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Improved time-lapse electrical resistivity tomography monitoring of dense non-aqueous phase liquids with surface-to-horizontal borehole arrays

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ABSTRACT

Electrical resistivity tomography (ERT) has long-standing potential to improve characterization of sites contaminated with dense non-aqueous phase liquids (DNAPLs). However, ERT is rarely used at DNAPL sites due to the complexity of the DNAPL target coupled with the inherent limitations of traditional (surface and cross-hole) ERT configurations. Horizontal boreholes are being increasingly used in remedial strategies at contaminated field sites. This paper presents a novel surface-to-horizontal borehole (S2HB) ERT configuration for DNAPL site investigations. This array configuration is combined with four-dimensional (4D) inversion methods (applied on two-dimensional (2D) time-lapse monitoring datasets) to explore the potential benefit of S2HB ERT for mapping the spatial and temporal evolution of DNAPL mass during remediation. A field scale DNAPL remediation scenario was first simulated by a coupled DNAPL-ERT model. This demonstrated that S2HB ERT may provide significant improvements over surface ERT, particularly for delineating DNAPL mass removal at depth. A laboratory experiment was then performed to validate the S2HB ERT approach in a physical system. The experiment confirmed that 4D S2HB ERT provides improved time-lapse monitoring of NAPL changes. Confidence in the ERT responses obtained from the experiment was increased by direct comparison to the actual distribution of NAPL mapped by excavation. Independent simulation of the experiment with the DNAPL-ERT model demonstrated that the model is reliable for simulating real systems. This initial study demonstrates significantly improved resistivity imaging with surface-to-horizontal borehole ERT and its potential as a non-destructive site characterization tool for mapping DNAPL mass changes during remediation.

1. Introduction

Cleaning up sites contaminated with non-aqueous phase liquids (NAPLs) presents an ongoing challenge in the field of environmental remediation. Denser-than-water NAPLs (DNAPLs), such as chlorinated solvents and coal tar, are a class of hazardous industrial organic liquids often introduced into the subsurface by uncontrolled releases (Pankow et al., 1996). Following a release, DNAPLs migrate through the subsurface as an immiscible 'oil' phase in response to gravity and capillary forces. Typically a release will penetrate the water table and the majority of the mass will occupy the saturated zone for decades if not remediated. The resulting DNAPL body can exhibit a wide range of forms, from a laterally extensive pool (i.e., highly saturated accumulation) to a complex, heterogeneous distribution of both pools and residual (i.e., disconnected blobs) (Gerhard et al., 2007). This DNAPL source zone can serve as a long-term source of groundwater contamination posing significant risks to human health and the environment.

One of the most challenging and important components of a successful DNAPL remediation program is effective characterization and temporal monitoring strategies (Kavanaugh et al., 2003). Conventional techniques, which typically rely on geochemical analysis and sampling from a sparse network of intrusive boreholes, are expensive and provide limited spatial and temporal resolution. Non-invasive geoelectrical methods, particularly electrical resistivity tomography (ERT), have long been proposed to improve characterization and monitoring at

Abbreviations: NAPL, non-aqueous phase liquid; S2HB, surface-to-horizontal borehole; ATC, active time constraint.

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contaminated sites (e.g., Brewster et al., 1995; Chambers et al., 2010). ERT is well-established and widely employed in hydrogeological applications (e.g., Loke et al., 2013; Slater, 2007). Time-lapse ERT is a strongly emerging branch in applied geophysics (Supper et al., 2014), monitoring dynamic processes such as surface water-groundwater interaction (e.g., Slater et al., 2010), salt-water intrusion (e.g., de Franco et al., 2009), and CO_2 migration (e.g., Sauer et al., 2014). In the context of DNAPL site investigations, ERT exhibits significant potential due to the typically highly resistive nature of DNAPLs relative to groundwater (Lucius et al., 1992). Thus, a DNAPL occupying the saturated zone at a contaminated site is expected to provide an electrical target amenable to ERT detection, with changes in DNAPL distribution, either by migration or remediation processes, providing electrical changes that can be monitored by time-lapse ERT. At some field sites, subsurface processes such as chlorinated solvent biodegradation or injection of certain remediation fluids may also influence the bulk resistivity (e.g., Chambers et al., 2010).

The application of ERT for mapping DNAPL in the subsurface has been suggested by a number of studies (e.g., Newmark et al., 1998; Power et al., 2013). However, ERT with electrodes applied at the surface to detect static DNAPL is difficult (e.g., Cardarelli and Di Filippo, 2009). One reason is the complexity of the electrical target: an intricate, unknown distribution of DNAPL in heterogeneous soil. Thus, surface ERT used in time-lapse mode to monitor temporal changes associated with DNAPL has more potential. This is particularly true with recent advancements in time-lapse ERT data acquisition (e.g., Wilkinson et al., 2013) and inversion (e.g., Karaoulis et al., 2014). Power et al. (2014) demonstrated the potential of four-dimensional (4D) surface ERT to monitor the remediation of various DNAPL spills. This study revealed that the technique showed promise, providing reasonable delineation of the remediated DNAPL region and estimates of remediated DNAPL volumes. However, reduced effectiveness was evident in field scale scenarios with DNAPL located at depth (e.g., greater than 2 m). DNAPL at depth is expected when significant volumes are released, soils are highly permeable, and/or the DNAPL has a high density (Gerhard et al., 2007). In such cases, surface ERT is hampered by a limited investigation depth and reduced vertical resolution with distance from the surface (Chambers et al., 2010).

ERT electrodes have been deployed in vertical boreholes at DNAPL sites to achieve superior depth resolution relative to surface ERT. Chambers et al. (2004) used cross-hole ERT to monitor the migration of DNAPL through a saturated porous medium in a laboratory column. Daily and Ramirez (1995) used cross-hole ERT to image the injection of methane as a metabolic carbon source at a trichloroethylene (TCE) site. At another TCE site, Newmark et al. (1998) used time-lapse cross-hole ERT comparison images to successfully monitor decreasing resistivity changes associated with the pumping of the pooled TCE. Goes and Meekes (2004) used cross-hole ERT to delineate DNAPL at two contaminated field sites, demonstrating a correlation between DNAPL presence and high electrical resistivity. Chambers et al. (2010) used high-resolution, cross-hole ERT in a pilot scale experiment to map groundwater chemistry changes associated with the bioremediation of a DNAPL source zone. However, cross-hole ERT also has practical constraints. To achieve sufficient resolution, the spacing between the vertical boreholes is constrained by the depth of the borehole (i.e., borehole depth/borehole spacing $\approx$ 1.5). Therefore, to provide adequate coverage of a DNAPL source zone, a large number of vertical boreholes may be required. This would be expensive and vertical boreholes in a source zone might induce DNAPL remobilization downwards into pristine aquifer.

Directional drilling and horizontal borehole technology, originally utilized sparingly at environmental sites (e.g., Plummer et al., 1997), have become increasingly popular due to improved installation, performance and cost (English, 2010). At DNAPL sites, horizontal remediation wells are being increasingly incorporated into remedial strategies including soil vapor extraction, air sparging, bioremediation and horizontal soil sampling (e.g., Moran and Losonsky, 2008; van Heest et al., 2013). Although individually more expensive to install than vertical wells, horizontal wells provide increased efficiency and performance with one well replacing a network of vertical wells due to the greater zone of influence and contact length between horizontal screen and contamination (van Heest, 2013). The same benefit is expected to apply to ERT, namely electrode placement in proximity to the DNAPL target at depth.

Recent ERT work has applied electrodes in horizontal tunnels (i.e., tunnel-to-tunnel) to image geological conditions in advance of tunnel boring (Danielsen and Dahlin, 2010) and mining (van Schoor and Binley, 2010). Harro and Kruse (2013) used direct push technology to implant electrodes horizontally at depths to improve the resolution of ERT-imaged limestone boundaries. Simyrdanis (2013) presented an initial exploration of the surface-to-tunnel ERT arrangement by means of numerical and experimental studies on a variety of subsurface targets with relatively simple geometries. Although surface-to-tunnel ERT shares many similarities with cross-hole ERT and can use the same electrode arrays (e.g., Bing and Greenhalgh, 2000), the main difference relates to the different sensitivities provided by surface electrodes compared to borehole electrodes. Simyrdanis (2013) examined a number of electrode arrays and proposed a geometrical factor threshold to ensure viable electrode arrays with a sufficient signal-to-noise ratio. Simyrdanis (2013) recommended an optimum vertical separation of seven times the electrode spacing between surface and tunnel electrodes for resolving resistive targets.

In this work, surface-to-horizontal borehole (S2HB) ERT is proposed by recording ERT measurements in a combined mode using electrodes on the surface and within a horizontal borehole to obtain increased resolution in the area between them. While the spacing between the vertical boreholes in cross-hole ERT is constrained by borehole depth, greater coverage of the subsurface can be obtained with S2HB ERT due to the larger distances permitted between the surface and horizontal borehole (Simyrdanis, 2013). It is expected that a single horizontal borehole could replace a large number of vertical boreholes. To the authors' knowledge, geophysical arrays have never been considered for horizontal boreholes in environmental applications.

The objective of this study is to evaluate the potential of two-dimensional (2D) time-lapse surface-to-horizontal borehole ERT as a means for monitoring changes in DNAPL distribution. These changes may correspond to DNAPL migration or remediation. Both numerical simulations and laboratory experiments were conducted to accomplish this objective. A published DNAPL-ERT model was employed to provide an initial, theoretical evaluation of the performance of time-lapse S2HB ERT for monitoring the remediation of a realistic, field scale DNAPL source zone. A laboratory experiment was then performed to demonstrate the S2HB ERT approach for a real system involving a changing NAPL distribution over time. The experimental results were then compared to an independent simulation of the experiment using the DNAPL-ERT model. In all cases, surface ERT surveys were also conducted to provide a reference to evaluate the performance of S2HB ERT. All experimental and simulated ERT surveys were analyzed with newly developed 4D ERT inversion algorithms (applied in 2D plus time) to provide spatial and volume estimates of NAPL change as a function of time.

2. Numerical modeling

2.1. DNAPL-ERT model

First, a field scale DNAPL scenario was simulated to provide an initial, theoretical estimate of the potential improvement of the S2HB ERT approach over surface ERT. This was simulated using 'DNAPL-ERT', a numerical model described by Power et al. (2013). DNAPL-ERT, which couples two models, DNAPL3D-MT and IP4DI, simulates a realistic initial distribution of DNAPL at a contaminated site and the complex pattern of