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Mapping Possible Flowpaths of Contaminants through Surface and Cross-borehole Spectral Time-domain Induced Polarization

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Summary

Traditional methods for mapping possible flowpaths of contaminants in sedimentary environments by boreholes may often be insufficient. Additional information may be acquired by geophysical methods. In the present study, cross-borehole and surface measurements were performed using time-domain induced polarization (TDIP). After measurements the entire test site was dug out, and the geology was described. Despite of being above the groundwater table, it was possible to retrieve exceptionally well the distribution of sand lenses/layers at the site, with clear signature in both the DC conductivity and the IP parameters, as confirmed by the excavations carried out for verifying the geophysical results. Consequently, cross-hole TDIP imaging is a valuable tool for characterizing possible flowpaths of contaminants in in clayey moraines.
Introduction

In the Capitol Region of Denmark, several sites are contaminated due to various human activities. A large fraction of these sites are in clayey moraines, where the flow of pollutants predominantly occurs in sand lenses or sandy layers. Boreholes are normally drilled in order to describe the geology, but boreholes alone do not always provide the necessary resolution to map out such sand lenses, which is why the Capitol Region initiated a project to evaluate different cross-borehole geophysical methods for mapping sand lenses/layers. A test site was established in an uncontaminated gravel pit near Hedehusene, Zeeland, Denmark (Kallerup grusgrav). In this gravel pit the sand and gravel is overlain by 6-10 m of clayey moraine, with a few, thin sandlayers observed.

Our contribution consisted of spectral time-domain induced polarization, TDIP, (Fiandaca et al., 2012, 2013), due to its capability in lithotype discrimination (e.g. Chongo et al., 2015; Gazoty et al., 2012; Johansson et al., 2016), while other Danish research groups performed georadar and seismic cross-borehole acquisitions. After measurements the entire test site was dug out, and the geology was described and compared to the geophysical results.

Data acquisition

The measurements were carried out in the fall of 2015. The electrode array consisted of a NE-SW oriented surface profile and three boreholes, B1-3. The surface profile was 63 m long with an electrode spacing of 1 m. The boreholes were drilled at the 6.35 m, 12.15 m and 17.20 m positions along the surface profile (Figure 1), with 50, 45 and 47 electrodes, respectively. Custom made tubes fitted with circular electrodes, with a vertical spacing of 20 cm, were inserted in each borehole, and the boreholes were backfilled with sand and watered. In total ten data sequences were collected: one using only the surface electrodes; three using electrodes in a single boreholes; three using electrodes in two boreholes; three using electrodes in two boreholes together with surface electrodes. The measurements were performed using the ABEM Terrameter LS, with 100% duty cycle (Olsson et al., 2015), 4 seconds on-time and 3 pulses.

The contact resistance in the boreholes just after installation were in the order of a few kΩ, but soon after it increased to tens of kΩ, due to the drainage in the boreholes (the water table being well below the borehole depth). Test TDIP acquisitions with borehole sequences showed poor data quality due to...
the high contact resistance. Consequently, around 100 liters of salt water were poured in each borehole, resulting in a permanent decrease of contact resistance in the kΩ range.

**Processing and inversion**

The IP-decays were retrieved from the on-time of the 100% duty cycle measurements, with re-gating, stacking and normalizing of the full waveform recordings (3750 Hz sampling rate) as described in Olsson *et al.* (2015). Furthermore, the full waveform data were processed for removing spikes, background drift and harmonic noise following Olsson *et al.* (2016). The IP decays were further manually processed using Aarhus Workbench (Auken, 2009), for removal of apparent resistivity outliers and disturbed IP decays.

Figure 2 show some exemplary IP decays from the acquisitions carried out before and after the salt water injection. There is a clear improvement in data quality in the data acquired after the salt water injection, when much smaller contact resistances were measured, with almost one decade gained at early times and a smaller amount of spurious decays. Unfortunately, the added salt water significantly altered the resistivity distribution in the borehole surroundings.

![Figure 2](left) Exemplary IP decays before adding saltwater. (right) IP decays (same quadrupoles as left) after adding saltwater in the boreholes.

Data were inverted using the 2D TDIP inversion code developed by Fiandaca *et al.* (2013), modified for allowing buried electrodes. This inversion routine inverts the full IP decays and apparent resistivity values, taking into account transmitter waveform and receiver transfer function, in terms of a parameterization of the IP phenomenon. In this study, the Cole-Cole model (Pelton *et al.*, 1978) was adopted, re-parameterized in terms of the DC conductivity ($\sigma$), the maximum imaginary conductivity ($\sigma_{\text{max}}$), relaxation time ($\tau_\sigma$) and frequency exponent (C).

The inversion results are shown in Figure 3. A connected resistive layer is seen to be present at 2 m depth, characterized also by $\sigma_{\text{max}}$ and C values lower than the surroundings and higher $\tau_\sigma$ values. The top of a highly resistive layer is seen 6-7 m below the surface, which corresponds to the gravel layer exploited in the gravel pit. Layering is clearly visible in the moraine till between 2 m and 7 m, with the DC and IP parameters suggesting the presence of several clay-rich thin layers. The overall geology has been confirmed by the excavation performed for verifying the geophysical results, as clearly seen when comparing the inversion results with the delineation of the sand layers obtained by the excavation (dashed lines in Fig. 3).
Conclusions

DC resistivity and TDIP measurements were carried out in a cross-borehole setup at a test site, for mapping possible flowpaths of contaminants. Data were processed for harmonic de-noising, background removal and de-spiking from the full waveform acquisition, resulting in a first usable gate as early as 2 milliseconds. Since the boreholes were above the groundwater table, the electrode contact was initially poor. By pouring saltwater in the boreholes the electrode contact was greatly improved, and almost one decade of early time gates was gained, but the resistivity distribution in the borehole surroundings was altered. Despite of the alterations in the parameter distributions close to the boreholes, it was possible to retrieve exceptionally well the distribution of sand lenses/layers at the site, with clear signature in both the DC conductivity and the IP parameters, as confirmed by the excavations carried out for verifying the geophysical results. Consequently, cross-hole TDIP imaging is a valuable tool for characterizing possible flowpaths of contaminants in in clayey moraines.

Figure 3 2D TDIP inversion results. Shown here are DC conductivity ($\sigma$), maximum (surface) imaginary conductivity ($\sigma''_{\text{max}}$), relaxation time ($\tau_{\sigma}$), frequency exponent ($\mathcal{C}$). The dashed lines superposed to the inversion results represent the information retrieved from the geological excavation: at the top in each subfigure the dashed lines delimit a sand-lens layer, and the bottom dashed lines are a diffuse boundary between moraine and gravel.
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References


