Use of Multiple Direct-Sensing Technologies and 3-D Visualization to Complete a High Resolution Site Characterization of a DNAPL Pool

Tom Koester (tkoester@s2c2inc.com), Steven B. Gelb and Richard Matthew Ruf (S2C2 Inc, Raritan, NJ, USA) Kristen English and Mary Kay Morelli (Betts Environmental and Alternative Fuel Services, Butler, NJ, USA)

ABSTRACT: Previous groundwater investigations conducted at a site in New Jersey utilizing conventional monitoring wells and temporary points revealed the presence of dissolved chlorinated volatile organic compounds (CVOCs) in overburden groundwater. However, a source of the dissolved CVOCs was not identified. A dynamic high-resolution site characterization (HRSC) program was developed to rapidly delineate the on-site extent of the CVOC impacts and try to identify a source of such impacts. The Membrane Interface Probe (MIP) coupled with electrical conductivity (EC) sensor was selected as the primary investigative tool. A localized portion of the Site exhibited elevated MIP detector responses indicative of dense non-aqueous phase liquid (DNAPL). Information from the EC identified the depth of a continuous underlying clay unit. A localized depression in the clay surface corresponded precisely to the greatest MIP responses. Targeted groundwater and soil sampling at that location confirmed the presence of a DNAPL pool. It was determined that this specific DNAPL mixture does respond to ultraviolet (UV)-induced fluorescence using an Optical Image Profiler (OIP). Accordingly, the OIP was utilized as part of this program to verify and more accurately define the subsurface configuration and extent of the DNAPL pool. Earth Volumetric Studio was used to generate an updated HRSC three-dimensional conceptual site model (CSM).

INTRODUCTION

Traditional site investigation methods utilizing conventional monitoring wells rarely characterize groundwater plumes, or identify source areas, accurately. This was the case after previous groundwater evaluation activities were completed at a small manufacturing facility on an approximate 0.20-hectare (i.e., about 0.5 acre) parcel in New Jersey, USA (Site). Previous investigators at the Site had installed nine groundwater monitoring wells and collected groundwater samples from an additional 13 temporary well points. That sampling revealed the presence of dissolved chlorinated volatile organic compounds (CVOCs), primarily trichloroethylene (TCE). The highest dissolved TCE concentration measured was 123,000 micrograms per liter (μ g/L). However, the source of these CVOCs was not identified and the configuration of this plume had not been defined.

A dynamic high-resolution site characterization (HRSC) approach was implemented to rapidly delineate dissolved CVOC impacts and to identify a source of such impacts. To begin the HRSC program, the project team utilized the membrane interface probe (MIP) coupled with an electrical conductivity (EC) dipole sensor. A pool of dense non-aqueous phase liquid (DNAPL) was revealed by the MIP investigation. The DNAPL was sampled and tested for fluorescence response to ultraviolet (UV) light with the optical imaging profiler (OIP). After fluorescence was confirmed, the OIP was mobilized to the Site and the DNAPL pool was fully delineated. Finally, all data was integrated into an updated three-dimensional (3-D) conceptual site model (CSM) using C Tech's Earth Volumetric Studio (Studio).

Membrane Interface Probe (MIP). The MIP is manufactured by Geoprobe Systems® (Geoprobe®) and is a well-established and widely used direct-sensing tool capable of

continuously screening for volatile organic compounds (VOCs) in subsurface soils and groundwater (Christy, 1996). VOCs in the soil matrix are heated to enhance diffusion across a permeable membrane where they are swept into a nitrogen carrier gas and delivered to gas-phase detectors housed on a gas chromatograph (GC). Typical MIP detector configurations include a flame ionization detector (FID), a photoionization detector (PID), and a halogen-specific detector (XSD).

Prior to the addition of the XSD to the MIP Standard Operating Procedure (SOP), most MIP investigations for CVOCs utilized the FID, PID and electron capture detector (ECD) (Adamson et al., 2014). The ECD requires molecules with three or more chlorines to clearly respond with the MIP (i.e., TCE daughter products are not detectable with the ECD). Additionally, the ECD has a narrow linear working range and will exhibit a "flatline" response well before the CVOC water solubility value is reached, providing limited utility in MIP source area evaluations. The XSD, meanwhile, can clearly detect dissolved TCE daughter products such as cis-1,2-dichloroethylene and vinyl chloride. The XSD also has a very wide linear working range. When used as a MIP detector, the XSD can typically identify dissolved CVOC concentrations as low as 100 μ g/L, and also distinguish responses associated with free phase CVOC DNAPL by simply making adjustments to the GC range and MIP software attenuation.

A supplemental heated trunkline (HTL) may also be advantageous for MIP source area investigations. When the MIP encounters highly concentrated dissolved VOCs and/or NAPL, the membrane and trunkline can become fouled by contaminant adsorption. The HTL heats the entire length of the return carrier gas tubing to 100°C, allowing for a more rapid return to detector baseline following probing through high dissolved phase concentrations and/or DNAPL. (Extreme caution and consideration should be used prior to advancing any probe beyond suspected DNAPL zones). Without use of a HTL, detector signals remain elevated for longer, making it more difficult to determine when the MIP has been advanced beyond highly impacted zones and into zones with less concentrated VOC impacts. The HTL also reduces downtime between logging by reducing the amount of time for the detectors to stabilize.

Optical Imaging Profiler (OIP). The OIP, also developed by Geoprobe®, is a new directsensing technology that allows enhanced detection of free phase and residual product for a wide range of product types containing polycyclic aromatic hydrocarbons (PAHs). The OIP tool uses a downhole UV light source to emit monochromatic UV light at a wavelength of 275 nanometers through a probe-mounted protective sapphire window. After being subjected to UV light energy, PAH molecules, if present, will absorb that energy and emit a light photon which is the resultant fluorescence. A camera within the probe continuously captures images of the soil and the images are analyzed for fluorescence. The percent area (%) of the OIP window that contains fluorescence is output. At any point during the downhole logging process, probe advancement can be suspended, and a visible light image can be obtained. The OIP is ideal for logging in source zones as it only detects nonaqueous phase liquid hydrocarbons and is 'blind' to high dissolved phase concentrations.

Electrical Conductivity (EC). An EC dipole is an integral component of both the MIP and OIP tool strings. The dipole sends a current into the soil formation which is measured along with the voltage that results. The conductivity is a ratio of current to voltage times a constant and is read in milli-Siemens per meter (mS/m). Because fine grain soils have more surface area over which to conduct electricity, EC is effectively a measurement of the predominant soil grain-size and can be used to identify lithologic changes.

MIP INVESTIGATION

The initial MIP program conducted at this Site was intended to verify the results from previous field work completed many years earlier and to attempt to identify a source for the previously identified dissolved phase TCE. Because high concentrations of CVOCs were anticipated, the HTL was used from the start. Several MIP borings were first advanced adjacent to previous sampling locations to assess the current conditions. Subsequent borings were spaced approximately 15 meters apart to provide adequate coverage across the Site while maintaining an acceptable level of productivity. As the investigation progressed, spacing between borings was reduced to provide higher horizontal resolution in specific areas. In six field days, a total of 43 MIP borings were advanced to depths up to 6 meters below ground surface (m bgs).

Monitoring well logs generated by previous investigators indicated the presence of a clay unit from approximately 3.2 to 4.4 m bgs. The EC was used to determine the precise location of the clay which had exhibited a ramping in the EC signal to approximately 50 mS/m. The MIP identified the clay interface to occur between 1.37 to 4.53 m bgs. Soil borings confirmed the depth of the clay as well as its presence across the Site.

Multiple MIP logs exhibited very high detector signal response with XSD values exceeding 30 volts (V). The author's extensive experience with the MIP and XSD led to the determination that DNAPL was likely present (i.e., prior investigations by the authors had confirmed TCE DNAPL presence with XSD values > 10 V). Additionally, the elevated detector responses were coincident with a localized depression in the clay surface (Figure 1).



FIGURE 1. EC/XSD cross-section through DNAPL pool.

Confirmatory soil and groundwater sampling was conducted within the area where presence DNAPL was suspected. A soil core advanced to the interface of the overlying sandy soil and underlying clay unit confirmed the presence of DNAPL within the sandy soil immediately overlying the depression in the clay surface. A temporary groundwater well screened in the DNAPL zone just above the clay was also installed. Initial purging with a

TABLE 1. Summary VOC results from DNAPL

Compound	Groundwater Concentration (µg/L)	Soil Concentration (µg/kg)
Trichloroethylene	221,000,000	33,400,000
Toluene	3,090,000	463,000
Tetrachloroethylene	582,000	88,900
Methylcyclohexane	352,000	73,700
Chloroform	64,000	3,460
Total Xylenes	63,600	14,100
cis-1,2-Dichloroethylene	58,000	2,630
1,1,1-Trichloroethane	53,700	6,320

peristaltic pump removed a very small volume of water (< 100 milliliters) before producing free phase DNAPL. A sample of the DNAPL was collected and analyzed for VOCs along with soil collected from the sandy soil. Summary analytical results from the VOC analysis of the DNAPL are presented in Table 1.

OIP INVESTIGATION

Although DNAPL will typically not fluoresce with the OIP, given the number of VOC constituents present in this particular DNAPL mixture, the authors suspected that the DNAPL was likely a waste mixture that may also contain fluorescing polycyclic aromatic hydrocarbons (PAHs). An aliquot of the DNAPL was collected in a cuvette and bench tested on the OIP for UVinduced fluorescence. The DNAPL exhibited fluorescence of > 60 % (Figure 2) which made field mobilization of the OIP a viable option for corroborating the MIP findings and refining the delineation of the DNAPL.

In just over one and a half field days, 36 OIP borings were completed within the area where DNAPL was inferred to be present based upon MIP responses. As with the MIP, multiple OIP logs exhibited fluorescence coincident with a low point in the clay surface (Figure 3). Because the OIP does not detect dissolved phase VOCs, very close spacing between borings (< 0.6 m in some cases) was required to define the edge of the DNAPL pool. With the additional locations spaced so closely together, a much higher resolution of the clay contact was also achieved, and the deepest depth of the clay surface was found to be 4.83 m bgs.

FIGURE 2. DNAPL sample results from OIP bench test.

FIGURE 3. EC/percent fluorescence through DNAPL pool.

In addition to verifying the precise subsurface configuration of the DNAPL pool, OIP results were also used to help confirm/deny the source of the DNAPL found to be present in the pool. It was believed that residual DNAPL in the area around the pool may help identify the location where the DNAPL originated. Information collected suggests that the DNAPL is likely from an off-site source.

THREE-DIMENSIONAL VISUALIZATION AND ANALYSIS (3DVA)

High vertical data density obtained from direct-sensing tools such as the MIP and OIP lends itself to three-dimensional visualization and analysis (3DVA). 3DVA greatly enhanced the CSM for the Site by displaying DNAPL and dissolved phase CVOC impacts as related to lithology. This was key not only to convey the CSM to stakeholders with technical and non-technical backgrounds but also for the Site investigators to better understand the source of on-going dissolved phase CVOC impacts on-site, and to help focus the evaluation of the likely source of the on-site DNAPL pool itself.

The first step in the 3DVA process was acquiring accurate horizontal and vertical spatial data for the direct-sensing locations. A survey of horizontal locations utilizing the Global Positioning System (GPS) was conducted at the conclusion of the field investigation. Due to the proximity of many of the direct-sensing locations situated adjacent to the DNAPL pool, manual measurements were made to confirm and adjust locations. To obtain surface elevations, United States Geological Survey Light Detection and Ranging (LiDAR) data were obtained and used to create a one-half meter resolution topographic surface of the Site. Boring elevations were then calculated based on the elevation of the topographic surface at each location. This method is a rapid, cost efficient way to provide a reliable placement of subsurface plumes and lithologies.

The next step was to create a geologic model of the Site. With the first surface being the topography, the next surface defined in the geologic model was the top of clay. Clay contacts at each of the 79 direct-sensing boring were made based on a ramping in the EC signal to 50 mS/m. The clay presence was visually confirmed in the five soil borings

conducted as part of the MIP confirmation sampling and collaborated with the EC signature in the collocated MIP borings. This provided a high level of confidence when assigning the depth of the clay. Clay depth was then converted to elevation by subtracting from the surface elevation. The final surface for the geologic model was an arbitrary flat bottom elevation. These geologic surfaces were kriged within a two-dimensional (2-D) finite difference grid. Cells range in size from 0.9 x 3 m at the edges of the study area where there is sparse data, to 0.08 x 0.08 m in the vicinity of the observed DNAPL zone where data points are very dense.

Once the geologic model was finalized, all direct-sensing data were individually kriged using Studio's 3-D kriging module within the geologic grid described above using a vertical resolution of 100 cells. Kriging settings were set individually for each data set based on individual data properties. Grid node values for direct-sensing data were calculated in Studio utilizing an ordinary kriging algorithm using all data points with a spherical semivariogram and zero nugget. Figure 4 presents a 3-D rendering of the DNAPL pool as detected with the OIP and the clay unit taken from EC data.

FIGURE 4. DNAPL pool as detected by OIP with clay from EC data.

In addition to the 3-D kriging described above, 2-D kriging was conducted on the full 3-D direct-sensing data sets to create 2-D maximum outputs for the data. Note that there is no interpolation completed in these calculations and as such confidence is always 100%. The 3-D data sets are collapsed by the maximum value and then kriged in 2-D. Since the nodes of the collapsed 3-D data set match the 2-D grid, the predicted value is simply the maximum value of the 3-D data. Figure 5 shows the kriged 2-D maximum response of the XSD while Figure 6 compares the XSD 2-D maximum to that of the OIP percent fluorescence.

FIGURE 5. XSD 2-D maximum response.

FIGURE 6. OIP 2-D maximum response with XSD 2-D maximum response.

CONCLUSIONS

HRSC investigations utilizing direct-sensing tools such as MIP and OIP combined with 3DVA have the potential to reveal and accurately delineate the subsurface configuration of NAPL source zones and/or dissolved VOC plumes that is typically not achievable with the use of conventional site characterization techniques (such as the installation and sampling of groundwater monitoring wells). When using MIP to delineate CVOCs, it is critical that the XSD is selected as the primary MIP detector over the ECD. Although the OIP is not designed to specifically identify CVOC DNAPL, it is possible that the presence of PAHs commingled within DNAPL will allow the OIP to represent an effective option to provide a collaborative dataset that complements and confirms XSD MIP findings. Comparing the 2-D maximum responses of the OIP % fluorescence and XSD (as shown on Figure 6), confirms that the XSD was effective at identifying and delineating the DNAPL zone at this Site. In addition to successfully identifying CVOC DNAPL zones, the MIP with XSD is very effective in efficiently delineating dissolved phase CVOC impacts in groundwater. By doing so, groundwater monitoring wells can be placed at appropriate locations and depths. Perhaps most importantly, HRSC results can provide information needed to accurately evaluate and implement cost-effective and appropriate remedial measures.

REFERENCES

- Adamson, D.T., S. Chapman, N. Mahler, C. Newell, B. Parker, S. Pitkin, M. Rossi, and M. Singletary. 2014. "Membrane interface probe protocol for contaminants in low-permeability zones. *Groundwater*. 52(4): 550–565.
- Christy, T.M. 1998. "A permeable membrane sensor for the detection of volatile compounds in soil." *Proceedings of the Annual Meeting of the Environmental and Engineering Geophysical Society*. 65-72.