Unravelling Contaminant Pathways through a Detailed Seismic Investigation, Varberg - Southwest Sweden

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Summary

As demand for underground infrastructure grows worldwide, and in particular in Sweden, concerns on their environmental impact and disturbance in the subsurface increase too. A major issue with underground infrastructure projects can sometimes be connected with their vicinity to potential contaminated sites from industrial works in the past (e.g., over 80,000 are known in Sweden). In such circumstances, any excavation may accelerate mobilization of subsurface contaminants into aquifers and fertile soils. It is therefore important that migration pathways that these contaminants may use are delineated in a great level of details, so the appropriate remediation strategies are applied. To study potential contaminant pathways (bedrock depressions and fractures) in preparation for the construction of a double-track underground train tunnel, we acquired 12 seismic profiles in the city of Varberg, Sweden. The profiles were acquired using a combination of a state-of-the-art seismic MEMs-based landstreamer and wireless seismic recorders. Traveltime tomography results were complemented by more than 20 new boreholes, and together helped to identify contaminant pathways and connect them to a series of observed highly-contaminated zones away from the site. Prior to our seismic survey, these have been sought of having a different origin than from the main contamination site.
Introduction

Over 80,000 potentially contaminated sites have been identified in Sweden. Among those, Renen 13 in Varberg is among the highest priority sites in the county of Halland requiring remediation and detailed investigations (Varberg Kommun, 2014). The contamination started back in the late 19th century through chemicals (e.g., Cr, Zn and Cd) used for chemical cleaning of textile materials and continued during the 60s through a precision mechanics industry where chlorinated solvents (e.g., TCE and TCA) as well as cyanide and metals were leaked into the subsurface and gradually moved away from the factory in the subsurface. The TCE and TCA are the main sources of contaminations in the vicinity of the property. The site has been investigated by a number of boreholes, wells, as well as resistivity-type measurements (Åkesson, 2015; Sparrenbom et al. 2017). However, detailed seismic studies became necessary given the success of the method used for the planning of a double-track train tunnel (Malehmir et al. 2015; Dehghannejad et al. 2017) in the city (red lines in Figure 1) and potential contaminant mobilization should excavation for the planned tunnel starts. To provide information about depth to bedrock and potential fracture zones within it, a dedicated seismic survey comprising of 12 profiles within an area of about 400 m by 300 m was conducted. A digital-based seismic landstreamer (Brodic et al. 2015) combined with wireless recorders as used earlier in the city was employed to overcome challenging situations such as the existing train track area and roads that could not be blocked during the survey. Here, we present tomography results from the active-source seismic experiment integrated with boreholes using GeoBIM (building information modelling) as the common place for the organization of the data and where the modelling was conducted. We map potential pathways within the bedrock from which contaminants may mobilize (or even have) towards the southwest that need to be considered during the site remediation.

Varberg tunnel and the contaminated site

Planned Varberg double-track train tunnel is about 3 km long and will be excavated in crystalline bedrock (Figures 1). The first 700-800 m of the tunnel (from north to south) will be concrete trench north of the current train station, followed by a 300 m long roofed concrete tunnel. After this section, the overlying rock thickness would be sufficient to host a tunnel in the rock. It is within this region that the contaminated site is situated and will likely have the highest impact with respect to the planned tunnel. The groundwater table measurements indicate water flowing towards the sea, crossing the planned tunnel track. A major concern is when
the excavation begins and the groundwater level is lowered, the water table disturbance may then result in rapid mobilization of the contaminant, hence a prompt remediation of the site should be considered. The main objectives behind the seismic survey and a series of other measurements conducted within the same project to tackle the aforementioned issues. Use of reliable and non-invasive methods in environmental hazard investigations is another objective since any invasive methods may further complicate the situation and contribute into further contamination of the site and areas around it. The seismic study therefore was also aimed to optimize the location of additional boreholes (both sounding and core drilling) to obtain a detailed subsurface geological model and optimize drilling investigations.

Seismic data acquisition and traveltime tomography

To acquire the data, a digital-based seismic landstreamer system, recently developed with the aim of tackling noisy urban environment, was used. At the time of the survey, it consisted of four segments, each of 20 3C-MEMS sensors of 2 m spacing (i.e., 160 m long) and one segment with 20 sensors each 4 m spaced (i.e., 80 m long) providing a totally 240 m long landstreamer. We complemented the landstreamer with 154 wireless recorders (89 randomly distributed, 43 inside existing train track and up to 22 at temporary locations on 9 profiles) connected to single 10 Hz vertical-type geophones (Figure 2). These were used to provide longer offsets and avoiding issues with blocking roads and having recorders at the current location of the train tracks (about 50 m wide). The Sercel Lite™ 428 recording system was used for both GPS time stamping and sampling. The GPS times of the shot records from the landstreamer data were used to extract the data from the continuously recording wireless recorders. Most of the data were recorded during the daytime to avoid residential disturbance by overnight shooting. Overnight data acquisition was only possible two nights and only close to the existing train station. This allowed 4 of the 12 profiles to be recorded overnight. Repeated source records (at least three times) were generated and vertically stacked to reduce cultural noise in most cases. Busses and trains, however, caused short breaks in the data acquisition due to their high noise level. An accelerated 45-kg weight drop source and a 5-kg sledgehammer were used as the main seismic energy source. We chose source intervals of 4 m and a mainly fixed geometry spread setup to

![Figure 2](image)

**Figure 2** Different set-ups used for the data acquisition. (a) The digital-based seismic landstreamer comprising of 100-MEMS sensors, (b-c) combined landstreamer and wireless recorders connected to 10 Hz geophones were used to provide large offsets and avoid blocking roads, and (d) at the train track only wireless recorders (43 of them) operating in an autonomous mode were used.
enable high fold data acquisition. Shots were recorded collocated both with landstreamer and wireless stations. Nearly 2500 shots at approximately 750 source locations were done during 8 acquisition days. Geodetic positioning was carried out using a differential GPS (DGPS) system. After merging the streamer data with the data of the wireless stations, the combined datasets were vertically stacked for the repeated shot records for improving the S/N ratio. Subsequently, first-break picking on nearly 75000 traces was carried. Both 2D layered-based ray-tracing generalized linear inversion (GLI) method and traveltome tomography were employed. To overcome issues due to complex geology and nonlinear profile geometries, traveltome tomography results using the 3D PStomo_eq code (Tryggvason et al. 2002) were mainly used for the modeling work, however, results were cross checked against each other. During the inversion, smoothing constraints were applied to prevent large velocity variations, which were gradually relaxed with the increasing iteration numbers to allow sharp velocity variations where required by the data and to reduce the traveltime misfit. Nine iterations were applied to achieve a sufficient misfit (2-3 ms) for the final velocity models. We tested different inversion parameters, which lead to optimum cell sizes of 2 m horizontal (inline) and 1 m vertical. Cell dimensions in the crossline were set to 3-5 m in most cases. A velocity of 340 m/s was used above the ground surface representing the air, to prevent ray errors caused by the topography during the inversion. Below the surface a velocity range of 700-1000 m/s was used and gradually increased to 5500 m/s. Figure 3 shows tomography results visualized in 3D with the existing and complementary boreholes from the study area.

**Figure 3 First-break traveltome tomography results visualized in 3D showing complex bedrock morphology and effects in the data. White bars are the existing boreholes and red bars are those recently drilled through guidance from the tomography results.**

**GeoBIM and modelling fractured bedrock**

Two issues rose during the interpretation of the seismic results namely identification of (1) bedrock level and (2) fractured bedrock, along with potential misinterpretation of later as the bedrock depression and vice-versa. Follow-up drilling results further confirmed this complication. To automatically model bedrock level, a velocity threshold obtained by comparison with the drilling results was used while honoring places where bedrock was exposed (Figure 4a). Another model was obtained where a maximum velocity of 5500 m/s was reached (this was visually inspected to avoid false interpretations). The latter model then was subtracted from the bedrock level model to help identifying regions of low-velocities in the bedrock potentially representing zones of weaknesses (Figure 4b). The modeling work was done in a GeoBIM environment allowing all the design works, tunnel model, cultural data and tomography results to be well integrated.

**Conclusions**

In this integrated study we have identified a major SW-NE striking zone of weakness in the bedrock linking it to the contaminants found by drilling away from the Renen 13, representing a major potential pathway that should be considered for the remediation of the site. Other E-W striking zones have also been identified crosscutting the SW-NE zone. This study clearly demonstrates the potential of high-resolution seismic studies and the digital-based landstreamer for environmental hazard investigations in urban environment and is therefore highly recommended.
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Figure 4 (a) Bedrock model obtained automatically through a velocity threshold honoring existing drillhole data and (b) fractured bedrock model obtained by subtracting the bedrock level from regions of low-velocities under the bedrock model. Hashed zones represent regions where major zones of weaknesses are inferred in this study.

References


