resulting from the collision of mass and air molecules (Laine and Mougenot, 2014).

⁸ According to Wikipedia:"Brownian motion is the random motion of particles suspended in a fluid (a liquid or a gas) resulting from their collision with the quick atoms or molecules in the gas or liquid".



Figure 2.3. (a) Various components of a DSU3 sensor, MEMS-ASIC chips and the schematic operating principle (Laine and Mougenot, 2014) and (b) DSU3 sensors used in the landstreamer and partial cuts showing the internal parts of the sensor (Photo provided by A. Malehmir, 2013).

A fundamental difference between MEMS sensors and geophones is in their design. MEMS-based sensors are designed to work below their resonance frequencies (e.g., below 1 kHz) while geophones are built to work above their resonance frequencies (e.g., most commonly 4.5-40 Hz). The key advantage of the MEMS sensors lies in their broadband linear phase and amplitude response, where theoretically frequencies in the range from 0 to 800 Hz are recorded without attenuation (Mougenot and Thorburn, 2004). Recording of the direct current related to gravity acceleration is enabled by their high resonant frequency (1 kHz), and the gravity vector can be used for sensitivity calibration and tilt measurements (Gibson et al., 2005; Kendall, 2006; Mougenot and Thorburn, 2004). Aside from the digital data recording and transfer, broadband signal and tilt control, the DSU3 is a single point 3C receiver, recording the ground motion on all three sensor axes, making it a powerful tool for a variety of high-resolution applications, no attenuation of surface waves and essentially better wave field sampling (Brodic et al., 2015; Malehmir et al., 2015a, 2015b, 2015c; Moreau et al., 2014; Stotter and Angerer, 2011). DSU3 MEMS sensor offer the measurement of gravity, distortion, gain, phase, crosstalk, tilt and spread noise, making them superior to the other MEMS available (Laine and Mougenot, 2014).

An ongoing debate still exists concerning the *pros and cons* of MEMS sensors compared to geophones and other types of accelerometers, and here I will try to summarize some field and lab experiences reported in the literature:

According to Laine and Mougenot (2014), the noise floor of the DSU3 sensors is 40 ng/(Hz)^{1/2}, but in the frequency range from 10

to 200 Hz. Below 5 Hz, the noise floor can exceed the ambient noise. Below 55 Hz, it becomes higher than that of a single geophone connected to a digitizer, making the recognition of weak low frequency reflections questionable;

- Gibson and Burnett (2005) give a nice overview of the DSU3 sensors, with the conclusion that the tilt limits of about 27° for the horizontal components and about 57° for the vertical component. Above these tilt angles the recording of the signal cannot be achieved;
- Hons (2008) concludes that the MEMS sensors have a lower noise floor at high frequencies and are more suitable for detecting small high frequency signals. If the dominant frequency of a geophone lies in the range from 5-60 Hz, geophones may have the advantage of detecting the frequencies down to 5 Hz, for a 10 Hz resonant frequency geophone. This indicates that the MEMS sensors are more suitable for small to medium offsets, where the high frequencies may exist and are not detectable by geophones.

To conclude this chapter, I provide the transfer function of a MEMS sensor and a MEMS-to-geophone transfer function, without derivation (Hons, 2008). Using the same terminology as with the geophone transfer function, the MEMS transfer function can be defined as:

$$R_a(\omega) = \frac{9.81K_a}{\omega_0},$$

with ω_0 being the MEMS resonant frequency in rad, and K_a the sensitivity of the MEMS sensor equal to 0.2 (Hons, 2008). Taking the ratio of the two transfer functions gives us a scaling factor to obtain geophone data from acceleration, and its inverse to transform the geophone data into MEMS response.

3. Paper summary

3.1. Paper I: Multicomponent broadband digital-based seismic landstreamer for near-surface applications

3.1.1. Summary

In the last half a century, urban life as the basis for the social organization has been showing a continuously increasing trend, and is expected to reach around 60 % in 15 years from now (Whiteley, 2009). Urbanization process imposes the need for more infrastructures, where understanding of shallow subsurface conditions is necessary to build safely and in an environmental friendly manner (Fenning et al., 1994; Miller, 2013; Whiteley, 2009). This has pushed geophysical methods to the "shallow domain", opening the research field area of "urban geophysics" (Fenning et al., 1994; Henderson, 1992; Miller, 2013).

To cope with the challenges of urban geophysics, at Uppsala University (UU) a prototype 3C MEMS-based seismic landstreamer (Figure 3.1). A landstreamer represents as an array of sensors that can be dragged along the surface without the need for planting. The UU landstreamer system is fully digital, hence less sensitive to electrical or EM noise. Table 3.1 shows a summary of UU landstreamer properties and a comparison with the ones commonly employed nowadays.

The sensors are mounted on the "sleds" (Figure 3.1a,b) and everything connected by non-stretchable airplane cargo straps (Figure 3.1b). Total weight of the sled-sensor assembly is about 5 kg (Figure 3.1b). Present configuration consists of 5 segments with 20 sensors each. Four segments have the sensor spacing of 2 m, while the spacing of 4 m is used for the fifth one, making the maximum spread length of 240 m. The segments are connected by small trolleys with powering units inside (Figure 3.1c).



Figure 3.1.(a) MEMS-based seismic landstreamer developed in this study towed by a relatively light vehicle. (b) A close-up showing the installation of the 3C sensor on the sled. (c) Small carriage connecting different segments (typically 20 sensors 2–4 m apart per segment) of the landstreamer carrying also a power unit. Photos were taken as a part of Backyard tests in Uppsala, Sweden at the early stage of the development of the streamer.

Parameters	Developed in this study	Existing landstreamers
Sensor type	DSU3 (3C MEMS-based)	Geophones (1C or 3C)
Frequency bandwidth	0 - 800 Hz	4.5 ~ 400 Hz
Tilt measurement	Recorded in the header	Not possible
Acquisition system	Sercel Lite (MEMS + geophones)	Most commonly Geometrics Ge- ode (geophones only)
Max number of channels	1000	24 (per unit)
Sensor spacing	Adjustable 0.2 - 4 m	Adjustable
Cabling	Single	Several
Data transmission	Digital	Analog
Data format	SEGD	SEG2
GPS time	Recorded in the header	Often not possible

Table 3.1. Summary of the properties of the landstreamer system developed in this study.

In an early development stage, we tested the 20 units landstreamer (1 segment) against two planted lines with 28 and 10 Hz geophones (20 geophones, each line). Recording was done simultaneously for all three lines using the same acquisition system, with a 5 kg sledgehammer as seismic source. Figure 3.2 shows example shot gathers recorded with 10 (a) and 28 Hz (b) vertical geophones, and all three components (vertical (c) and horizontal inline (d) and crossline (e)) of the landstreamer after integration, with their corresponding amplitude spectra. Figure 3.2f,g shows an overlay of the amplitude spectra of the vertical components for all the receivers, with both DSU3 non-integrated and integrated data, scaled and unscaled, respectively.



Figure 3.2. Example shot gathers (after vertical staking of three repeated shots) with the corresponding amplitude spectra from landstreamer versus geophones test for (a) 10 Hz planted geophones, (b) 28 Hz planted geophones, (c) vertical component of the DSU3 sensors from the streamer, (d) horizontal inline component of the DSU3 sensors from the streamer and (e) horizontal crossline component of the DSU3 sensors from the streamer. (f) and (g) show amplitude spectra of all vertical components overlaid, normalized and raw, respectively, along with DSU3 vertical before and after integration. MEMS data (acceleration) have been integrated to provide comparable data to the geophones (velocity) and the amplitude spectra calculated without three traces closest to the shot. AGC has been applied (100 ms window) for display purposes.

Clearly observed reflection on the DSU3 vertical component data (red arrow in Figure 3.2c), indicates higher quality data recorded with the streamer, then the data recorded with geophones used in the test. No decrease of amplitudes, phase changes, reverberations or other unwanted effect that may be related with the streamer assembly could be noted in the results shown. Evidences of a mode-converted reflection can be seen on the horizontal components of the DSU3 sensors, indicating the streamer's potential for mode converted wave imaging. The amplitude spectra of the landstreamer sensors show more energy in the higher frequency part of the signal compared with the geophones tested, making them more suitable for near surface applications (Figure 3.2f,g).

A complementary test of the previous one was conducted with 12streamer mounted DSU3 sensors against 12 DSU3 planted next to them. The aim was to check if any possible phase, time or particle polarization differences might be introduced by the sleds, particularly for the horizontal components. Figure 3.3 represents a side-by-side comparison of the streamer mounted DSU3 sensors versus their planted pairs on both shot gathers and particle motion plots (hodograms) of different seismic events to judge if the sleds introduce any distortions of the particle motion.

Identical phases with similar arrival times and shapes can be noted by the examination of all components and trace pairs shown on Figure 3.3a,b,c. Minor distortion of the near offset traces seen on the crossline component may be connected to either the bad coupling or the local ground conditions. Particle motion plots show no significant polarization changes induced by the sleds holding the sensors. Results shown on Figure 3.3, further support the claim that no negative effect of the landstreamer design can be noted in the data. Amplitude spectra shown on Figure 3.3, indicate a slightly lower level of the high frequency amplitudes for the streamer sensors then their planted pairs and is an effect that needs to be investigated in the future.

To test the streamer in an urban environment, a test was carried out at a planned access ramp "Vnsta" of the Stockholm Bypass tunnel in the southern part of Stockholm. During two nights of acquisition, two seismic lines were acquired. One of the lines crossed a major road and was positioned parallel to the tram tracks. To cross the road and obtain information about the structures under it, the streamer was coupled with 12 wireless seismic recorders. Inspection of the shot gathers and their accompanying amplitude spectra showed no traces of electric or EM noise contamination. Finite difference elastic modeling done with the site parameters extracted form the seismic data has shown that reflection imaging on this site requires denser station spacing and higher frequency sources, therefore our attention was diverted to 3D P-wave first arrival traveltime tomography. Figure 3.4 shows visualization of the final 3D inverted tomographic model with an RMS of about 3 ms (after 7 iterations), with part of the Stockholm Bypass tunnel model and

access ramp, LiDAR data, location of bedrock outcrops and poor quality rock zones inferred by the geotechnical site investigations in boreholes.



Figure 3.3. Example shot gathers (after vertical stacking of three repeated shots) and hodograms from the side-by-side planted (black color wiggles) and streamer mounted (red color wiggles) DSU3 sensors test showing (a) vertical, (b) horizontal inline, (c) horizontal crossline component data. (d) Hodograms of noise, first break and later arrivals window from a far-offset trace from the streamer mounted sensor. (e) Hodograms of noise, first break and later arrivals time window of the same position trace but from the planted sensor. AGC has been applied (100 ms window) for display purposes. Different gains were applied for the particle motion plots for display purposes.

The 3D visualization shown on Figure 3.4 illustrates a clear correlation of the poor quality rock and relatively low velocity zone (3000–4000m/s). Here, the tomography results indicate a change in the bedrock geometry, with a small depression zone in the middle, suggesting a possibility of a fracture system under the road where the two seismic lines intersect. Our field observations of the bedrock outcrops match the locations where the velocities higher then 5000 m/s can be seen, supporting the tomography result. Delineation of the depression zone itself was enabled using the wireless units coupled with the streamer, without causing any disturbance of road traffic. As shown on Figure 3.4c, the access ramp will be located in this zone where a potential risk of lateral water inflows exists.



Figure 3.4. 3D views showing visualization of the refraction tomography results with the model of the planned tunnel and the access ramp. (a) Aerial photo projected onto the elevation data obtained from LiDAR measurements showing the location of the seismic profiles and main anthropogenic features. (b) Tomography results (3D model) visualized with the tunnel indicating a low velocity zone where the bedrock deepens and where rocks have poor quality. (c) Closer view on the tomography results along with the interpreted depth to the bedrock (black dashed line) and the planned tunnel model. The tunnel model was kindly provided by the Swedish Transport Administration (Trafikverket).

3.1.2. Conclusion

In this study, a three-component MEMS-based seismic landstreamer was developed and tested versus different type of planted geophones and same type of sensors as used on the streamer. At the Stockholm Bypass site, 3D first arrival tomography inversion was done using a combination of the streamer recorded data and the data recorded with wireless recorders. Good match between our site observations and borehole information with the tomography results showed the capability of the streamer for urban site characterization. Elastic finite-difference seismic modeling showed that, with the given acquisition parameters, it is difficult to image reflections from the bedrock at this site. Comparison of the results with real shot gathers supported the initial model used to generate synthetic shot gathers. In all the data sets, no negative effect such as phase or time difference, polarity change or other effects induced by the overall landstreamer assembly have been noted. The results obtained with the streamer indicate a better signal quality compared to the geophones tested, while the sensitivity and broadband nature of the 3C sensors open great potential to use it for various near surface applications.

3.2. Paper II: All wave-modes converted and reflected from fracture systems: A tunnel-surface seismic experiment

3.2.1. Summary

Within the framework of TRUST (TRransparent Underground STructures), a nationwide academia-industry consortium, the Uppsala University Geophysics team conducted a seismic experiment between an existing tunnel and the surface (surface-tunnel seismics) at the Äspö Hard Rock Laboratory (HRL). Äspö HRL is an underground research facility located in southeastern Sweden, operated by the Swedish Nuclear Fuel and Waste Management Company (SKB). The laboratory itself consists of surface infrastructure and a tunnel going for approximately 1,6 km downwards until it reaches the depth of -230 m. At this depth, the tunnel continues spirally downwards till the final depth of -450 m below sea level. The total length of the tunnel is about 3.6 km, and within the spiral part (Figure 3.5), an elevator shaft connects the different depth sections of the tunnel and the main building on the surface.

Motivation behind this test were known fracture systems crossing the tunnel at different depths, where the digital 3C seismic landstreamer (Brodic et al., 2015; Malehmir et al., 2015c; Malehmir et al., 2015a; Malehmir et al., 2015b) could be tested in their detection and its recording properties in full 3D space evaluated. Seismic survey at the Äspö HRL site was conducted using a combination of a Sercel Lite acquisition system with 10 Hz vertical geophones, a seismic landstreamer developed at Uppsala University and Sercel 1C and 3C wireless units. Bobcat mounted drop hammer was used as the seismic source. The seismic spread was consisting of 4 parts, with 279 10 Hz vertical geophones planted 4 m apart in the tunnel making the first part (Geophones I; Figure 3.5). Seismic landstreamer (Brodic et al., 2015) with its 200 m length was used as a continuation of this line, making the second part and covering the intersection of the tunnel with the two known fracture systems (NE-1 and EW-3, Landstreamer; Figure 3.5). Third part of the spread were 54 10 Hz vertical geophones planted following the end of the streamer 4 m apart (Geophones II, Figure 3.5). These three parts made the seismic line inside the tunnel approximately 1.5 km long. Fourth segment of the seismic spread were 75 wireless recorders (both with DSU3 sensors and 10 Hz vertical geophones), planted along the surface with spacings of 8-16 m, enabling simultaneous recording of the seismic wave field both inside the tunnel and on the surface (tunnel-surface seismics). Figure 3.5 shows major tectonic and geological features of the test site, with the horizontal projection of the tunnel and different segments of our seismic spread, both inside the tunnel and on the surface.



Figure 3.5. Geology and structural map of the Äspö HRL site, with surface projection of the tunnel track and location of the seismic lines inside the tunnel and on the surface. Arrows show dip direction of the structures while the structure orientation corresponds to true azimuths.

Figure 3.6a shows the different raw data characteristics of the three parts of the seismic spread inside the tunnel (Geophones I and II and DSU3 landstreamer), with the accompanying amplitude spectra graphs. The streamer segment is here shown after removal of the two horizontal components. Figure 3.6b,c,d shows an enlarged view of the vertical, radial and transverse landstreamer components, respectively, and their accompanying amplitude spectra. These results complement the study shown by Brodic et al. (2015), where the DSU3 units of the landstreamer appear unaffected by the severe electric power contamination seen on both planted geophones line segment (Geophones I and II). Aside from the 50 Hz electric power grid frequency, both higher and lower order power harmonics can also be seen in the data.



Figure 3.6. An example of a raw shot gather from the seismic line inside the tunnel with normalization applied. (a) First 279 planted 10 Hz geophones (Geophones I), followed by 80 DSU3 units landstreamer (DSU3's landstreamer) and 54 planted 10 Hz geophones (Geophones II), with their corresponding amplitude spectra graphs. (b); (c) and (d) show an enlarged view of the DSU3 vertical, radial and transverse components, respectively, and their accompanying amplitude spectra.

Same shot gather shown on Figure 3.6a, after preprocessing and trace normalization applied, is shown on Figure 3.7. Some events that can be seen on the raw data (Figure 3.6a) are here successfully enhanced, and are shown by the arrows on the same figure. Most of the events shown here occur in the part where the NE-1 fracture system is intersecting the tunnel. To check if any of the events shown on Figure 3.7 can be related with the mentioned fracture system, we modeled the traveltimes from the system using a 3D constant velocity ray tracing method (Ayarza et al., 2000; Lundberg et al., 2012). Figure 3.8 shows the resulting modeled traveltimes superimposed on the same shot gather shown on Figure 3.7. Only the modeled traveltimes that are interpreted to correspond to the fracture system are shown on Figure 3.8.



Figure 3.7. Same example shot gather with preprocessing applied and different events marked with arrows. Source was located at the last receiver (receiver 413) in the tunnel.



Figure 3.8. Results of ray tracing traveltime modeling from the fracture system NE-1 superimposed on the same example shot gather. For plotting purpose, trace normalization was applied.

Regardless of the parameters used for ray tracing modeling, only modeled traveltimes that were matching the evens shown by the arrows on Figure 3.7 were P-S and S-P direct and reflected waves shown on Figure 3.8. To test if the NE-1 fracture system can generate the interpreted to be P-S and S-P converted energy, we used finite difference modeling code available from Seismic Unix (Juhlin, 1995). Here, both the NE-1 and EW-3 systems were included in the modeling, and the resulting synthetic seismograms with superimposed traveltimes obtained from ray tracing modeling are shown on Figure 3.9.



Figure 3.9. Synthetic seismograms with superimposed traveltimes from NE-1-III fracture systems modeled using 3D ray tracing approach, and the apparent direct P- and S-wave velocities.

Results shown on Figure 3.9 indicate that the fracture systems, with the modeling parameters used, can generate a significant amount of P-S and S-P converted energy. Due to the opposite dip angle of the two fracture systems, detection of the events originating from the fracture systems individually is strongly depending on the source location. With the source located at the end of seismic line (as shown on the example shot gather), only the events originating from the NE-1 can be detected, since the EW-3 is dipping in an opposite direction. A matching result of this modeling approach with both the shot gather shown on Figure 3.7 and the ray tracing calculated traveltimes supports the parameters used for modeling purposes. The same results confirms the interpretation of the P-S and S-P direct and reflected events shown on Figure 3.8.

To image the structures between the tunnel and the surface, wireless and tunnels data sets were merged and used for first break picking. For each shot, first break arrivals were picked for both receivers in the tunnel and on the surface, resulting in 226 shots and 68704 picked traces. First break tomography was done in 2D space using the PS_tomo 3D diving-wave tomography code (Tryggvason et al., 2002; Tryggvason and Bergman, 2006). Figure 3.10 shows the final inverted model with RMS of 2.3 ms obtained visualized in 3D, with the tunnel model and aerial photo projected on LiDAR elevation data. Arrows point at locations where the NE-1 and EW-3 fracture systems intersect the tunnel.



Figure 3.10. Final velocity model obtained from the tomography inversion with aerial photo projected on top of the LiDAR data. Arrows point at the locations where the NE-1 and EW-3 fracture systems intersect the tunnel. Red and the tunnel. Red survey features.

At Figure 3.10, we can notice a decrease of velocities in the zones where both of the fracture systems are located, where the lateral extent, location and dip angle of the EW-3 system corresponds to the field observations. The location of the NE-1 system, and partly the dip angle correspond to the field observations, while its lateral extent needs further constrains for interpretation.

3.2.2. Conclusion

A tunnel-surface seismic experiment was conducted at the Äspö HRL site. We used a combination of planted 10 Hz geophones and a 3C seismic landstreamer in the tunnel, and 75 wireless seismic recorders on the surface. The 3C seismic landstreamer was positioned along two known fracture system called NE-1 and EW-3. We used a Bobcat mounted drop hammer as a seismic source and shooting was done both in the tunnel and along the receivers on the surface. First arrivals from all the receivers were manually picked and used for 2D first break traveltime tomography. The obtained velocity model shows a low velocity zone that may be correlated to the EW-3 fracture system. In the case of NE-1, a low velocity zone is notable, but with a lateral extent far exceeding the actual zone with, making the interpretation of this low velocity zone seen in the model uncertain. Nevertheless, the tomography results indicate that imaging of the rocks between the surface and the tunnel using this source-receiver setup is possible. Inspection of the shot gathers shows that the NE-1 fracture system is responsible for mode conversions of the direct P-waves into direct S-waves and vice versa. With that in mind, we modeled the traveltimes using a 3D ray tracing code and the results show that this fracture system is generating only P-S and S-P mode converted events, namely P-S and S-P reflections. These converted reflections matched the events seen on the shot gathers. The parameters extracted from the seismic data and ray tracing modeling were used further to model the two fracture systems using a finite difference elastic modeling code. The results of the modeling suggest that P-S and S-P energy conversion from the two fracture systems is possible, and synthetic seismograms are matching almost perfectly both real shot gathers, and the traveltimes modeled using the ray tracing approach. This result further supported the interpretation of the events as the mode converted P-S and S-P reflections.

4. Conclusions

This thesis is based on two papers that deal with the development and testing of the Uppsala University's 3C MEMS-based seismic landstreamer. Presently, it is a unique seismic acquisition system and I will now summarize its main properties. The system is built using 3C MEMS -based seismic sensors. Significant amounts of time were spent on designing the sleds holding the units, and selecting the proper materials for the materials used to connect them to limit the possibility of damage to the equipment and poor ground coupling. The system can be easily deployed and towed by ordinary fieldtype vehicle. It is based on Sercel Lite technology and DSU3 (MEMS-based) sensors, can be combined with wireless units and supports both geophones and MEMS-based units. Three component data recording in digital format, fully digital data transmission, measurement of the gravity vector that is used for obtaining the tilt information, broadband unit character (0-800 Hz), high sensitivity, along with dense unit spacing, makes the developed landstreamer a powerful tool for various applications, especially in urban areas. The landstreamer consists of five segments, with 20 3C sensors in each. Every segment connects to the next by a small trolley carrying a line-powering unit. Four segments have sensors 2 m apart, and the fifth one 4 m apart. Field campaigns have shown that data acquisition starts after approximately 1 hour upon arrival to the site, and with a team of 3 to 4 persons data acquisition vary from 600 m/day to 1200 m/day of seismic line.

Paper I deals with testing the system's properties at different development stages, using different sources and in different environments. The results show no negative effect of the overall landstreamer assembly, regardless of the environment or source used. It shows that the landstreamer is capable to record high quality data important for urban environments. At the Stockholm Bypass site (Förbifart Stockholm), a truly urban environment, no electric or EM noise pickup were noted in the data, while the results obtained suggest that, in certain areas, wireless seismic recorders are essential and can be complementary to the streamer if the poor quality rock zones are to be imaged under major roads, without influencing the traffic.

Paper II is an ongoing study to further test the recording capabilities of the landstreamer, this time located inside the Äspö HRL tunnel at a depth of -160 to -200 m below sea level, targeting known fracture systems. Here, the results show that the landstreamer can easily be combined with planted geophones and wireless units, enabling successful tomographic imaging of the rock masses between the tunnel and the surface. The data recorded inside the tunnel with geophones show severe electric (or electromagnetic) noise contamination, while the landstreamer is entirely unaffected, supporting the results of the Paper I and one of the goals behind the design of the streamer. Inspection of the shot gathers from the Äspö HRL site has shown that strong mode-converted energy was observed from the fracture systems. The landstreamer recorded data were used to extract the dynamic mechanical properties of one of the fracture system. The interpretation of different P-S and S-P mode converted events generated at the fracture zones inside the tunnel would have been a difficult task without the 3C landstreamer units. These allowed the possibility of data inspection in different components and analysis of particle motion plots. Further work using various modeling approaches was helpful to validate the interpretation of the mode-converted signals from the fracture systems.

This licentiate thesis provides an overview of the problems encountered in near surface seismic imaging and methods commonly employed in engineering site characterization. The literature referred to in the text of the thesis relates to the success of the seismic method in preliminary site characterization, monitoring of the rocks during the construction phase, monitoring of the constructions themselves during and after constructing phase, and the monitoring of terrain subsidence, subsurface stress field regime or hydrological parameter changes due to the constructions. I tried to give an overview of the systems commonly used for seismic data acquisition, their good and weak sides, and some personal opinions on how the landstreamer developed at Uppsala University can be used for obtaining useful parameters for the construction industry and in particular for planning of major underground infrastructures. With the literature review of the geophones and MEMSbased sensors, I tried to be unbiased and also summarize the pros and cons of the MEMS-based sensors. Personally, I agree with some of the reported studies summarized in Part II of this thesis stating the deviation of the theoretical MEMS-based sensor properties from the practical achievements. Nevertheless, they are still the only 3C broadband sensors capable to provide tilt measurements and are not influenced by the electric or EM noise, making them, at least to me, a logical selection for a seismic receiver. Based on my own experience from data acquisition campaigns, I prefer to combine the landstreamer with 1C wireless seismic recorders to obtain both data acquisition using MEMS accelerometers and geophones. In this way, one can exploit the benefits of both types of seismic receivers and also to overcome logistical (and large offsets) challenges encountered in urban environments.

4.1. Future work

Even though many tests have been conducted using the landstreamer in different environments, still, none of them exploit the full potential of the DSU3 sensors. No mode converted imaging has been done with any of the datasets acquired. Generally, the two horizontal components of the DSU3 are seldom used for any kind of analysis, expect particle motion inspection. An exception is however the study conducted in Laisvall (Malehmir et al., 2015a), Sweden, where imaging using shear waves showed superior resolution than with compressional waves. At the beginning of my PhD studies, a commercial small shear wave vibrator (ELViS) was purchased, a P-wave vibrator was developed based on the IBEAM shaker systems (with the ultimate goal to be coupled by a half sphere or topless pyramid and utilized as both P, SV and SH source). Aside from the two, I participated in development and testing of a low frequency mini-vibsist source that was also purchased in the end. I tested and discussed about the way they should be built several different SH sources, like metallic I-beam (I-shaped profile metallic beam) and two trapezoidal prisms (one made of granite, other of concrete). All these now stand in the storages waiting to be used to explore the full potentials of the streamer. The streamer is still in its infancy period and much more can be done with it if it is properly linked to multi-component seismic sources.

Surface wave inversion and the possibility of using the streamer data was discussed during a 5-day workshop in March this year, and I will try work more on that idea until the end of my PhD studies. The streamer and the broadband nature of the signal should be exploited to provide information about geo-mechanical properties. These ideas remain to be tested in the continuation of my PhD thesis. In the 9C seismic world, 1C data have been given the focus and that leaves a lot of space for improvement in the future.

5. Summary in Swedish

Konventionella seismiska undersökningar i urbana miljöer medför många utmaningar såsom svårigheter med att plantera geofoner på grund av asfalterade ytor, men också elektriska och elektromagnetiska störningar.

För att övervinna dessa utmaningar, och som en del av denna undersökning, har en 3C MEMS-baserad seismisk landstreamer utvecklats vid Uppsala universitet. Landstreamern består av en rad seismiska sensorer som registrerar seismiska vibrationer i tre riktningar och är designad för att kunna bogseras med till exempel ett fordon längs profilen. De 3C MEMSbaserade sensorerna gör systemet unikt då de till skillnad från konventionella geofoner är de utvecklade för att arbeta under sin resonansfrekvens (1 kHz) med bredbanding linjär amplitud- och fasrespons (0-800 Hz). Andra fördelar med MEMS är att de inte behöver planteras i marken och de är inte heller känsliga för tiltning eller elektriska och elektromagnetiska störningar. Landstreamern är baserad på Sercels Lite-teknologi med Sercels DSU3 (MEMS-baserade) sensorer. Sensorerna är monterade på metallslädar vilka i sin tur är sammanlänkade med ett icke töjbart textilband av en typ som används inom flygindustrin. Lite-systemet stödjer både geofoner och DSU3sensorer och kan kombineras med trådlösa enheter som stödjer någon av de båda. I dagsläget består systemet av 100 sensorer fördelade på 5 segment med 20 sensorer vardera. Segmenten är sammankopplade med små vagnar där batteriförsörjningen placeras. Fyra segment har enheter placerade med 2 meters mellanrum och det femte segmentet har enheterna placerade med 4 meters mellanrum. Med ett fältteam på 3-4 personer kan mätningar på 600-1200 m profillängd utföras per dag om avståndet mellan punkterna där källan aktiveras är 2-4 m.

Ett test av landstreamern jämfört med planterade geofoner (både 10 Hz och 28 Hz) visar att landstreamern genererar bättre datakvalitet än de båda typerna av geofoner. Inga negativa effekter såsom fasförskjutning eller förändring av partikelpolarisering orsakad av landstreamerns konstruktion med sensorerna monterade på slädar kunde noteras när datan jämfördes med data från DSU3 sensorer som var planterade på traditionellt vis. Inte heller några elektriska eller elektromagnetiska störningar kunde noteras i datan från mätningarna i Förbifart Stockholm (Johannelund). En kombination av fristående trådlösa seismiska stationer och landstreamern var avgörande för att kunna genomföra mätningar som gav en seismisk avbildning av zoner med låg bergkvalitet utan att störa trafiken. Likaså visar ett pågående test med landstreamern i en tunnel 160-200 m under havsnivå att inga störningar plockas upp av systemet. På shot-gathers från tunneln kan man se att energi konverterar från P till S-våg, vilket vi tolkar som en effekt av sprickzoner. Bergvolymen mellan tunneln och markytan har analyserats med tomografi.

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Bojan Brodic, Uppsala, November 2015

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