Passive (Aggressive) Barriers for Plume Remediation

Pete Craig
Geo-Solutions

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Passive (Aggressive) Barriers for Plume Remediation

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- > 30 PRBs (> 1500 total projects)
- Only firm in North America with biopolymer slurry trenching, continuous trenching and soil mixing under one roof
- $50 to $70 M/year worldwide
- Bonding to $75M+ (aggregate)
- Own fleet of specialty equipment
- 200+ years senior staff experience
The Permeable ("Passive") Reactive Barrier

- Suggested, e.g., by McMurty and Elton [1985]
- Gillham and O'Hannesin Field Test (U of Waterloo: Borden) [1991]
- First full-scale: Sunnyvale, California [1995]
- Moffett Field, Dover Air Force Base (long-term monitoring sites) [1996/97]
- 40 to 50 PRBs in operation [2000]
- First PRB in Italy [2004]
- Deep soil mix BOSS-100 (impregnated carbon) at Vandenberg [2009]
- Over 200 in operation [2010]
- First multi-stage barrier in Australia [2010]
- ETI US ZVI Patent expires [2010]
- CH2M multi-trench for LNAPL (Brazil) [2014]
- Fenton et al.: nitrogen and phosphorous treatment [2014]
- 4th International Conference on Sustainable Remediation [2016]
### Contaminants of Concern

<table>
<thead>
<tr>
<th>Contaminants of Concern</th>
<th>ZVI</th>
<th>Biobarriers</th>
<th>Aquifer</th>
<th>Zeolite, SMZSlag (BOF), Metal Oxides</th>
<th>Apatite</th>
<th>GAC/PAC</th>
<th>Proprietary Carbons (ZVI/GAC)</th>
<th>Organophilic/modified clays</th>
<th>Transformed Red Mud</th>
<th>Calcite with CO$_2$ Injection</th>
<th>Limestone, lime, quicklime</th>
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<td>Chlorinated methanes, propanes</td>
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<td>Strontium-90</td>
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</table>

F - Full Scale; P - Pilot Scale; L - Benchtop/Laboratory Scale

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### NPV ($M$) vs. Time (years)

- **Break Even**
- **Pump and Treat**
- **7 Year PRB**
- **10 Year PRB**
- **15 Year PRB**
- **30 Year PRB**

(ITRC 1999)
More PRBs

Proven Long Term Performance

GSR

Cost Pressure

Widening Range of Contaminants

[Diagram of PRB systems with text]

Benner, 1995 – Nickel Rim (University of Waterloo)
\[ Z = PRB \text{ thickness} \]
\[ K = \text{hydraulic conductivity of the reactive media or zone (m/day)} \]
\[ i = \text{hydraulic gradient through the reactive media or zone} \]
\[ n = \text{porosity of the reactive media or zone} \]
\[ Ct = \text{contaminant concentration in solution at time t (mg/l)} \]
\[ Co = \text{influent concentration (mg/l)} \]
\[ k = \text{first-order rate constant (d}^{-1}) \]
\[ SF = \text{safety factor} \]
Above: Golder (2009) Sequential Sawdust/ZVI (Bellevue, Australia, w/ GSI);
Right: CH2M (2014) NAPL Skim & Polish (Brazil, w/GSI)

Trend #1: Sequential Barriers
Left: Penn (2011) - “PRI” using BOF for Phosphate; 

Trend #2: Low Energy Systems for Non-Point and Agricultural Pollution

The following conclusions were derived for the 68 PRBs where reviewable site data were readily available [2005]:

- 90% of the sites are reportedly meeting regulatory objectives
- 6% of the sites had hydraulic issues that have required system expansion (additional iron to address incomplete plume capture) or were related to construction artefacts
- 4% of the sites implemented pump and treat alternatives to ensure capture of the portion of the plume bypassing the PRB.

...To date, no ZVI PRB has required rejuvenation due to hydraulic plugging or loss of reactivity due to precipitate formation. In most environments, ZVI PRBs are expected to last at least 15 years before refurbishment or replacement is considered. However, for the 10% of the PRBs with relatively poor performance, it is apparent that hydraulic issues (rather than geochemical) have been the primary cause. Potential problems include unrecognised variability in plume dimensions, groundwater flow velocity and/or direction, and problems with PRB construction....

Causes of Failure:

(1) Incorrect or incomplete conceptual site model

(2) Improper construction
## Construction Methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Relative Mobilization Cost</th>
<th>Approx. Max. Depth (m)</th>
<th>Relative Cost</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct Placement</td>
<td>Low</td>
<td>6'</td>
<td>Very low</td>
<td>Wide (&gt;1.3 m), dewatering issues, safety, very depth limited</td>
</tr>
<tr>
<td>Trench Box</td>
<td>Low</td>
<td>6'</td>
<td>Low</td>
<td>Wide (&gt;1.3 m), dewatering issues, very depth limited</td>
</tr>
<tr>
<td>Sheet &amp; Shore</td>
<td>Medium</td>
<td>12</td>
<td>High</td>
<td>Slow, possible dewatering issues, smearing, vibrocompaction.</td>
</tr>
<tr>
<td>Caissons</td>
<td>Medium</td>
<td>&gt;12**</td>
<td>High</td>
<td>Slow, wastage in overlapping columns, smearing, vibrocompaction.</td>
</tr>
<tr>
<td>Continuous Trencher</td>
<td>High</td>
<td>12'</td>
<td>Moderate</td>
<td>Limited soil types, limited width, difficult to verify key.</td>
</tr>
<tr>
<td>Biopolymer Trench</td>
<td>Medium</td>
<td>&gt;25</td>
<td>Moderate</td>
<td>Slurry requires expert contractor, slower than trencher in shallow (&lt;12 m) sandy soil.</td>
</tr>
<tr>
<td>Hydrofracturing, Injections</td>
<td>Low/Medium</td>
<td>&gt;40</td>
<td>Low to Moderate</td>
<td>Gaps in coverage</td>
</tr>
<tr>
<td>Jetting/jet grouting</td>
<td>Low/Medium</td>
<td>30</td>
<td>Very High</td>
<td>Potential gaps in coverage</td>
</tr>
<tr>
<td>Soil Mixing</td>
<td>Very High</td>
<td>30</td>
<td>High</td>
<td>High cost</td>
</tr>
<tr>
<td>Mandrels, Vibrating Beams</td>
<td>Medium</td>
<td>30</td>
<td>Low to Moderate</td>
<td>Gaps in coverage, extremely thin (0.15 m), QA/QC difficult, Smearing, vibrocompaction. No spoils, though.</td>
</tr>
</tbody>
</table>

* Benching (digging down to create a work platform) extends depth
**Hypothetically, very large caissons and very large depths are possible. Most experience, however, is with caissons <2.5 m in diameter to depths < 12 m


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## Conventional Shoring

[Image of conventional shoring setup]
(Un)Conventional Shoring

Bio-Polymer Slurry Trenches

- Backhoe Excavates Trench
- Reactive Iron/Sand Mixture Added to Open Trench
- Biodegradable Slurry holds trench open
- Reactive Iron and Soil
- Bedrock

water table
Bio-Polymer Trenching
Soil Mixing

Mechanical Mixing
Jet Grouting

- Similar to soil mixing
- Soils are eroded and mixed by high pressure (400 bar) streams of fluid
  - Can go through slab, in between (steel, concrete) utilities, drill on angle
  - (Potentially) smaller rig
  - More expensive

Continuous Trenchers
- Extremely effective in shallow (<12 m) sandy soil
  - Production rates of 60 to 120 m per day are possible
- Box limits PRB installs with trenchers to shallow depths
  - 15 m claimed: 8 to 9 m is the common maximum
- Cut width is set by chain
  - Hypothetically 30 cm (12") to 1.2 m (claimed): generally 60 cm to 76 cm Built width is narrower
  - Box is narrower than cutting chain (nominal 76 cm trench is usually closer to 69 cm)
  - Up to 25% compression of width in situ observed (Puls et al. 1999: Elizabeth City, NC).
SRB for AMD
Falconbridge Nickel Rim Mine, Sudbury, ON (1995)

- U of Waterloo (Benner, Blowes, Ptacek, Waybrant)
- Mulch wall downgradient of tailings dam (in bedrock trench)
- Slightly acidic: pH 6 [iron oxidation not complete]
- High sulfate & iron – also nickel, zinc
- Water flowing through is net acid consuming
Modified from Benner et al. (1997)

Iron Oxidation
\[ \text{Fe}^{2+} + \frac{1}{4} \text{O}_2 + \frac{5}{2} \text{H}_2\text{O} \rightarrow \text{Fe(OH)}_3(s) + 2\text{H}^+ \]

Sulfate Reduction
\[ \text{SO}_4^{2-} + 2\text{CH}_2\text{O} \rightarrow \text{H}_2\text{S} + 2\text{HCO}_3^- \]

FeS + H₂S → FeS + 2H⁺

Sulfide Oxidation
\[ \text{FeS}_2(s) + 7/2\text{O}_2 + \text{H}_2\text{O} \rightarrow \text{Fe}^{2+} + 2\text{SO}_4^{2-} + 2\text{H}^+ \]

Benner et al. (1997)

Acid Generating Potential (meq/L)
- Sand: >2000
- Reactive material sands: 1500-2000
- 1000-1499
- 500-999
- <500

Sulfate (mg/L)
- >2000
- 1500-2000
- 1000-1499
- 500-999
- <500

Iron (mg/L)
- >350
- 250-350
- 150-249
- 50-149
- <50

Acid Generating Potential (meq/L)
- >20
- 10 - 20
- 0.0 - 10
- <10 - 0.0
- <10
Passive Non Aqueous Phase Liquid (NAPL) Physical Barrier
Binghamton, NY (2006)

- Design-Build (Arcadis: GSI as sub)
- Former Manufactured Gas Plant (MGP)
- 30 m from river, ~20 abandoned pipes & conduits
- Passive Dense and Light NAPL (DNAPL/LNAPL) collectors
- 2,800 m² biopolymer slurry trench
- Jet grouting under infrastructure (diversion barriers)
- Up to 17.4 m bgs

Permeable Absorbent Barrier (PAB)
Mogi das Cruzes, Brazil (2014)

- CH2M/GSI
- Replace multiphase extraction system
- Phthalate LNAPL
- Passive NAPL collection trench & sumps (116 m)
- Low permeability cement-bentonite slurry wing wall
- Organoclay/activated carbon absorptive barrier for dissolved phase (4 m deep)
Two-Stage Permeable Reactive Barrier
Perth (Bellevue), Western Australia (2010)

- LandCorp; first biopolymer PRB in Australia (40% lower than next bid)
- Golder; Menard Oceania/GSI as contractor (GHD as superintendent)
- Multiple contaminants (incl. TCE, BTEX) entering Helena river after 2001 fire at waste treatment facility
- Two continuous 76 m long, 11 m deep reactive barriers
50% sand with 50% sawdust

Two mixes: 28% ZVI with 72% sand and 49% ZVI with 51% sand
Soil Mixed Carbon Permeable Barrier
Vandenberg AFB, CA (2009)

- AECOM/GSI
- Injection failed
- BOS-100 (iron impregnated carbon)/sand mix for TCE/DCE
- Bio-polymer slurry drilling fluid
- 30 m long, 21 m deep (max.)
- 2000 m² face area

High-Dose ZVI Soil Mixing (Barrier Repair)
Ripley TN (2016)

- GSI/USA Environment
- Hexavalent chromium plume at a plating facility.
- Fix an existing PRB, treat hot spots
- 437 m³ of soil with 191 tonnes ZVI (0.44 tonnes/m³) to 8 m.
Technical papers, case studies, specifications:

http://www.geo-solutions.com/technical-papers

Contact Us:

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Reference Repositories – PRBs

- Geo-Solutions On-line Library (8 hand-picked PRB papers, including geotechnical guidance):
  - http://www.geo-solutions.com/technical-reactive-barriers
- Interstate Technology and Regulatory Council (ITRC):
    (This site includes links to recordings of previous ITRC training!)
- US EPA’s Contaminated Site Clean-Up Information (Clu-in.org):
- Remediation Technologies Development Forum (RTDF) Permeable Reactive Barriers Action Team (references through 2009 only):
Selected References – PRBs


Report No. 25. CRC for Contamination Assessment and Remediation of the Environment, Newcastle, Australia.

Selected References – PRBs


