Enhancement of LNAPL in situ recovery using soil washing with a surfactant solution

By:

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Presentation Objectives

(1) Present the facilities for Site Remediation at the INRS-ETE laboratory in Quebec City;

(2) Present our current research project: a 3D lab-scale soil and groundwater remediation test using a technology train, including both Slurping and SEAR.
Project Background – *In Situ Limitations*

- Successful GW remediation requires almost **total** LNAPL mass reduction from source zone;
- *In situ* technologies have mass-reduction limitations:
  - Slurping: leaves residual LNAPL trapped in the saturated zone by capillary forces;
  - SEAR: requires large volumes of solutions and effluent treatment is not economically interesting.
Project Background – *Recovery Mechanisms*

- SEAR targets 2 LNAPL recovery mechanisms:

  1) LNAPL mobilisation
     - Reduction in capillary forces;
     - Increase in oil relative permeability;

  2) LNAPL increased dissolution in water
     - Micelle formation above the critical micelle concentration.
Project Background – 3D Lab. Experiments

• 1D experiments are usually promising – but what is the performance in a 3D environment representing field conditions?
  – Actual field-like injection/extraction pattern with RADIAL FLOW;
  – Analysis of 3D phenomena:
    • Sweep efficiency (contact) and preferential flow effects on recovery
    • Dispersion in the soil and dilution at extraction wells
  – Field-characterisation tests can be performed inside the 3D model and results can be compared with actual field values:
    • Slug tests
    • Inter-well tracer tests

KEY PARAMETER FOR IN SITU SUCCESS!
**Methodology - Laboratory setup (1/4)**

**Triangular Stainless Steel Tank**
holding up to 4 m³ of soil

- 3,0 m
- 1,8 m

**Controlled Temperature Lab (8 deg. C.)**

- 1 m³ reservoir (injection)

- **Flow Meter**

- **1 m³ reservoir (extraction)**

**Ball Valves Diaphragm Pumps**
Methodology - Laboratory setup

1/8 of a 5-spot pattern

1 Injection well: PP1

1 Extraction well: PP2

7 Observation wells: PO1 to PO6, PP3

6 Three-levels sampling wells: MP1 to MP6

4 Pressure probes: PP1, PO1, PO3, PO5

4 Salinity probes: PO2, PO6, PP3, PP2
Slurping unit

Water deaeration towers

Data acquisition and operation control

Automatic water samplers
Methodology - Washing solution selection

- Confidential blend (Ionic surfactant + Co-solvent + Polymer + NaCl)
- Injection concentration is over 60 X CMC (Enhance LNAPL solubility)
- Sand column experiments: 94%-mass removal of weathered gasoline after a 1,8 PV flush (both mobilisation and solubilisation observed)
- Potential impact on IFT and on BTEX dissolution:
Methodology- Washing solution selection

- **Co-solvent (ex. alcohol):**
  - Increases surfactant solubility in solution;
  - Contributes to enhanced oil solubilisation;
  - Contributes to IFT reduction.

- **Shear-thinning polymer:**
  - Stabilize the sweeping front (favourable mobility ratio);
  - Increase viscous forces.

Example of mobility control from a previous project (DNAPL)
*From Robert et al. 2006*
Methodology- Overall experiment

1. Water saturation;
2. Water flood for tank conditioning (pH, EC, ORP, T)
3. Tank drainage (down to 0.5 m elevation)
4. Model oil injection through all wells present in the tank (up to 1 m elevation)
5. Water flood in order to reach an equilibrium:Remove excess oil in tank
6. Remediation:
   – Slurping
   – Salinity conditionning
   – Micellar flood
   – Micellar+ polymer flood
   – Polymer Flood
7. ISCO (to be planned)
### Results - Sand Tank Physical Characteristics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil Surface Area</td>
<td>m²</td>
<td>2.3</td>
</tr>
<tr>
<td>Soil Thickness</td>
<td>m</td>
<td>1.5</td>
</tr>
<tr>
<td>Volume of Soil</td>
<td>m³</td>
<td>3.3</td>
</tr>
<tr>
<td>Mass of Soil</td>
<td>Kg</td>
<td>6540</td>
</tr>
<tr>
<td>Dry Soil Density</td>
<td>Kg/m³</td>
<td>1980</td>
</tr>
<tr>
<td>Total Soil Porosity</td>
<td>-</td>
<td>0.27</td>
</tr>
<tr>
<td>Pore Volume</td>
<td>L/saturated m</td>
<td>620</td>
</tr>
<tr>
<td>$d_{50}$</td>
<td>1.5 mm (medium sand)</td>
<td></td>
</tr>
<tr>
<td>$d_{10}$</td>
<td>0.1 mm</td>
<td></td>
</tr>
<tr>
<td>Mineralogy</td>
<td>Mainly Quartz (dominant) + Calcite</td>
<td></td>
</tr>
</tbody>
</table>
Results - Saturated Zone Properties

- Soil hydraulic conductivity: $2 \times 10^{-5}$ m/s to $8 \times 10^{-5}$ m/s (slug tests)

- Tracer test (prior to contamination):
  
  $0.7 \text{ m}^3$ injected @ $[\text{Cl}^-] = 1000 \text{ mg/L}$, followed by $1.9 \text{ m}^3$ of water

![Tracer Breakthrough Curve At Extraction Well (PP2)](image)

- Effective porosity = 0.25 ($92\% \times \text{total porosity}$)
- 1 Transport Pore Volume = 660 L
Results - Saturated Zone Properties

- Water elevations and piezometric map under stable conditions (steady-state, $Q_{\text{injection}} = Q_{\text{extraction}}$, $dh = 0.2\,\text{m}$)

![Groundwater flowpath diagram]

[Diagram showing groundwater flowpath with labeled points and values]
Results - Saturated Zone Properties

- Sweep efficiency: analysis of tracer front breakthrough

Arrival of tracer front at MPs as a function of injection volume (m³):

- Mil-level screens (0.6 m elevation)

After injection of 220L (1/3 transport PV)
- 440L (2/3 transport PV)
- 660L (1 transport PV)
Results - Unsaturated Zone Properties

- Volumetric water content profile:

- Aquifer solids
- Water contained in soil pores
- Injected LNAPL displaces air in larger pores
## Results- LNAPL recovery by Slurping

- **Operation parameters:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum Pressure at Extraction Well</td>
<td>(cm water)</td>
<td>-25</td>
</tr>
<tr>
<td>Vacuum Pressure at Pump</td>
<td>(inch Hg)</td>
<td>-22</td>
</tr>
<tr>
<td>Air Extraction Flow Rate</td>
<td>(m3/hr)</td>
<td>9.3</td>
</tr>
<tr>
<td></td>
<td>(scfm)</td>
<td>5.5</td>
</tr>
<tr>
<td>Total Operation Time</td>
<td>(hrs)</td>
<td>4 X 8 hrs</td>
</tr>
<tr>
<td>Volume of Water Injected During Operation</td>
<td>(L)</td>
<td>670 (1 transport VP)</td>
</tr>
</tbody>
</table>
Results - LNAPL recovery by Slurping

- Slurping performance assessment:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>LNAPL Volume in Soil</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial</td>
<td>(L)</td>
<td>44</td>
</tr>
<tr>
<td>Final</td>
<td>(L)</td>
<td>27</td>
</tr>
<tr>
<td>Total Volume Removed</td>
<td>(L)</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(39% reduction)</td>
</tr>
<tr>
<td>LNAPL thickness in wells</td>
<td>(cm)</td>
<td>24</td>
</tr>
<tr>
<td>Initial</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Final</td>
<td>(cm)</td>
<td>1.6</td>
</tr>
<tr>
<td>Oil Saturation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial</td>
<td>(%)</td>
<td>14</td>
</tr>
<tr>
<td>Final</td>
<td>(%)</td>
<td>9</td>
</tr>
</tbody>
</table>
Results - SEAR

- Operation parameters:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection Rate</td>
<td>(L/min)</td>
<td>0.24</td>
</tr>
<tr>
<td>Injected Volume</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water + NaCl</td>
<td>(L)</td>
<td>560</td>
</tr>
<tr>
<td>Micellar Solution</td>
<td>(L)</td>
<td>310</td>
</tr>
<tr>
<td>Micellar + Polymer Solution</td>
<td>(L)</td>
<td>310</td>
</tr>
<tr>
<td>Polymer Solution</td>
<td>(L)</td>
<td>760</td>
</tr>
<tr>
<td>Total</td>
<td>(L)</td>
<td>1940</td>
</tr>
<tr>
<td></td>
<td>(days)</td>
<td>6</td>
</tr>
</tbody>
</table>
Results- SEAR

- Samples collected at extraction pump (PP2)
- LNAPL recovery mechanisms observed at extraction well (PP2):
  - Some mobilization ahead of the surfactant solution front;
  - Enhanced solubilization is the main recovery mechanism.
Results - SEAR

- BTEX and surfactant concentration at extraction well (PP2):

**Mobilisation**

Eff. Porosity = 0.11 (40% x total porosity):
Oil saturation caused A 50% decrease in eff. porosity

[BTEX] drops rapidly behind the Micellar Solution Front: Preferential flow and dilution (underiding of washing solution)

Impact of polymer-induced mobility control
Results - SEAR: [BTEX] inside the tank

After injection of 300 L of washing solution

Preferential flow and dilution (underdraining of washing solution)

Rapidly decreasing [BTEX] after solution breakthrough

Dilution at extraction well
Conclusions

• Overall recovery:
  - Slurping - Mobilised oil 21%
  - Slurping - Volatilised oil 18%
  - Soil Washing (SEAR) 5%
  - Oil Still Trapped in Soil 56%

• Impact of remediation on soil concentrations:
  - Bioslurping: 3500 mg/kg reduction
  - Soil washing: 350 mg/kg reduction

• No significant impact on dissolved flux exiting the treatment area
Conclusions - SEAR

• Seep efficiency was not uniform inside the tank:
  – Effective porosity globally dropped by 50% after oil injection;
  – Dissolution not uniform behind micellar solution front;
  – Preferential flow and under-rinding is suspected (3D effects).

• A total of 2 kg of BTEX was removed by dissolution
  – Equivalent to a 350 mg/kg BTEX reduction in soils
Conclusions

• Pros of laboratory tests in large sand tanks:
  – True test prior to field since 3D effects have a huge impact on remediation performance
    • 1D test (column experiment) overestimated the performance
  – Experimental control over data
    • Mass balance was acheived
  – Reduced costs vs. field pilot study, allows optimisation process

• Room for improvement – other tank tests are planned!
Thank you!