TESTING THE USEFULNESS OF GROUND PENETRATING RADAR TO DEFINE BOUNDARIES OF DNAPL CONTAMINATION

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Abstract

This paper summarizes the methods and results from an environmental geophysical investigation conducted on a brownfield site located in Toronto, Canada. The site was assumed to be contaminated with DNAPLs which was verified through borehole testing and monitoring wells. These methods gave critical data but were extremely coarse in sampling and limited in coverage. Important data uncovered through the borehole extraction included variation in contaminant type and density across the site, with several boreholes recording no contamination on the southern and western portions of the site. Plans to control and mitigate environmental repercussions required clearer understanding of the potential boundaries of contamination. This project utilized ground penetrating radar (GPR) with a 250 MHz antenna integrated with GPS to map the electromagnetic properties of the soil. The literature is unclear regarding the expected GPR signature of contamination. Results from previously published field investigations suggest higher rates of signal attenuation in areas with high concentrations of contaminants, but other experimental data indicate high amplitude reflection responses where DNAPLs have pooled in the subsurface. While these are not mutually exclusive, the results from our field investigations indicate that areas of contamination rapidly attenuated the GPR signal which was distinctly different from areas devoid of contamination or having only trace levels. This helped identify probable boundaries of high concentrations of contaminants with relatively high confidence and identify a probable location of initial release. We did not identify areas with pooled DNAPLs, but this is likely due to the water table being deeper than the GPR could effectively investigate at this site. The site contained permafrost, some standing water, and other obstructions which caused some difficulty in data acquisition and interpretation. Overall, the results were compelling and indicate that GPR can be rapidly deployed and provide important information to help delineate boundaries of contamination plumes and locations of initial release.

Introduction

This case study was conducted on a brownfield site located in the Greater Toronto Area. The site was known to be contaminated with dense non-aqueous phase liquids (DNAPLs) following demolition of a building with the highest concentrations of cis- 1,2-Dichloroethylene, Trichloroethylene, and Tetrachloroethylene being measured near the center of the property. While some LNAPLs were identified in a single borehole extraction, the concentrations were significantly less than those recorded of DNAPLs. Ground penetrating radar (GPR) was deployed to test the technology's ability to define boundaries of infection. While many experimental studies have been conducted that prove the effectiveness of GPR for DNAPL contaminant identification (Orlando and Palladini, 2019; Orlando and Renzi, 2014; Sneddon et al., 2000; Sneddon et al., 2002), there are limited comprehensive studies published in the literature from field tests (See Redman, 2009 for examples). Our goals were to collect GPR data from the site with as complete coverage as possible, match those results with validated and tested borehole extractions, and develop conclusions regarding GPR effectiveness for DNAPL mapping on difficult urban brownfield sites.

The site consisted of clayey silt fill ranging from 0.6 m to 2.2 m thick beginning between 0.2-0.5 mbgs. The water table varied from 4.4 mbgs to 5.7 mbgs. Since our assumption was that the GPR signal would not penetrate to the depths of the water table given the conditions, we did not expect to record reflection responses from pooled DNAPL below the water table where they typically form (Redman, 2009). Rather we would use evidence of rapid signal attenuation as a possible signature of infected areas since soils containing non-aqueous phase liquids (NAPLs) are generally more conductive than soils whose pores are filled with air (Mako et al., 2009; Monier-Williams, 1995). Also, in areas where the water table is deep, the total quantity of DNAPL in the vadose zone may be large (National Research Council, 1999). While DNAPLs will migrate downward into the subsurface, residual saturation may remain in soil pores because of capillary forces creating the possibility for characterization with GPR (National Research Council, 1999).

Methods

This investigation used a Sensors & Software Noggin Smartcart with a 250 MHz antenna integrated with a Topcon DGPS (Figure 1). A step-rate of 5 cm was used and transects were acquired in both north-south and east-west orientations. The time-window was set to 60 ns after initial testing suggested that signal attenuation would not allow for penetration deeper than approximately 2 m. All data were processed through Ekko-Project software. Time-slices were generated using the georeferenced data. Basic filtering was applied to remove noise. Migration and Hilbert transform were applied to account for signal distortion and phase prior to slice generation. Slices were produced with thicknesses of 0.125 m.

Figure 1: Photograph facing west of GPR data acquisition at the project site.

Results

As expected, the GPR signal attenuated rapidly in contaminated areas of the site (Figure 2). Much of the signal was absorbed by the contaminated soils by roughly 0.5 mbgs, though this fluctuated some from north to south. Signal strength remained high until approximately 2.0 mbgs in areas unlikely to be infected by contamination. Some limited attenuation began occurring near the surface approximately 16 m to 19 m into the profile shown in Figure 2. This may be the most probable location for initial release since it marks the shallowest effects of signal decay. The GPR was also able to reasonably define boundaries of the attenuation zone in the top two meters. These hard vertical boundaries to the north and south suggest a high correlation between contamination, soil conductivity, and signal attenuation.

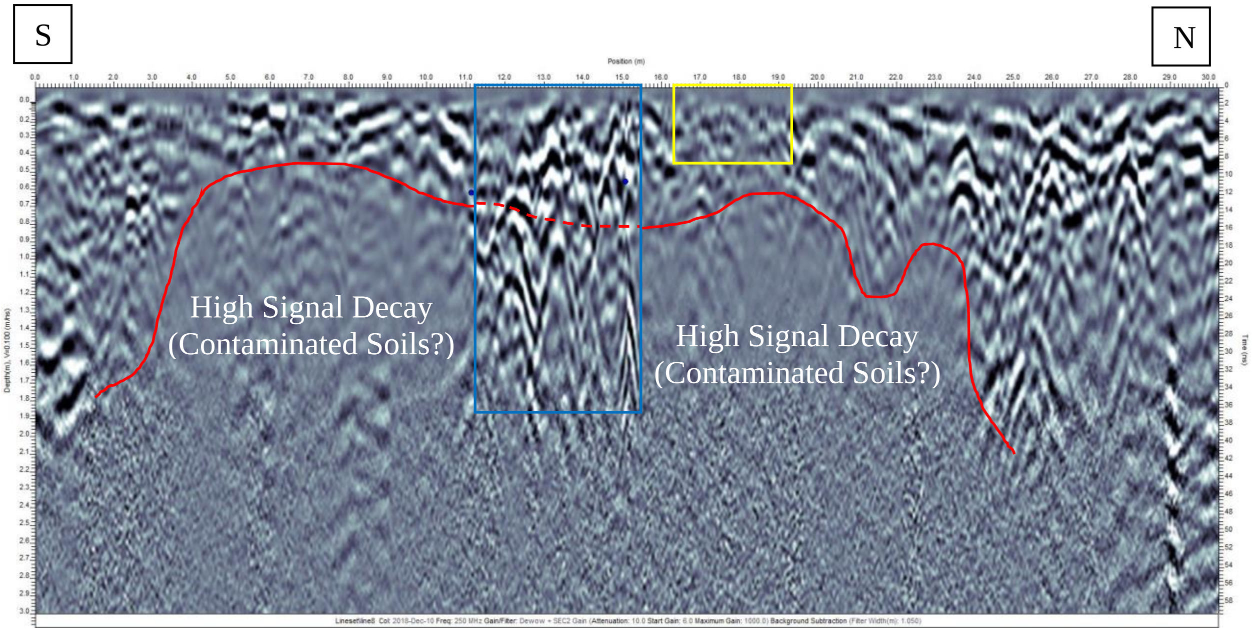
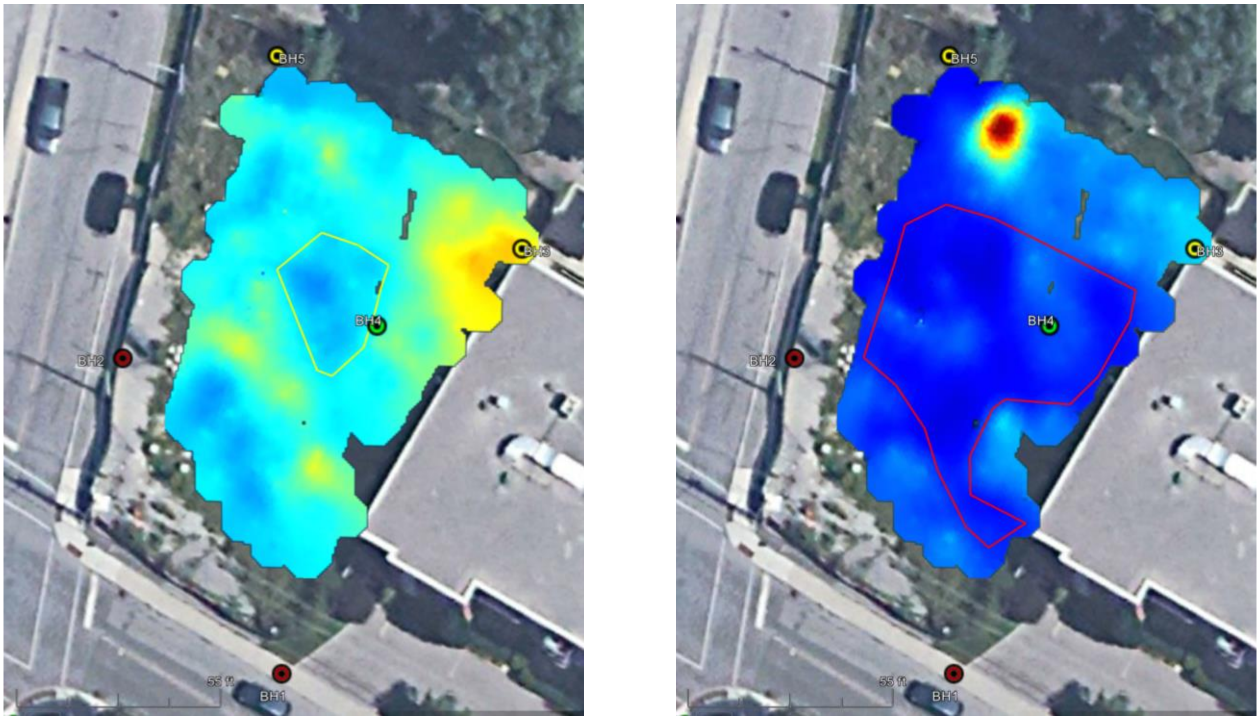


Figure 2: GPR profile indicating high signal attenuation rates in the center of the study area. Solid red line indicates obvious attenuation, while dashed red line indicates assumed attenuation. Blue box indicates effects from pool of standing water. Yellow box indicates suppressed signal just below ground surface compared to the north and south, suggesting possible location of initial intrusion.

Time-slices indicate a localized zone of ultra-shallow (less than 0.25 mbgs) signal attenuation near the center of the site (Figure 3a). This zone measures 10 m north-south at its longest, 8 m east-west at its widest, and covers an area approximately 60 m^2. This is the location identified in profile view (Figure 2) with the early signal decay just north of the surface water. The evidence supports the conclusion that this is the location of initial DNAPL release. Of the five boreholes extracted, BH4 had the highest concentration of DNAPLs by an order of magnitude. The location of this borehole appears to be near the eastern boundary of this anomalous area of low signal strength. There is another area of high signal attenuation in the near surface located in the southern portion of the site, but BH1 and BH2 recorded no contamination and indicates the surface attenuation is unrelated to DNAPL release.

The slice map at approximately 1.0 mbgs indicates a larger area approximately 289 m^2 of attenuated signal at this depth (Figure 3b). It is believed that this is related, at least in part to contamination since there remain indications of strong GPR signals in the northern and southern most areas of the site. This suggests some spreading of the DNAPLs above the water table which was unexpected. An understanding of material properties and experimental results suggest limited lateral movement at the point of injection (Orlando and Palladini, 2019; Orlando and Renzi, 2015) until reaching the saturated zone (National Research Council, 1999). This might be a function of shallow layering where DNAPLs might pool at the interface of coarse and fine grains, and then spread across the layer though we recorded no evidence of pooled DNAPLs, but no pooling was recorded (possibly a result of our antenna frequency choice). Another possibility is multiple locations of release across the site. There is limited evidence of this, but a close look between 3m to 5m into the GPR profile presented in Figure 2 might indicate another location of release. There is some evidence of migrating contaminants from the center of the site to the southeast (Figure 3b). This also is an unexpected movement of the DNAPLs in the vadose zone, but might be a result of runoff.

While trace levels of contamination were present in the water table tested at BH3 and BH5, there appears to be a vertical boundary in the north above the water table that does not reach these outlying locations (Figure 3b). Thus, the highest concentrations of contamination in the top 2 meters of the unsaturated zone appear to remain in the central portion of the site with possible limited migration to the southeast.



(a) (b)

Figure 3: Aerial photograph with time-slice overlays at (a) 0.125-0.25 mbgs and (b) 0.875-1.0 mbgs. Yellow line indicates approximate boundary of interpreted DNAPL release zone. Red line indicates possible distribution of DNAPLs at approximately 1.0 mbgs. Red borehole points indicate no evidence of contamination, yellow borehole points indicate trace levels of contamination >4 mbgs, green borehole point indicates high concentrations of contamination.

Conclusion

The results of this study encourage the use of GPR for mapping contamination in the unsaturated zone of brownfield sites. GPR signal attenuation showed a strong correlation with high concentrations of DNAPLs. The GPR did not record evidence of pooling which was likely due to the depth of water table, but also did not record any pooling at the interfaces between soil layers. Surficial signal attenuation in an area approximately 60 m^2 near the center of the site indicated the probable location of initial DNAPL release. This was a novel discovery during our study and could be used by other researchers in the future working on forensic environmental investigations. A critical step in reconstructing forensic scenes is identifying the origin of an activity. Finally, the apparent lateral spread of contaminants in the unsaturated zone was unexpected. This may have been due to post-release precipitation or other natural processes, additional unidentified release points, or heterogeneous soil distribution that encouraged migration of DNAPLs in unexpected pathways. This result suggests more experimental research should be conducted on contaminant movement in inconsistent sub-surfaces. Much of the experimental data focuses on homogeneous layers that vary in grainsize at clear boundaries in vertically stratified layers.

References

Orlando, L, Palladini, L, 2019, Time-lapse laboratory tests to monitor multiple phases of DNAPL in a porous medium, Near Surface Geophysics, 17, 55-68.

Orlando, L, Renzi, B, 2015, Electrical permittivity and resistivity time lapses of multiphase DNAPLs in a lab test, Water Resources Research, 51, 377-389.

Mako, A, Elek, B, Dunai, A, Hernadi, H, 2009, Comparison of nonaqueous phase liquids' conductivity and air permeability of different soils, Communications in Soil Science and Plant Analysis, 40, 787-799.

Monier-Williams, M, 1995, Properties of Light Non-Aqeous Phase Liquids and detection using commonly applied shallow sensing geophysical techniques, Symposium on the Application of Geophysics to Engineering and Environmental Problems Proceedings, January 1995, 1-13.

Redman, JD, 2009, Contaminant Mapping, in Jol, HM edited, Ground Penetrating Radar: Theory and Applications, Elsevier, 247-269.

Sneddon, KW, Powers, MH, Johnson, RH, Poeter, EP, 2002, Modeling GPR data to interpret porosity and DNAPL saturations for calibration of a 3-D multiphase flow simulation, US Geological Survey, Open-File Report 02-451.

Sneddon, KW, Olhoeft, GR, Powers, MH, 2000, Determining and mapping DNAPL saturation values from noninvasive GPR measurements, Symposium on the Application of Geophysics to Engineering and Environmental Problems Proceedings, January 2000, 293-302.