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SH- and Surface-wave Imaging Potential of a 3C-digital-based Seismic Landstreamer Illustrated at an Esker Site in SW Finland

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Summary

Within the last decade, multicomponent seismic imaging has proven to be beneficial in various areas of applications, from hydrocarbon to mineral exploration, as well as for environmental and infrastructure planning investigations. To demonstrate the potential and need for multicomponent seismic imaging for infrastructure planning project, we show an example of a seismic profile acquired using a recently developed digital-based 3C seismic landstreamer and a cost-effective drop-hammer seismic source for planning of wells for pumping water (aquifer recharge) at an esker site that supplies drinking water for the entire city of Turku, Finland. The study illustrates the importance of 3C data recording and shows the potential of the landstreamer in imaging the shallow subsurface using both P- and SH-waves generated from the vertical impact source. Synthetic modeling, particle motion studies and surface-wave analysis of the data are used to scrutinize the data and investigate the nature of the signal and underlying physical properties of the subsurface.

Introduction

Within the last decade, multicomponent seismic imaging has proven to be beneficial in various areas of applications, from oil and gas exploration to mineral environments, as well as for environmental and infrastructure planning studies. Compared to only P-wave images, shear-wave seismic sections are often of higher resolution, while both P- and S-wave imaging offers extraction of additional parameters such as Vp/Vs, Poisson's ratio and porosity estimation, among others. Coupled with digital sensors, multicomponent seismic methods offer several advantages also in the near-surface domain. This is particularly true for the urban environments, where the digital sensors are unaffected by the electric/electromagnetic (EM) noise (Brodic *et al.* 2017).
Apart from the electric/EM noise, urban environments are also challenging due to asphalt and paved surfaces making planting of seismic sensors a difficult task. Additionally, urban seismic surveys need to be done in a fast and effective manner to cause the least amount of disturbance to the residents, environment and the traffic. To cope with all the challenges, and exploit the benefits of multicomponent seismic data, a three-component (3C) micro-electromechanical sensor (MEMS) based seismic landstreamer was recently developed at Uppsala University and tested for several infrastructure planning projects in Sweden, Finland, Norway and Denmark (e.g., Brodic *et al.* 2015; Malehmir *et al.* 2015a,b and 2017; Dehghannejad *et al.* 2017). Compared to other available landstreamers, 100-3C MEMS-based sensors, data GPS time stamped, sensors mounted on 5 kg sleds, spaced 2 to 4 m, along 240 m long spread, makes the landstreamer rather unique.

To demonstrate the benefits and need for multicomponent seismic imaging for infrastructure planning project, we will show an example of a seismic profile acquired using the landstreamer and a commercially available vertical drop-hammer seismic source. The profile was acquired for planning wells of pumping water at an esker site near the city of Turku, Finland.

Data acquisition

With the aim of imaging esker structures (glacial sediments), depth to the bedrock and water table, we conducted a seismic survey in Virttaankangas esker chain, in southern Finland. A bobcat-mounted vertical drop hammer (500 kg), due to its low cost, was used as the seismic source. To obtain better source coupling, a 75 cm by 75 cm by 1.5 cm steel plate was mounted on the bottom of the hammer casing and all the hits were made on this plate after placing it firmly on the ground at every shot point.

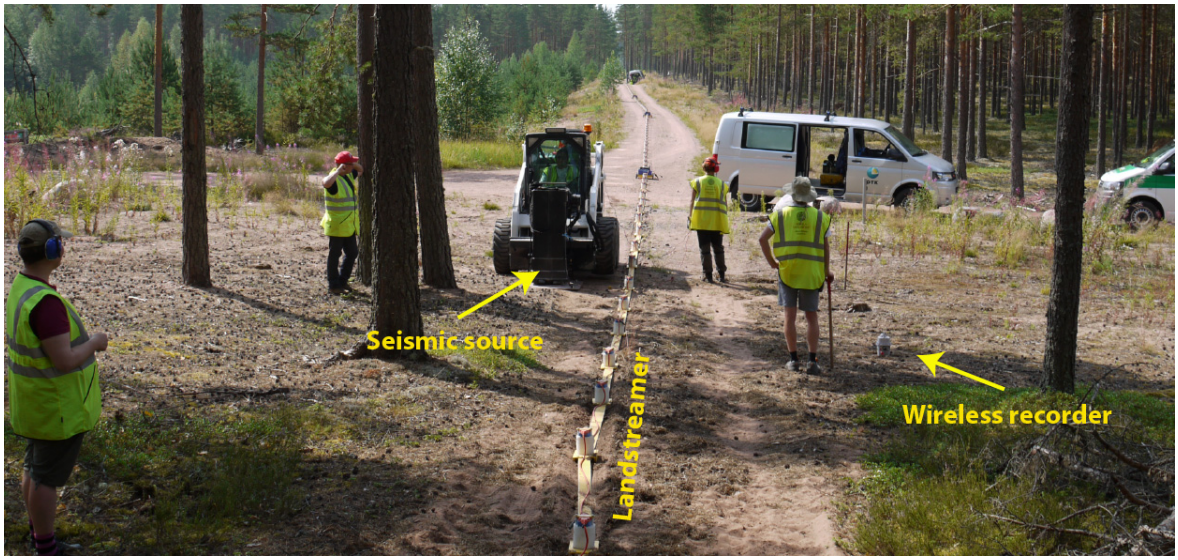

Figure 1 *Field photo from the acquisition of the seismic profile (Turku-Finland) using the 3C seismic landstreamer and Bobcat 500-kg drop-hammer source. Photo by Alireza Malehmir (July 2014).*

For the recording purpose, we used the landstreamer and combined it with wireless seismic recorders connected to 10 Hz vertical-component geophones (Figure 1). Along approximately 1 km long

profile, wireless units were deployed with a spacing of 20 m. The 200 m long (at the time of the acquisition, July 2014) was then moved 5 times along the entire ca. 1000 m long profile with no overlap between the previous streamer positions. Source spacing was 4 m and after all the shots along one streamer location were recorded, a 4WD vehicle pulled the streamer to the next position. The wireless units provided long offset data and enabled constant data coverage along the whole profile, even though there was no overlap between the previous streamer positions. Due to their nature (vertical component type geophones), this is particularly notable on the P-wave refraction tomography and stacked section (Maries *et al.* 2017), and also surface wave analysis.

Results

Figure 2 shows the unmigrated seismic section of the profile using only vertical component data 8inclduign the wirelesses). It clearly images the internal architecture of the eskers and correlates well with the available boreholes in many places. A morphologically undetectable kettle hole (MUKH) is also observed illustrating that the landstreamer was capable of delineating these detailed structures down to bedrock. Maries *et al.* (2017) presented results of this study including first break traveltime tomography.

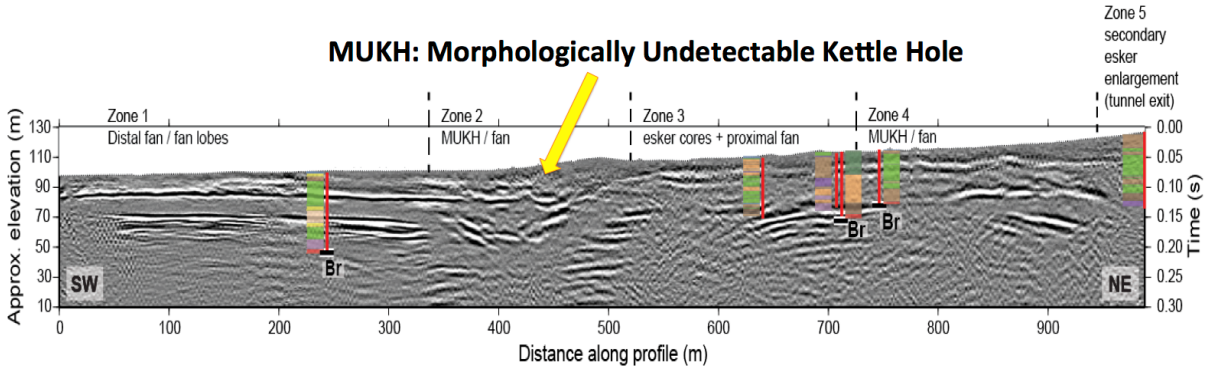

Figure 2 *Unmigrated P-wave reflection seismic section (time-to-depth converted using a constant velocity of 800 m/s) with the existing borehole data near the profile and interpreted depositional zones, borehole stratigraphy and indication of bedrock from the boreholes. Modified from Maries et al. (2017).*

Although the source that was used is a typical vertical impact source, aside from the P-wave stacked section, clear reflections were also notable in the SH-wave component (transverse) shot records (Figure 3). To check if the reflections in Figure 3 are of the SH-wave nature, we analyzed the particle motions around the reflections using hodograms, with the angles between P- and S-waves in different planes shown in Figure 4. From this figure and similar ones studied we argue that the reflection is purely shear and generated likely at the source location. The reflection data processing was then followed using a conventional processing algorithm including bandpass filtering (20-30-80-90 Hz), AGC (250 ms), surgical mute of the direct arrivals, velocity analysis, NMO corrections, stack and post-stack FX-deconvolution. Figure 5 shows the final stacked section obtained from the transverse component data of the streamer. Although the profile was about 1 km long, the SH-wave reflectivity is only notable in the first 450 m, hence the focus of the imaging.
Additionally, surface-wave analysis was conducted using the vertical component data; a shear-wave velocity profile of the upper 40 m was extracted (not shown here) to support the velocities found for reflection imaging of the transverse-component data. To obtain constant data coverage along the entire profile, surface-wave analysis was done combining streamer and wireless data. Minimum number of stations used for picking the dispersion curves was 10. Using both positive and negative offset data, separately, surface-wave analysis was carried out. To suppress the source noise contamination, stations with offsets less than 15 m were excluded from the analysis and since no higher modes could be seen, only the fundamental mode was used for the inversion.

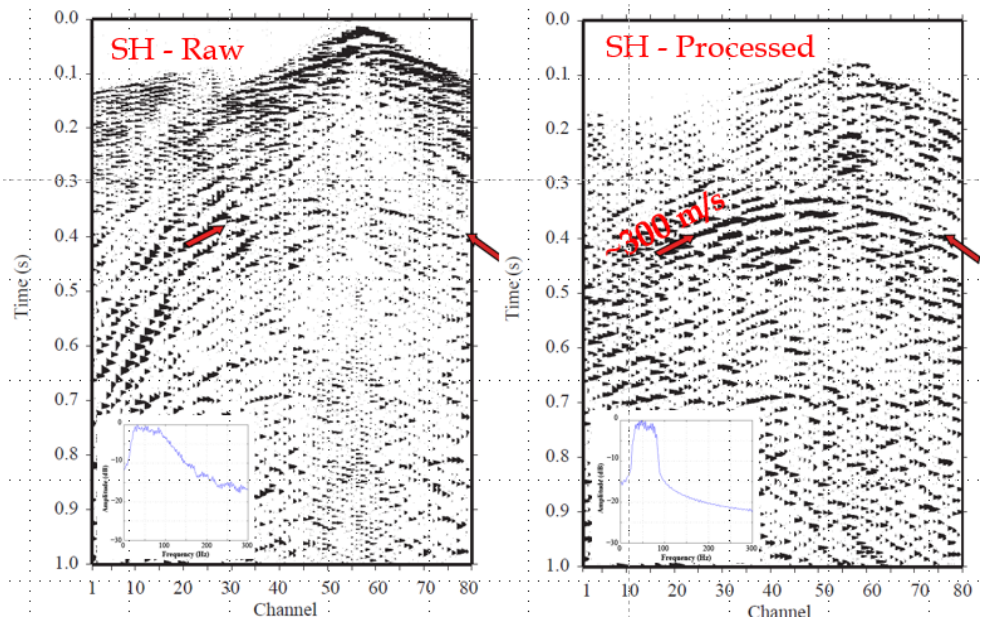

Figure 3 *Example shot records illustrating a potential SH-reflection observed (after some processing steps) in the transverse component shot record with a hyperbolic nature. An apparent dip to the right-hand side of the section (north of the profile) is also evident in the hyperbola's shape.*

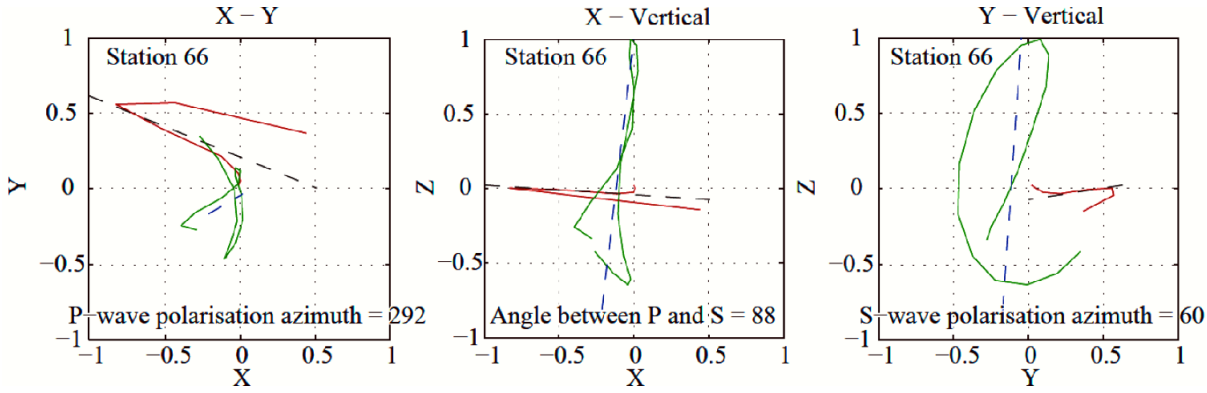

Figure 4 *Example hodograms (particle motion) from the receiver location 66 (near the shot location) showing P- and S-wave particle motions (vertical vs. transverse component) are nearly orthogonal as expected for the reflection observed in Figure 3. Hodograms (not shown here) for other receivers suggest angles ranging from 85-100° consistent with that the reflection has a shear nature.*

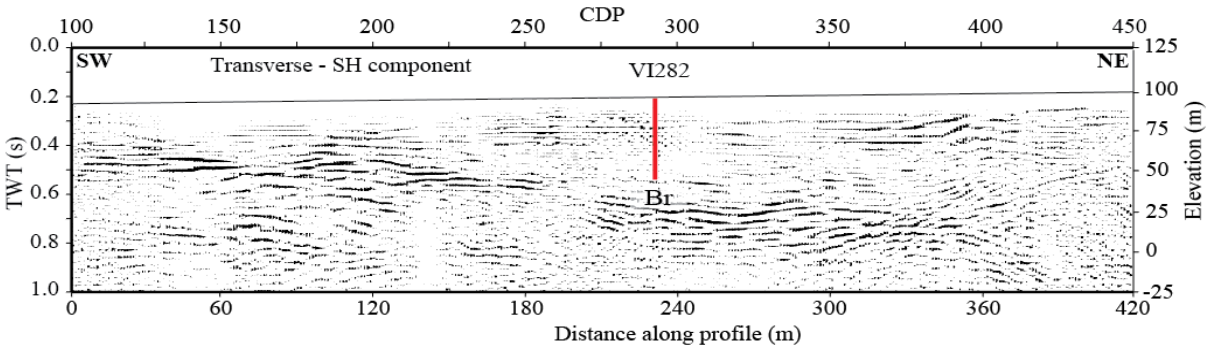

Figure 5 *SH-wave stacked reflection seismic section along part of the profile where reflectivity in the transverse component could be seen. Red line marks the drilled depth to bedrock that better matches the bedrock in the SH section than the vertical component (P-wave) shown in Figure 2.*

Conclusions

The results obtained indicate that shear-wave imaging using vertical-type sources is possible at the site and demonstrate the potential of the MEMS-based sensors and the developed landstreamer for surface-wave analysis. Such results would not have been possible with only vertical component or single SH-component landstreamers. SH-wave stacked section indicates clear reflection that follows the known bedrock dip and matches well with the results shown in Maries *et al.* (2017). Preliminary results of the surface-wave analysis indicate similar results as the aforementioned study and we aim to use the result for obtaining Vp/Vs ratio along the entire profile and see if this may be correlated to the lithological signature of the esker chain or other glacial sediments at the site.

We summarize the main findings from this case study using the streamer and why multicomponent data should be acquired for infrastructure planning purposes:

- Although a vertical source was used, SH-wave reflections were observed on the transverse component data.
- Particle motions and synthetic results support shear-wave nature of the reflections.
- Stacked SH-wave reflectivity correlates better with the depth to bedrock than the P-wave section. The reflection seen in the shot records is likely only from the bedrock. Hence, it appears the overlying materials have little sensitivity to be imaged using SH-component data and that P-wave data should be used to complement this shortcoming.

Acknowledgments

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