INVESTIGATION AND REMEDIATION STRATEGIES FOR A DNAPL IMPACTED SITE IN STRATIFIED SOILS

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INTRODUCTION

Historically, the use of chlorinated solvents in commercial industry has resulted in Dense Non Aqueous Phase Liquid (DNAPL) impacts beneath structures associated with many blending, storage or manufacturing facilities. The characteristics of these compounds, though useful for their designated applications, pose significant challenges for facility owners and environmental consultants attempting to define their extent and implement effective remediation programs.

DNAPLs are heavier than water and therefore descend through an aquifer until they reach an aquitard or other stratigraphical barrier (i.e. finer grained soils). DNAPL migration can also be controlled by the structure and topographic relief of an aquitard and may migrate opposite to the groundwater flow direction thus traditional hydrogeological contaminant study methods can not be simply applied. A schematic of these characteristics is illustrated in Figure 1 below.

DNAPLs typically have very low solubility and persist in the environment, which can result in a continuous source of impact to local aquifer systems regardless of the groundwater remedial approach.
Characterization of DNAPL impacted soil and groundwater plumes therefore require a focus on both the physical/structural nature of the subsurface such as fractures, permeable lenses, shape/slope of the top of the aquitard, and existing anthropogenic structures as well as traditional hydrogeologic flow parameters.

Determination of well defined migration pathways focusing on identifying free product source areas and sorbed phase impacts can be used in the development of more effective remediation strategies. While no single applied remediation method has proven beneficial in all DNAPL impacted scenarios, combining different remedial methods may prove more effective and even lower the total remedial costs if strategically implemented.

This paper examines DNAPL characterization techniques within stratified soil conditions and presents a case study where the determination of migration pathway and contaminant mass was used to construct an effective, multi-tiered remediation strategy.

CASE STUDY
Site History
The subject site was originally constructed as a chemical handling, storage and distribution warehouse in the 1970s. It is situated within an industrial city sector, with undeveloped lands that lie adjacent to the east. A rail line runs through the eastern edge of the property, which includes a parallel spur line next to the building. A creek meanders in a general southerly direction approximately 10 to 110m from the northeastern property line (see Figure 2 below).
In 1984, a surface spill of solvent consisting predominately of tetrachloroethylene (perchloroethylene (PCE)) was released from a rail car on the east side of the building. While the volume of the PCE release is unknown, estimates at the time suggested as much as 12,000 litres may have been discharged. Preliminary remedial efforts included surface liquid recovery of 1,500 litres and excavation of visually impacted soils near the surface.

Additional site investigation/clean-up activities began in 1989 and several phases of intrusive site investigation were completed over the last decade. The following provides a summary of previous environmental activities completed at the subject facility.

- **1989:** Removal of PCE-impacted soils from below the active rail spur and the installation of soil vapour extraction (SVE) system adjacent to the building foundation. The excavated soils were stockpiled along the northern property boundary and SVE piping installed within the stockpile to reduce contaminant levels (connected to the existing SVE system).
- **1992/1993:** Evidence of DNAPL discharge from seeps along the bank of the adjacent creek resulted in the installation of a liquid collection trench. This granular filled collection trench was advanced to a maximum depth of 6m, and extends along the entire length of the northeast property boundary. The trench was equipped with five (5) submersible pumps, which operate continuously, discharging liquid to a water treatment system (O/W separator, Air Stripper, Granular Activated Carbon – both liquid/vapour phases) located in the adjacent warehouse, prior to discharge to the municipal sanitary sewer (under agreement with municipality).
- **1994/1995:** Excavation of PCE-impacted soils on the adjacent lands to the southeast and the installation on an impermeable barrier along the adjoining property boundary.
- **1999:** Off site investigation was commissioned to assess the effectiveness of the collection trench at controlling off site contaminant migration. Monitoring wells were installed off site, at depths both similar to and below the bottom of the trench.
- **2002:** Monitoring results reported from the off site monitoring wells detected the presence of DNAPL (PCE) within wells screened below the base of the collection trench.

**Stratigraphy**

Site stratigraphy generally consists of a clayey silt upper fill unit underlain by three (3) low permeability stratigraphic units (including: upper zone Clay Silt, mid zone Sand Silt and lower zone Clay Silt and/or Sandy Silt) and three (3) distinct groundwater systems, extending to the regional bedrock surface at a depth of approximately 20m below ground.
surface (bgs). Small (<40mm), silt and sand seams were identified at depths of 5m to 6m bgs in the upper zone Clay Silt.

**Hydrogeology**

The depth to groundwater varies between each stratigraphic unit. Water levels in the upper zone ranged from 2.5 to 4m bgs, flowing east toward the collection trench. The mid zone water levels were measured to be between 2.8 to 3.9m bgs, flowing northeast toward the creek. Static water levels measured in the lower zone ranged from 4.5 to 6m bgs, flowing north/northeast towards the creek.

**Field Investigation Program**

In response to the identified off site impact, a *Joint Investigation* was commissioned in August/September of 2002 by the current property owner and former property owner to fully delineate the degree and extent of subsurface impacts both on and extending off of the property to the east. (Previous real estate agreements appointed the current owner to be responsible for on site impacts while the former owner remained responsible for off site impact) Nested wells were installed at various locations across the two properties with one well in each of the three major stratigraphic units observed.

A total of seven well nests were installed on site by SEACOR with an additional seven nests installed off site by the former property owner’s consultant. Each nest, except for location OW-414, included three wells; one in each major stratigraphic unit: the upper zone soils (< 10m), mid zone soils (10 - 14m) and the lower zone soils (> 18 m) soils. Nest locations are shown in Figure 2 in the appendix. An additional seven well nest locations were installed offsite by the former property owner's consultant (Joint Consultant).

Consistent with standard protocol, care was taken to minimize cross-contamination of PCE between major soil units. Telescoped drilling was used on the initial well nest (Location MW-404) whereby, large-diameter, hollow-stem augers were advanced into the first soil unit while continuously sampling the soils for evidence of impact. Upon observation of PCE impact, the borehole was grouted and allowed to set. Further sampling and characterization was then continued through the grouted borehole with smaller diameter augers. In addition, all wells were completed with non-shrink grout tremied in place above the sandpack.

**PCE IMPACT**

**DNAPL**

Monitoring results from the *Joint Investigation* detected approximately 50mm of DNAPL within the middle zone monitoring well (screened interval 9 m to 13 m) at sampling location MW403. Measurements following bailing indicated DNAPL thickness reduction to 30mm. Trace evidence of DNAPL was identified within collection trench
monitoring wells and collected through on-going groundwater extraction activities. Existing off site wells installed previously near the northeastern property line were noted to contain DNAPL (302 and 309). Groundwater concentrations detected in the upper and middle aquifer units in the central portion of the study area would suggest the potential presence of other localized areas of DNAPL.

**Residual Phase PCE**
Elevated PCE concentrations in soil were generally restricted to the upper zone clay silt unit (depth range 1m to 10m), with limited exceedances detected in the upper portion of the underlying sand silt unit (depth >10m) within the immediate vicinity of the historic release area (between MW404/MW405). Headspace Total Organic Vapour (TOV) levels were found to provide an excellent correlation with the reported analytical results, enabling the accurate extrapolation of field screening program results. Grain size/hydrometer results confirm accuracy of field geologic assessment. Soil impacts in the upper zone were reasonably delineated to the west of well nest MW402 where there was no observed impact at MW401. Impacts were observed to extend to the south/southeast and northeastern property line, and the last well nest to the north (MW414) indicated lower concentrations of PCE in soil.

**Dissolved Phase PCE**
Elevated dissolved phase concentrations of PCE were detected within the upper and middle groundwater monitoring wells at five (5) of the seven (7) monitoring locations completed on the subject property. Marginal deep groundwater impacts were restricted to MW405, with results consistent with soil sampling observations. Groundwater impacts in the upper and middle zones were reasonably delineated to the west of well nest MW402 where there was no observed impact at MW401. Impacts were observed to extend to the south/southeast and northeastern property line, and the last well nest to the north (MW414) showed greater dissolved PCE impacts than MW406.

**Slug Testing of Soil Zones**
Pressure transducers were suspended in various wells across the site, and bail-down testing was performed to observe water level recovery. Recovery data results estimated low hydraulic conductivity in the various soil units as outlined in Table 1 below.
### Table 1

<table>
<thead>
<tr>
<th>Soil Unit:</th>
<th>Upper Zone</th>
<th>Mid Zone</th>
<th>Lower Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clayey Silt</td>
<td>3.5 - 6.5 m</td>
<td>9 - 13 m</td>
<td>16 - 19 m</td>
</tr>
<tr>
<td>Sandy Silt</td>
<td>2.1x10⁻⁸</td>
<td>2.0x10⁻⁷</td>
<td>2.5x10⁻⁷</td>
</tr>
<tr>
<td>Sandy Silt/Clay Silt</td>
<td>2.5x10⁻⁷</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### VEMPE PILOT TEST

**Field Program**

SEACOR completed a pilot test using a Vacuum Enhanced Multi-Phase Extraction (VEMPE) system following the *Joint Investigation*, assessing potential effectiveness within each/any of three impacted soil zones and providing preliminary design parameters.

The pilot tests involved three wells (PW22, PW45 and PW65) located in the vicinity of the historic release area along with several observation wells. All wells tested were 50mm in diameter. The pilot test system equipment consisted of a 25 horsepower liquid ring pump, inlet separator, and an existing air stripper/ granular activated carbon treatment system.

Monitoring points were installed at 2, 4.5 and 7m away from each pilot test well to monitor hydraulic and pneumatic influence. All tests were conducted by applying varied vacuums to each soil zone with the drop tube set at the bottom of the well or effective soil zone. The vacuum was set on the well casing at the highest possible vacuum, a moderate vacuum setting and a either a low vacuum or completely passive (no vacuum) setting. Once a steady state was achieved at one particular vacuum setting, the vacuum was adjusted to the next lower setting. The extraction and monitoring well spacing as well as the vacuum schedule is illustrated below in Figure 3.
Results

Measured volatile organic compounds (VOCs) recovery data indicated PCE removal rates ranged from 300 g/day to 6500 g/day for the upper zone, 1.5 g/day to 2.1 g/day for the middle zone and 3.8 g/day to 8.9 g/day for the lower zone. The pilot test data indicated that 97% to 99% of the total volume recovered was through vapour extraction. DNAPL appeared to be recovered during the initial hours of the upper zone test (PW22) where dark, separate phase liquid was observed in the clear extraction drop tube and some plastic components in the flow totalizer of the recovery unit appeared to have sustained substantial chemical attack.

Groundwater recovery rates ranged from 1.5 L/hour to 5.1 L/hour per 50 mm diameter well.
Extraction well flow rates measured during the high vacuum testing (corresponding to the maximum extraction well flow rate) indicated maximum extraction well flow rates of approximately 2 cubic meters per minute (m$^3$/min) or 70 cubic feet per minute (cfm).

Based on Pilot Test data interpretation, a hydraulic radius of influence of 10m was estimated for the upper zone, 15m to 20m for the middle zone and <7m for the lower zone.

A pneumatic radius of influence of 7m was estimated for the upper zone from the pilot test results. For the middle zone, a pneumatic radius of influence of 2m was observed. For the lower zone, a pneumatic radius of influence of <2m was observed.

**Initial Evaluation of VEMPE Test**

Upper zone results showed excellent mass removal rates (upwards of >900g/hour on initial high vacuum testing), but inconsistent hydraulic and pneumatic influence. PW22 (upper zone test well) pilot testing was observed by one 2m, two 4.5m and one 7m radius monitoring wells. While the west 4.5m well and the 7m showed evidence of both hydraulic and pneumatic influence, the east 4.5m well showed no evidence of response. In addition, the 2m well stopped showing evidence of influence after the initial day of extraction on PW22. The construction details of a 'new utility collection trench', located near the study zone, were supplied after the installation of the pilot test wells. This trench, running northwest-southeast to the northeast of the facility warehouse, was located just west of PW22 and resulted in a short circuit of vacuum into the trench backfill. Both the west 4.5m and 7m wells appear to have been screened within the trench backfill, explaining the strong evidence of influence at these monitoring points and the lack of response from the 2m and east 4.5m wells screened in the native material. The Joint Consultant took part in reviewing field data, but was unfamiliar with VEMPE, and would not support the upper zone pilot test due to the lack of response in the 2m well.

For the Middle Zone, a substantial hydraulic radius of influence was observed (> 25m), such that similarly screened wells off site monitored by the Joint Consultant were shown to be within the zone of influence from the extraction test. The Lower Zone pilot test provided smaller radii of pneumatic and hydraulic influence, but was not considered as requiring mass removal or groundwater control at the time.

**VEMPE Planned for Hydraulic Control**

In 2004, SEACOR installed ten (10) 100mm diameter hydraulic control wells (H-wells) along the northeastern property line, advanced to a maximum depth of 14m (see Figure 4 in the Appendix for well locations). Wells were screened within the Middle Zone sandy silt, intended to prevent further off site migration below the collection trench. However,
given the discrepancy between field estimated hydraulic conductivities and the large groundwater control radius implied by the Middle Zone pilot test results, the Joint Consultant requested that direct rising-head testing of each H-well be performed to determine individual hydraulic conductivity. This testing was conducted on half of the H-wells (staggered, every other well) in the Fall of 2004 and completed in the Summer of 2005, while surrounding wells were monitored for effects by the pumping of these H-wells. Results of the rising head tests (as outlined in Table 2 below) showed an average hydraulic conductivity of 4.8x10^{-9} m/s.

<table>
<thead>
<tr>
<th>Well</th>
<th>K, m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2004</td>
</tr>
<tr>
<td>H2</td>
<td>5.8E-09</td>
</tr>
<tr>
<td>H4</td>
<td>1.4E-08</td>
</tr>
<tr>
<td>H3</td>
<td>1.7E-09</td>
</tr>
<tr>
<td>H5</td>
<td>1.1E-09</td>
</tr>
<tr>
<td>H6</td>
<td>7.0E-09</td>
</tr>
<tr>
<td>H1</td>
<td>5.8E-09</td>
</tr>
<tr>
<td>H7</td>
<td>3.2E-09</td>
</tr>
<tr>
<td>H8</td>
<td>(not tested)</td>
</tr>
<tr>
<td>H9</td>
<td>(not tested)</td>
</tr>
<tr>
<td>H10</td>
<td>1.0E-09</td>
</tr>
</tbody>
</table>

Table 2

Wells located near tested H-wells, as well as certain midpoint H-wells, showed a drawdown response suggesting an appropriate spacing to overlap capture. Charts 1 and 2 presented in the Appendix show the evidence of pumping influence.

While drilling and installing these H-wells, three strategic locations were also drilled between monitoring well locations OW405 and OW406, OW405 and OW404, and OW404 and OW403. These boreholes were advanced into the upper zone clayey silt to further estimate PCE soil impacts across the site, and observe if the silt and sand lenses found in some locations were generally continuous in the upper zone soils.

**CURRENT REMEDIAL ACTION PLAN**

**Property Politics**

The local regulator had requested a remedial approach/solution that utilized the investigative observations of both SEACOR and the Joint Consultant to assess the nature and extent of PCE both on and off site. This collaboration was intended to foster an agreement upon what types of remedial actions would address both the source zone as well as off site impacts. In addition, consequences of the real estate deal between the current and former property owner required that prior approval be obtained from the former property owner before any on site remedial actions could take place.
While SEACOR intended to remediate the Upper Zone soils with VEMPE, the former property owner and Joint Consultant opposed the strategy due to the masked results of the pilot test. The former property owner also insisted a large excavation be included in site remedial activities, as this was typically performed during prior site ownership.

Further meetings required the involvement of SEACOR's corporate hydrogeology and remediation support, as well as an independent DNAPL consultant to convince the former property owner and the Joint Consultant that the data obtained from the Joint Investigation and Pilot Test suggested options other than excavation also existed. A combined concept of 'Total Fluids Capture' (DNAPL, sorbed and dissolved phase) and partial excavation was presented and eventually accepted by the former property owner. This plan was presented as three 'phases' as outlined below, designed to control and recover DNAPL identified below the subject site in preparation for a risk management strategy to address the dissolved phase impact.

**Phase I: Excavation**

Recognizing that incorporating an excavation into the remedial action plan would gain quicker support from the former property owner, SEACOR proposed a 'strip excavation' to run below the rail line, a few meters southwest of the site property line. The intent of this excavation from SEACOR's perspective is to sever the hydraulic connection of the observed silt and sand seams, and create an impermeable boundary near the property line by use of fine-grained backfill. Figure 5a below outlines the proposed excavation cross-section (See Figure 5 in the Appendix for full excavation detail).

![Excavation Cross Section](image)

**Figure 5a**

The excavation dimensions for Phase I will be roughly 110m long by 26m wide at grade level, stepped inwards at an approximate 1:2 vertical:horizontal slope. The center of the
excavation will achieve an approximate depth of 7m or to the top of the mid zone soils, and will be 2m wide at full excavation depth. SEACOR has estimated a total of 2,900 m$^3$ of 'clean' soils will be removed and 7,900 m$^3$ of 'impacted' soils will be removed. The excavation stepping will require the eastern limits of the excavation to extend approximately 8m into the adjacent property road allowance to the east. Temporary haul roads will also be constructed adjacent to the excavation’s northeastern limits, as well as northwest of the site warehouse.

**Phase II: Property Line Hydraulic Control**

The second phase will focus on the recovery and capture of impacted groundwater and DNAPL from the ten (10) 100 mm diameter hydraulic control wells (H-wells) in the middle sandy silt unit (middle zone) already installed along the eastern property boundary. The method of extraction at the hydraulic control wells will be VEMPE. In addition, monitoring wells will also be installed to confirm drawdown between H-well points.

The design well spacing for Phase II is based on a 10 m and 20 m radius of influence (linear well spacing along the eastern property line) and a system capable of a total vapour flow capacity of 680 m$^3$/hour (400 scfm) at an operational vacuum of 380mm (15 inches) of mercury. The water treatment system will have a water flow rate capacity of 50 L/min which will treated by the site’s existing water treatment system prior to discharge.

**Phase III: VEMPE of the Source Zone**

Phase III will focus on the recovery of DNAPL in remaining upper zone soils that are not removed as part of the excavation. It is proposed to use a VEMPE system for the control and recovery of PCE within the upper zone soils (primarily within observed seams and smear zones) remaining in place west, north and south of the excavation limits as well as within potential DNAPL pooling areas such as the utility trench.

The design well spacing for Phase III is based on a 10 m radius of influence (20m grid well spacing) and a system of similar design specifications as outlined in Phase II. The water treatment system will also discharge to the site’s existing water treatment system as in Phase II. Proposed locations for the extraction points are outlined in Figure 6 of the Appendix.

**SUMMARY**

According to information gathered from the various investigations including the *Joint Investigation*, the Pilot Test and the Hydraulic Control Well installation program, PCE sorbed mass and liquid phase areas were identified along with potential migration pathways. A total fluids capture within the upper and mid zone soils coupled with a strip
excavation was designed to provide an effective remedial framework for the subject site. Remedial activities are planned to begin in the fall/winter of 2005.

REFERENCES

