LECTURE 8

SOURCE CONTROL AND MANAGEMENT OF MIGRATION
Classes of Site Remediation

Source control
Technologies to contain or treat sources of contamination (wastes or contaminated soil)

Management of migration
Technologies to control the movement of contaminants away from sources (usually in ground water)
Cover systems ("caps")

Prevent physical contact and exposure to waste
  Sufficient cap may be enough thickness of soil to prevent humans or animals from digging into waste

Reduce (or almost eliminate) precipitation infiltration
  Reduces/prevents transport of contaminants to ground water by infiltrating water
Landfill Cover Layers


Cap layers: Vegetation

Purposes:
- Erosion control
- Infiltration reduction by evapotranspiration

Characteristics:
- Shallow rooted plants
- Low nutrient needs
- Drought and heat resistant

Cap layers: soil layer

Purposes:
- Support vegetation
- Protect underlying layers

Typically 60-cm thick

Crushed stone or cobbles may substitute in arid environments

Cap layers: Protection layer

Also called “biotic barrier”

90-cm layer of cobbles to stop burrowing animals and deep roots
Not always included

Cap layers: Filter layer

Prevents clogging of drainage layer by fines from soil layer

May be geosynthetic filter fabric or 30-cm sand

Cap layers: Drainage layer

Minimizes contact between infiltrated water and low K layers below
Prevents ponding of water on geomembrane liner
Drains by gravity to toe drains
At least 30 cm of sand with $K = 10^{-2}$ cm/sec or equivalent geosynthetic

Cap layers: Low K layer

“Composite liner”: both geomembrane and low-K soil (clay)

Low K prevents infiltration of water into waste: hydraulic barrier

Geomembrane: at least 0.5 mm (20-mil) thick

Compacted clay: at least 60 cm with $K \leq 10^{-7}$ cm/s

Cap layers: Gas vent layer

Needed if waste will generate methane (explosive) or toxic gas
Similar to drainage layer: 30 cm of sand or equivalent geosynthetic
Connected to horizontal venting pipes (minimal number to maintain cap integrity)

Why a composite liner?

Geomembrane (or FML – flexible membrane liner)

Impervious for practical purposes except at holes, tears, imperfectly sealed seams

With good construction QA/QC (quality assurance/quality control), FML has one hole per acre (one hole per 0.4 hectare)
Why a composite liner?

Compacted clay liner
  Provides hydraulic and diffusional barrier at holes or breaks

Composite liner provides far more effective barrier than either FML or clay alone
What’s wrong with this picture?

Drainage layer between FML and clay removes the advantage of composite liner !!!
If clay is saturated and water is ponded to depth $h$: hydraulic gradient, $i$, through clay is:

$$i = \frac{h + D}{D} > 1$$

$$Q = K_i A$$

or, $q = K_i$

Flow through clay liner

Flow through 90-cm clay liner due to 30-cm head

<table>
<thead>
<tr>
<th>Liner quality</th>
<th>K (cm/s)</th>
<th>Rate of flow (gal/ac/day)</th>
<th>Rate of flow (L/ha/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poor</td>
<td>$1 \times 10^{-6}$</td>
<td>1,200</td>
<td>11,000</td>
</tr>
<tr>
<td>Good</td>
<td>$1 \times 10^{-7}$</td>
<td>120</td>
<td>1,100</td>
</tr>
<tr>
<td>Excellent</td>
<td>$1 \times 10^{-8}$</td>
<td>12</td>
<td>110</td>
</tr>
</tbody>
</table>
Flow through hole in FML

Orifice equation:

\[ Q = C_B a (2gh)^{0.5} \]

\[ C_B = \text{orifice coefficient} \approx 0.6 \]

\[ a = \text{hole area} \]
## Flow through FML

<table>
<thead>
<tr>
<th>Liner quality</th>
<th>Holes per acre</th>
<th>Rate of flow (gal/ac/day)</th>
<th>Rate of flow (L/ha/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poor</td>
<td>30 @ 0.1 cm²</td>
<td>10,000</td>
<td>93,000</td>
</tr>
<tr>
<td>Poor</td>
<td>1 @ 1 cm²</td>
<td>3,300</td>
<td>31,000</td>
</tr>
<tr>
<td>Good</td>
<td>1 @ 0.1 cm²</td>
<td>330</td>
<td>3,100</td>
</tr>
<tr>
<td>Excellent</td>
<td>none</td>
<td>0.01*</td>
<td>0.1</td>
</tr>
</tbody>
</table>

* flow due to vapor transport
Flow through composite liner

Empirical formula by Giroud et al.:

\[ Q = Ch^{0.9}a^{0.1}K^{0.74} \]

where: 
- \( C = 1.15 \) for poor seal between FML and clay
- \( C = 0.21 \) for good seal

h in meters, a in \( m^2 \), K in m/s, and Q in \( m^3/s \)

Equation assumes \( i = 1 \)
References for liner leakage formulas:


See also summary in course reader:

### Flow through composite liner

<table>
<thead>
<tr>
<th>Liner quality</th>
<th>Holes per acre</th>
<th>Rate through FML liner (gal/ac/day)</th>
<th>Flow through composite* (gal/ac/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poor</td>
<td>30 @ 0.1 cm²</td>
<td>10,000</td>
<td>19</td>
</tr>
<tr>
<td>Poor</td>
<td>1 @ 1 cm²</td>
<td>3,300</td>
<td>0.8</td>
</tr>
<tr>
<td>Good</td>
<td>1 @ 0.1 cm²</td>
<td>330</td>
<td>0.6</td>
</tr>
</tbody>
</table>

* with 60-cm clay liner with K = 10^{-7} cm/sec
### Flow through liners

<table>
<thead>
<tr>
<th>Liner quality and type</th>
<th>Holes per acre</th>
<th>Rate of flow (gal/ac/day)</th>
<th>Rate of flow (L/ha/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good FML</td>
<td>1 @ 0.1 cm²</td>
<td>330</td>
<td>3,100</td>
</tr>
<tr>
<td>Excellent clay</td>
<td>1 x 10⁻⁸</td>
<td>12</td>
<td>110</td>
</tr>
<tr>
<td>Poor composite</td>
<td>30 @ 0.1 cm²</td>
<td>19</td>
<td>180</td>
</tr>
<tr>
<td>Poor composite</td>
<td>1 @ 1 cm²</td>
<td>0.8</td>
<td>7</td>
</tr>
<tr>
<td>Excellent FML</td>
<td>none</td>
<td>0.01</td>
<td>0.1</td>
</tr>
</tbody>
</table>
Observations on composite liners

Composite liner (even poor quality) is significantly better than soil or FML alone

Seal between FML and clay is important:
  Ensure FML is wrinkle-free
  Ensure clay is rolled smooth
  Ensure clay is free of stones, etc.

Clay is “self-healing” to some extent
Capping as remedial action

Preferred remedial action for:
landfills, widespread soil contaminants

Approximate costs:
$175,000 per acre for non-hazardous waste
$225,000 per acre for hazardous waste

(per Federal Remediation Technologies Roundtable)
Geomembrane and Geosynthentic

Liner Installation


Vertical cut-off walls

Technologies include:
- Grout curtains
- Geomembranes installed vertically
- In-situ soil mixing
- Sheet-pile walls
- Slurry walls
Slurry walls

Most common cut-off wall technology

Possible materials include:

- Soil and bentonite clay (SB)
- Cement-bentonite (CB)
- Pozzolanic materials
Slurry Wall Construction

Extended Backhoe for Slurry Walls

Clamshell Bucket for Deep Walls

Clamshell Bucket

See image at the Web site of the Massachusetts Turnpike Authority, Central Artery/Tunnel Project.
Hydromill for Deepest Slurry Walls

See image at the Web site of the Massachusetts Turnpike Authority, Central Artery/Tunnel Project.
Slurry wall construction

Typical vertical section for slurry wall

- Cap
- Slurry wall keyed into "floor"
- Confining bed or bedrock
- Waste
Alternative vertical section for “hanging” slurry wall for LNAPLs

LNAPL

Hanging slurry wall

Confining bed or bedrock at depth
Alternative horizontal plans

Slurry wall encircles and isolates waste

Slurry wall delays eventual migration

Ground-water flow
Soil mechanics of slurry walls

During construction, wall stability maintained by higher head in trench than in ground water:

\[ \rho_{\text{water}} = 1.0 \, \text{g/cm}^3 \]

\[ \rho_{\text{slurry}} \geq 1.02 \, \text{g/cm}^3 \]

"filter cake" on trench walls

Slurry density should be 0.25 g/cm³ lighter than emplaced backfill.
Permeability of slurry walls

Materials for slurry walls

SB (soil-bentonite) have lower K, are less expensive
   Typical K = $10^{-7}$ cm/sec
   Reported K’s as low as $5 \times 10^{-9}$ cm/sec

CB (cement-bentonite) have greater shear strength, lower compressibility
   Use on slopes where strength is important
   Use in areas where appropriate soils (for SB) are not available
Materials for slurry walls

Additives to enhance CB and SB:
  Fly ash to increase carbon for adsorption
  Liners or sheet pile installed within wall to decrease K

Other necessary material: $$$
  Approximate costs (from FRTR web site):
  $540 to $750 per m² (1991 dollars)
Slurry wall performance

Performance has been mixed:
  - Slurry walls leak
  - Construction can be difficult
  - Waste may compromise wall
  - Requires long-term pumping in slurry wall enclosures

Slurry walls are good barriers to advection, but not to diffusion!
EPA review of slurry wall success

Reviewed 130 sites – 36 had adequate data:

8 of 36 met remedial objective
4 met objective except not yet for long term
13 appear to have met objective
4 appear not to have met objective
7 are uncertain

4 of 36 leaked and required repairs
(leaks most often at “key” with floor)

Potential sources of failure (leaks)

Construction:
- Improperly mixed backfill (CB, SB)
- Sloughing or spalling of soils into trench
- Inadequate bottom excavation for wall key

Post-construction:
- Wall properties changed by freeze-thaw cycles
- Wet-dry cycles due to water table fluctuation
- Degradation due to contact with chemicals

Interlocking Sheet Piles

Sheet Pile Installation

Sheet Pile Grouting

Grout curtains

Subsurface emplacement of grout to form containment

Installation methods:

Jet grouting – inject grout into soil, mixing soil and grout
Pressure grouting – forces grout into fractures in rock
Deep-soil mixing – grout-bentonite slurry mixed into soils to create wall
Grouting methods

Schematic Showing Different Grouting Techniques

Penetration (Intrusion)
Penetration (Permeation)
Displacement (Compaction Grouting)
Jet Grouting (Displacement, Replacement)

Grouting patterns

Drilling Pattern

Primary

Secondary

Completed Overlapping and Complete Treatment

Primary and Secondary overlapping patterns for in-situ soil mixing processes
[Geo-Con, Inc., 1990].

Grout materials

Solid suspensions:
  Clay, bentonite, cement, and combinations

Chemical grouts:
  Silica- or aluminum-based solutions
  Polymers
Solidification/stabilization (S/S)

Solidification: encapsulation of waste in cement or other monolithic material
Stabilization: mixing of stabilizer with waste so as to alter the chemistry of the waste and make it less toxic, less soluble, and/or less mobile (does not necessarily alter physical character of waste)
Used both in-situ and ex-situ – ex-situ is most common
S/S is second most common source-control technology at Superfund sites

<table>
<thead>
<tr>
<th>Technology</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil vapor extraction</td>
<td>28%</td>
</tr>
<tr>
<td>Solidification/stabilization (in-situ and ex-situ)</td>
<td>24%</td>
</tr>
<tr>
<td>Offsite incineration</td>
<td>13%</td>
</tr>
<tr>
<td>Bioremediation</td>
<td>11%</td>
</tr>
<tr>
<td>Thermal desorption</td>
<td>9%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Category</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metals only</td>
<td>56%</td>
</tr>
<tr>
<td>Organics only</td>
<td>6%</td>
</tr>
<tr>
<td>Metals and organics</td>
<td>31%</td>
</tr>
<tr>
<td>Radioactive wastes</td>
<td>5%</td>
</tr>
<tr>
<td>Nonmetals with and without organics</td>
<td>2%</td>
</tr>
</tbody>
</table>

S/S agents

Organic agents:
  Urea formaldehyde, polyethylene, bitumen, asphalt

Inorganic agents:
  Cement
  Lime
  Pozzolans
  Proprietary mixtures and additives ($$$

Select agents by bench-scale testing
Pozzolans

Pozzolan = alumino-silicate minerals that form cements when combined with lime and water
Reaction generates heat
Examples:
- Volcanic pumice (pozzolana)
- Kiln dust
- Fly ash
Inorganic agents

More commonly used than organic agents
Used on:
  heavy metals, soils, sludges, radioactive waste
Possible interferences from:
  oil and grease, surfactants, chelating agents
Not likely to be effective with volatile organics
PCBs can be stabilized
  (volatilization may be biggest removal factor)
Soliditech Ex-situ S/S Process

Ex-Situ Stabilization in Pug Mill

Screening soil prior to mixing in pug mill

Ex-Situ Stabilization in Pug Mill


**In-situ methods**

Shallow soil mixing – to about 10 meters deep
- Cost: ~$50-80/m³ (per FRTR)
- Backhoes can be used for small projects, shallow soil

Deep soil mixing
- Cost: ~$190-300/m³
- Vacuum hoods may be needed to control vapor and dust

Volume increase is typically about 15%
Shallow Soil Mixing
Large Diameter Auger for Soil Mixing

See image at Web site of Cobb County Government, Little Nancy Creek Interceptor, Chattahoochee Tunnel Project, Cobb County Water System. Marietta, GA.
http://www.chattahoocheetunnel.com/ln.htm
Soil Mixing Machine for Deep Soil Mixing

Deep Soil Mixer

**In-situ vitrification**

Formation of glass to encase waste

Rarely used – most use at radioactive waste sites

Cost at one Superfund site:

$350/m^3$ (cost varies with cost of electricity)

(Parsons Chemical/ETM Enterprises Site, Grand Ledge, Michigan)

Source: Federal Remediation and Technologies Roundtable
In-situ vitrification process

Install surface electrodes
Pass high electrical current through starter path of graphite and glass frit
Starter path and then soils start to melt at 1600 to 2000°C
Electrodes advanced through soil as molten mass enlarges
Can melt about 1000 tons of soil per melt
Melted soil hardens into monolithic, chemically inert vitreous slag
Chemical containment

Metal containment via chemical containment with organosulfur compound
Marketed as MRC – Metals Remediation Compound
Chemical first binds to metals
Organic portion is then biodegraded leaving metal sulfide precipitate

Decreases in dissolved arsenic, chromium and copper concentrations during aquifer simulation vessel (ASV) experiments. Data are average metal concentrations over all ports (left).