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)

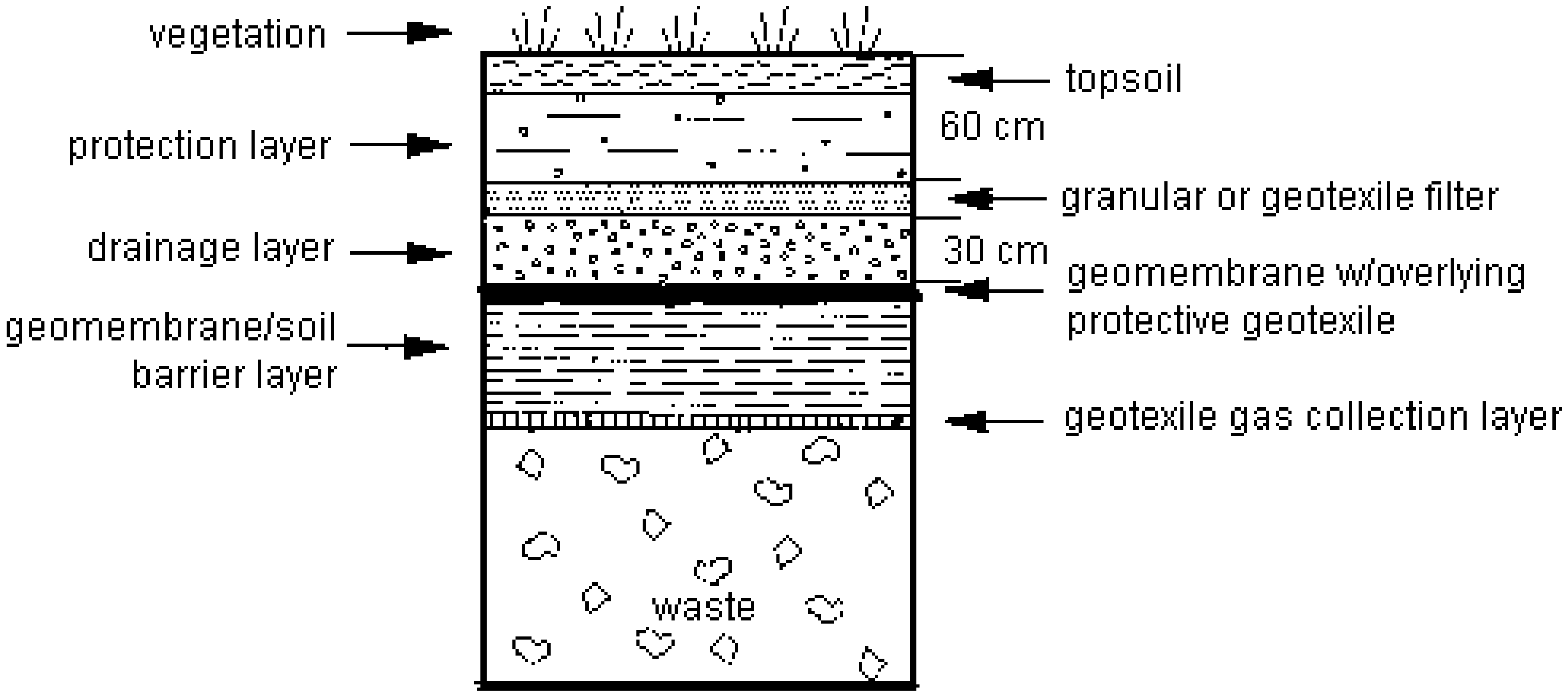
Management of migration

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



Source: Federal Remediation and Technologies Roundtable, February 12, 2003. 4.30 Landfill Cap (Soil Containment Remediation Technology).

Federal Remediation and Technologies Roundtable, February 12, 2003. 4.30 Landfill Cap (Soil Containment Remediation Technology). http://www.frtr.gov/matrix2/section4/4_30.html. Accessed February 26, 2003.

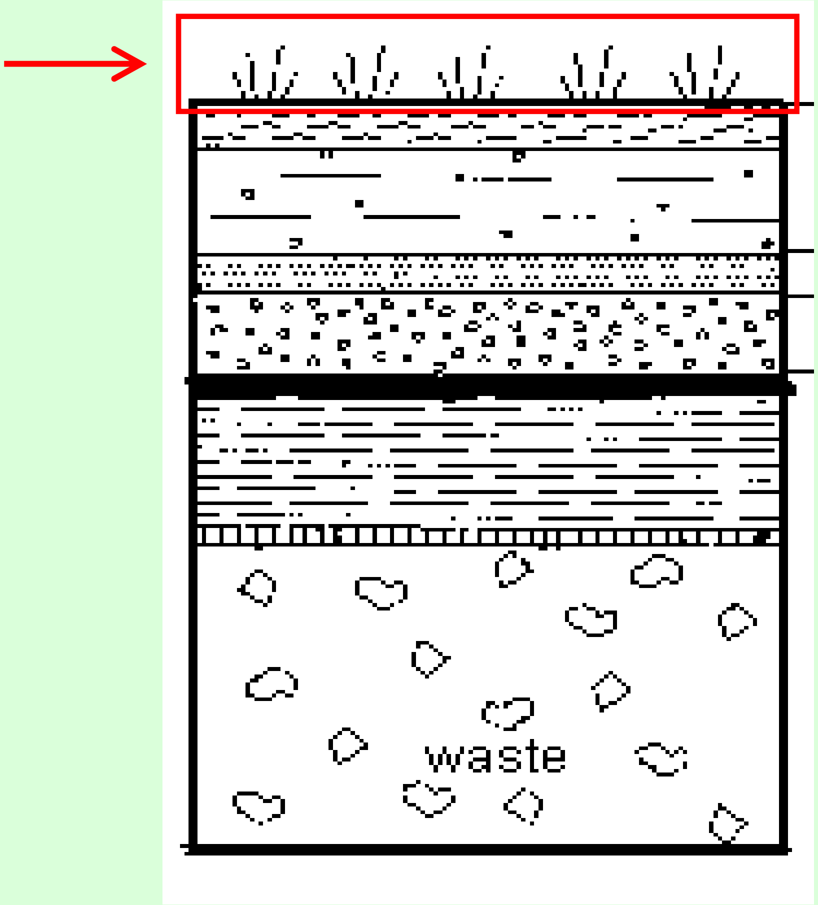
Cap layers: Vegetation

Purposes:

- Erosion control
- Infiltration reduction by evapotranspiration

Characteristics:

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



Source: Federal Remediation and Technologies Roundtable, February 12, 2003. 4.30 Landfill Cap (Soil Containment Remediation Technology).

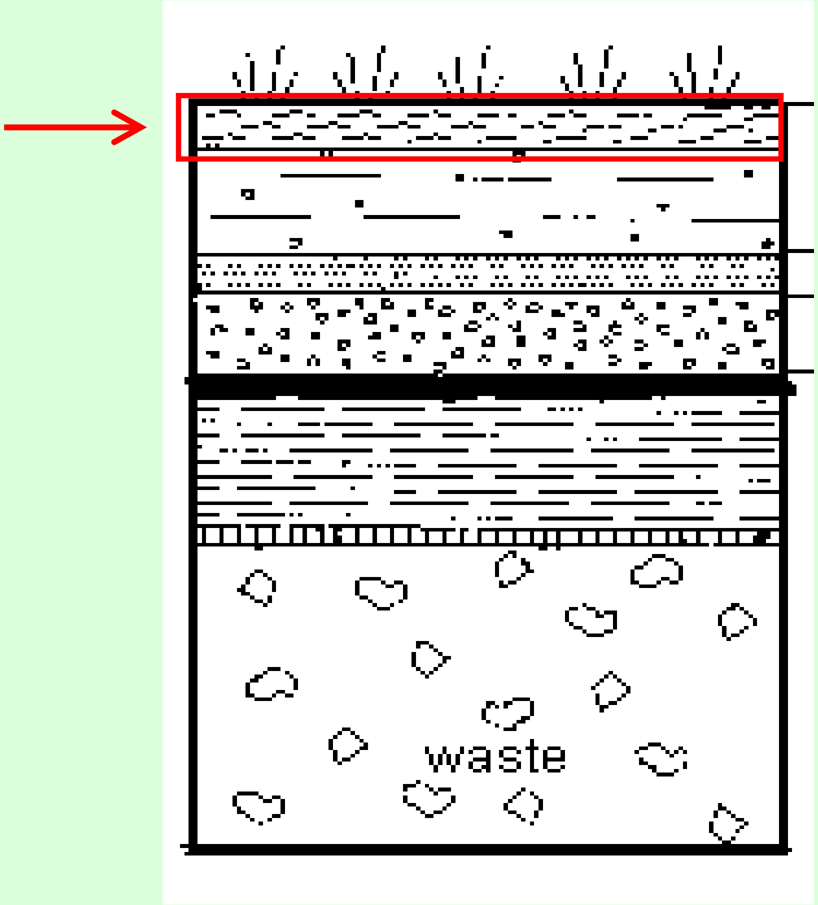
Cap layers: soil layer

Purposes:

- Support vegetation
- Protect underlying layers

Typically 60-cm thick

Crushed stone or cobbles may substitute in arid environments



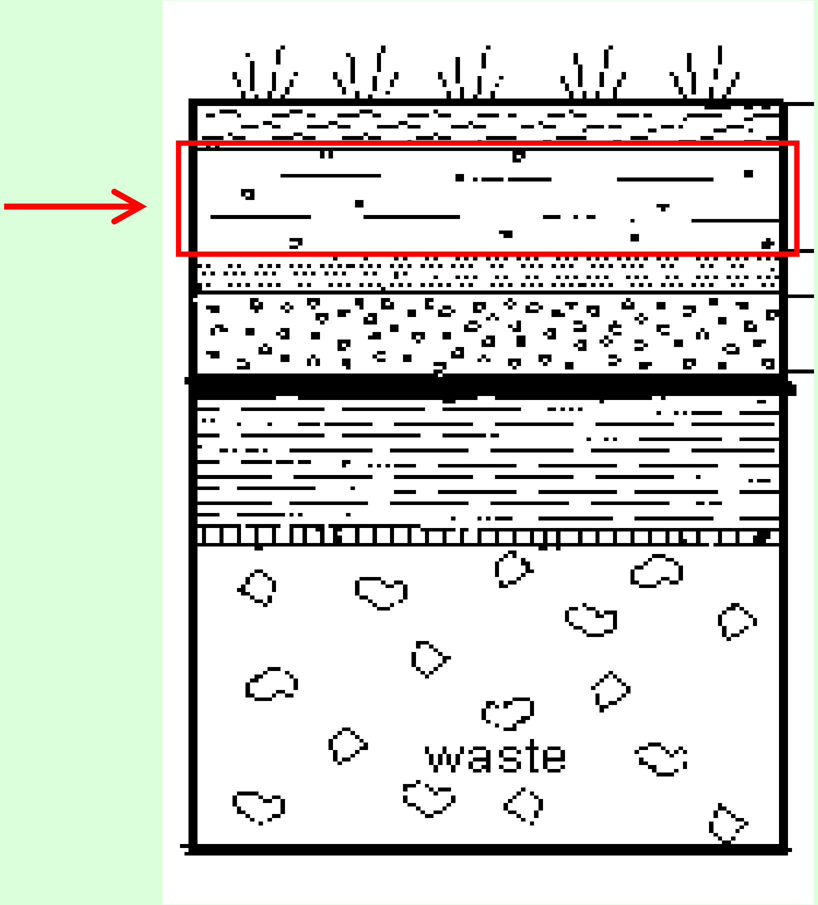
Source: Federal Remediation and Technologies Roundtable, February 12, 2003. 4.30 Landfill Cap (Soil Containment Remediation Technology).

Cap layers: Protection layer

Also called "biotic barrier"

90-cm layer of cobbles to stop burrowing animals and deep roots

Not always included

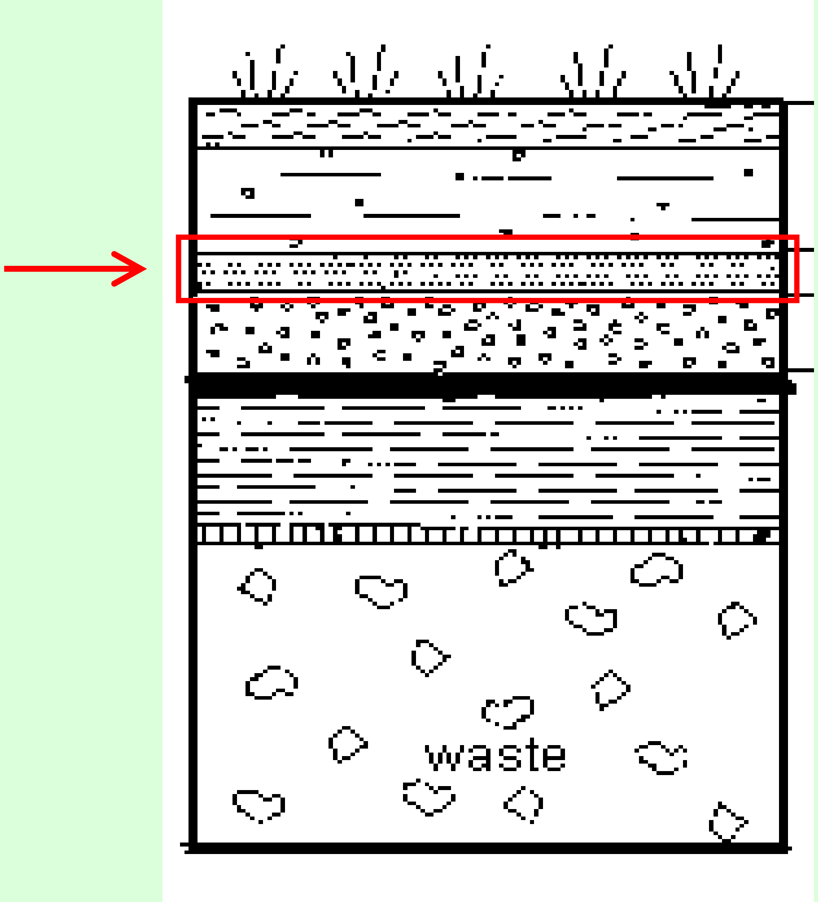


Source: Federal Remediation and Technologies Roundtable, February 12, 2003. 4.30 Landfill Cap (Soil Containment Remediation Technology).

Cap layers: Filter layer

Prevents clogging of drainage layer by fines from soil layer

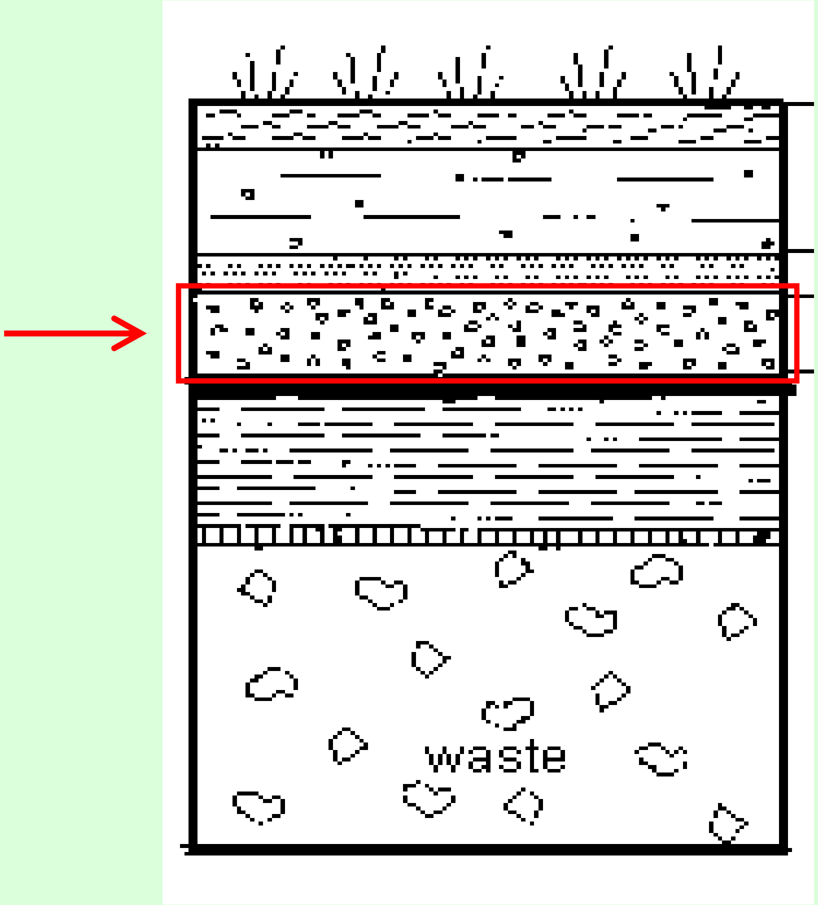
May be geosynthetic filter fabric or 30-cm sand



Source: Federal Remediation and Technologies Roundtable, February 12, 2003. 4.30 Landfill Cap (Soil Containment Remediation Technology).

Cap layers: Drainage layer

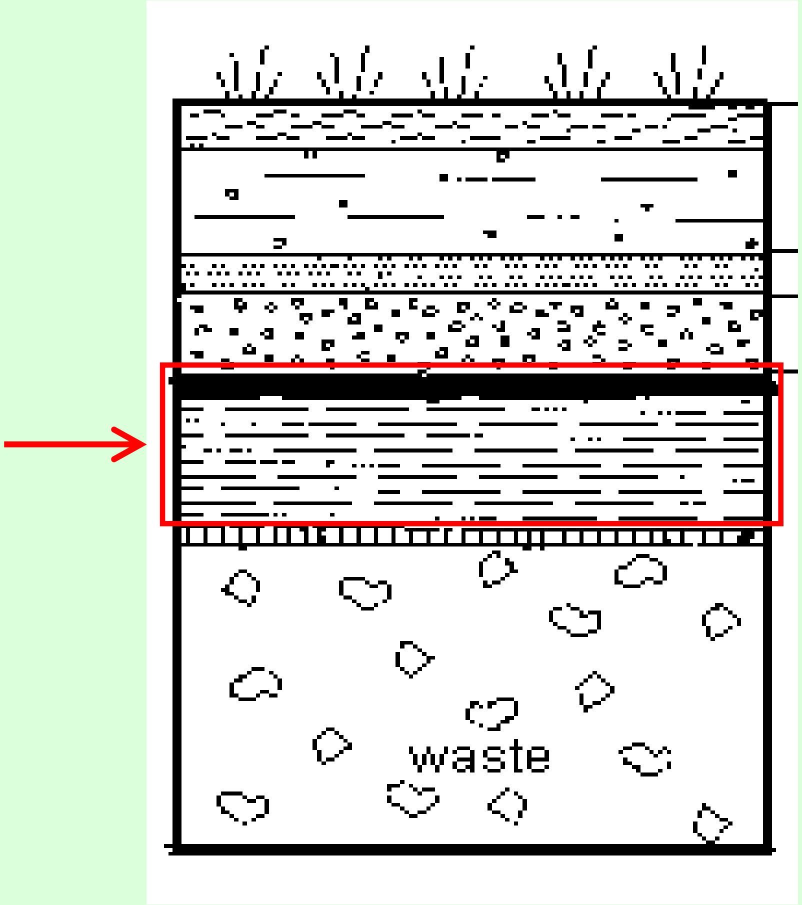
- Minimizes contact between infiltrated water and low K layers below
- Prevents ponding of water on geomembrane liner
- Drains by gravity to toe drains
- At least 30 cm of sand with $K = 10^{-2}$ cm/sec or equivalent geosynthetic



Source: Federal Remediation and Technologies Roundtable, February 12, 2003. 4.30 Landfill Cap (Soil Containment Remediation Technology).

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 ≤ 10^{-7} cm/s



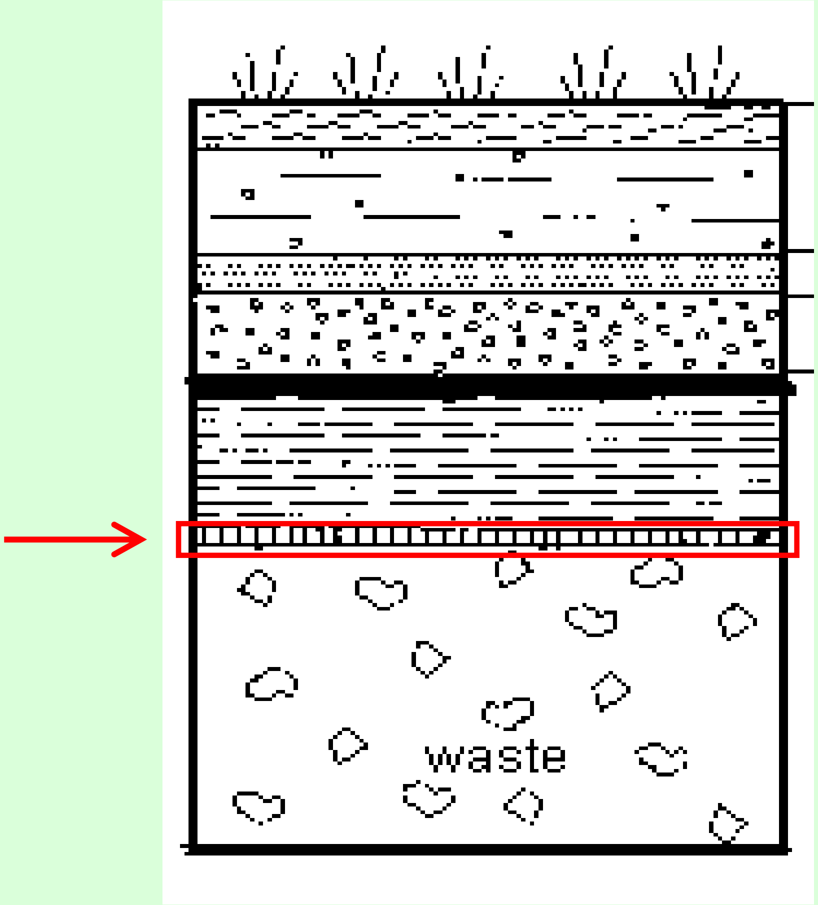
Source: Federal Remediation and Technologies Roundtable, February 12, 2003. 4.30 Landfill Cap (Soil Containment Remediation Technology).

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)



Source: Federal Remediation and Technologies Roundtable, February 12, 2003. 4.30 Landfill Cap (Soil Containment Remediation Technology).

Why a composite liner?

Geomembrane (or FML – flexible membrane liner)

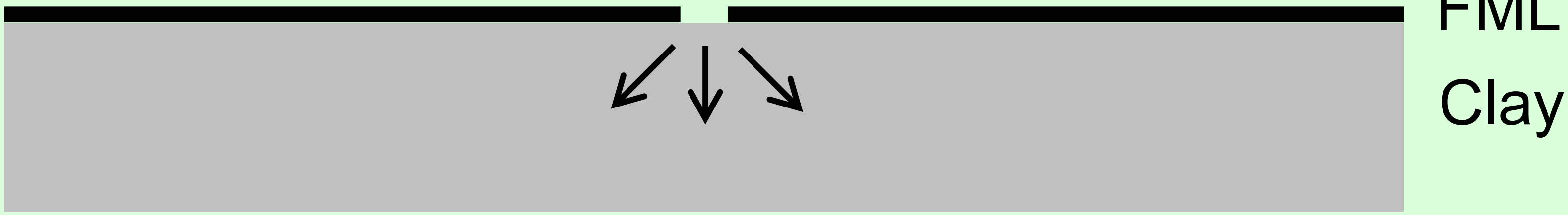
Impervious for practical purposes <u>except</u> at holes, tears, imperfectly sealed seams

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?

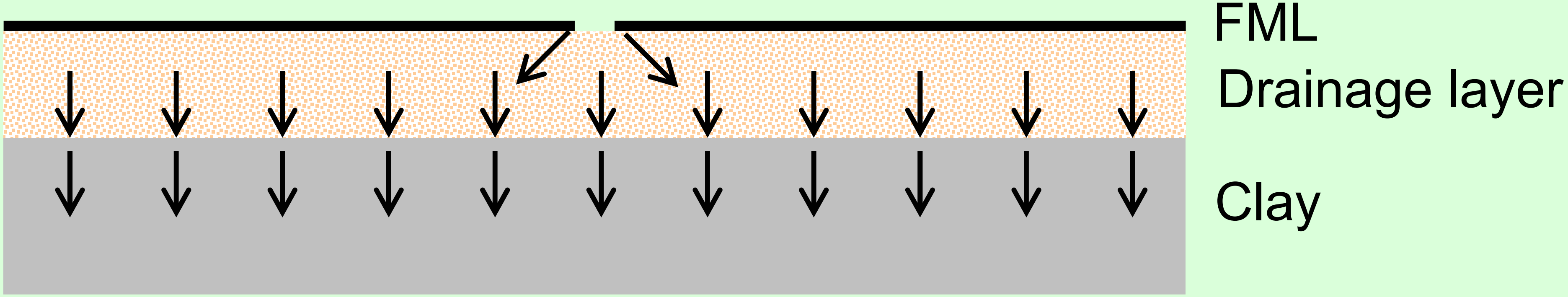
Compacted clay liner

- 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 !!!

Flow through clay liner

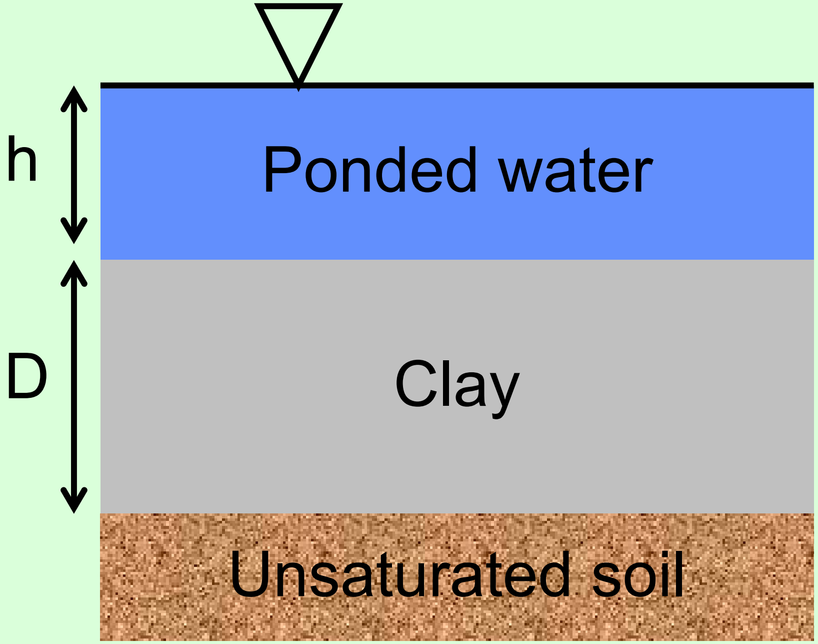
If clay is saturated and water is ponded to depth h:

hydraulic gradient, i, through clay is:

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

$$\mathbf{Q} = \mathbf{KiA}$$

$$\mathbf{or,\ q} = \mathbf{Ki}$$



Source for this and next several slides on flow through liners: U.S. EPA, 1991. Design and Construction of RCRA/CERCLA Final Covers. Report Number EPA/625/4-91/025. U.S. Environmental Protection Agency, Cincinnati, Ohio. May 1991.

Flow through clay liner

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

Liner quality	K (cm/s)	Rate of flow (gal/ac/day)	Rate of flow (L/ha/day)
Poor	1×10^{-6}	1,200	11,000
Good	1×10^{-7}	120	1,100
Excellent	1×10^{-8}	12	110

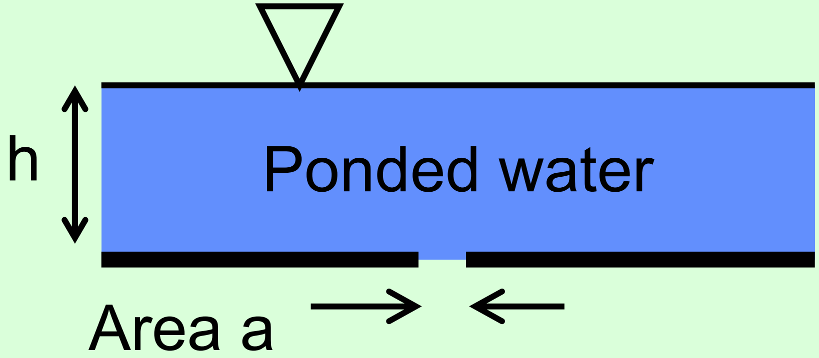
Flow through hole in FML

Orifice equation:

$$\mathbf{Q = C_B a \left(2gh\right)^{0.5}}$$

$$\mathbf{C_B = orifice\ coefficient \approx 0.6}$$

$$\mathbf{a = hole\ area}$$



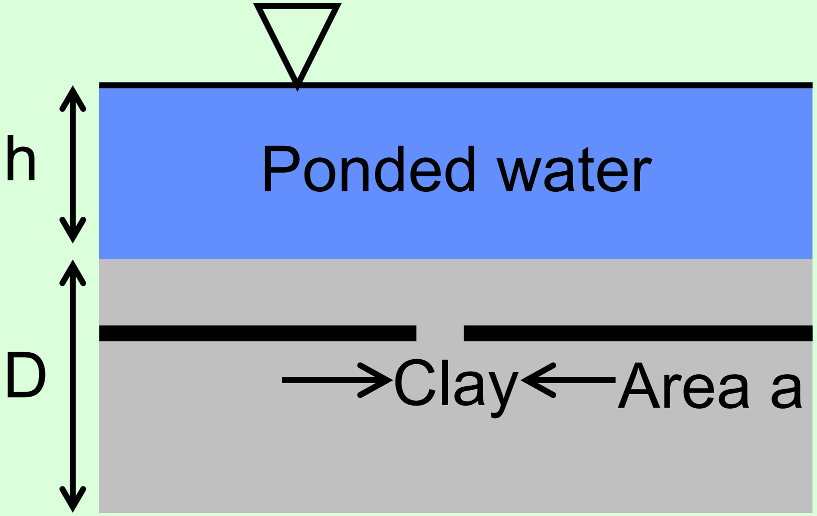
Flow through FML

Liner quality	Holes per acre	Rate of flow (gal/ac/day)	Rate of flow (L/ha/day)
Poor	30 @ 0.1 cm^2	10,000	93,000
Poor	1 @ 1 cm^2	3,300	31,000
Good	1 @ 0.1 cm^2	330	3,100
Excellent	none	0.01*	0.1

* flow due to vapor transport

Flow through composite liner

Empirical formula by Giroud et al.:



$$\mathbf{Q = Ch^{0.9}a^{0.1}K^{0.74}}$$

where: C = 1.15 for poor seal between FML and clay

= 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:

Giroud, J. P., and R. Bonaparte, 1989. Leakage through Liners Constructed with Geomembranes--Part I. Geomembrane Liners. *Geotextiles and Geomembranes*. Vol. 8, No. 1, Pg. 27-67.

Giroud, J. P., and R. Bonaparte, 1989. Leakage through Liners Constructed with Geomembranes--Part II. Composite Liners. *Geotextiles and Geomembranes*. Vol. 8, No. 2, Pg. 71-111.

Giroud, J. P., and R. Bonaparte, 1989. Technical Note: Evaluation of the Rate of Leakage Through Composite Liners. *Geotextiles and Geomembranes*. Vol. 8, No. 4, Pg. 337-340.

See also summary in course reader:
U.S. EPA, 1991. Design and Construction of RCRA/CERCLA Final Covers. Report Number EPA/625/4-91/025. U.S. Environmental Protection Agency, Cincinnati, Ohio. May 1991.

Flow through composite liner

Liner quality	Holes per acre	Rate through FML liner (gal/ac/day)	Flow through composite* (gal/ac/day)
Poor	30 @ 0.1 cm^2	10,000	19
Poor	1 @ 1 cm^2	3,300	0.8
Good	1 @ 0.1 cm^2	330	0.6

* with 60-cm clay liner with $K = 10^{-7}$ cm/sec

Flow through liners

Liner quality and type	Holes per acre	Rate of flow (gal/ac/day)	Rate of flow (L/ha/day)
Good FML	1 @ 0.1 cm^2	330	3,100
Excellent clay	1 x 10^{-8}	12	110
Poor composite	30 @ 0.1 cm^2	19	180
Poor composite	1 @ 1 cm^2	0.8	7
Excellent FML	none	0.01	0.1

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 Geosynthetic

Source: Fernald Environmental Management Project, undated. On Site Disposal Facility (OSDF), August 2002 Photo Tour. Fernald Environmental Management Project. Fernald, OH. http://www.fernald.gov/VImages/PhotoTour/2002/Aug02/pages/6319-D3684.htm. Accessed February 26, 2003.

Liner Installation

Source: Fernald Environmental Management Project, undated. On Site Disposal Facility (OSDF), October 2002 Photo Tour. Fernald Environmental Management Project. Fernald, OH. http://www.fernald.gov/VImages/PhotoTour/2002/Oct02/pages/6319-D3796.htm. Accessed May 11, 2004.

Yack, Joe and E.J. O'Neill. June 7, 1998. Protective Liner Uses and Application. Groundwater Pollution Primer, CE 4594: Soil and Groundwater Pollution, Civil Engineering Department, Virginia Tech. Blacksburg, VA. http://www.cee.vt.edu/program_areas/environmental/teach/gwprimer/landfill/liner.html. Accessed February 25, 2003.

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

See image at the Web site of the Seattle Daily Journal, “From wood preservation to site remediation — the Cascade Pole cleanup. Environmental Outlook 2001.” http://www.djc.com/news/enviro/11123736.html.

Accessed May 11, 2004.

Extended Backhoe for Slurry Walls

Source: U.S. Department of the Interior: Bureau of Reclamation, February 21, 2003. Site #8 Bradbury Dam. U.S. Department of the Interior: Bureau of Reclamation, Mid-Pacific Region. Sacramento, CA. http://www.mp.usbr.gov/mpco/showcase/bradbury.html. Accessed February 23, 2003.

Clamshell Bucket for Deep Walls

See image at the Web site of the Massachusetts Turnpike Authority, Central Artery/Tunnel Project. http://www.bigdig.com/thtml/gw_sw.htm. Accessed May 11, 2004.

Clamshell Bucket

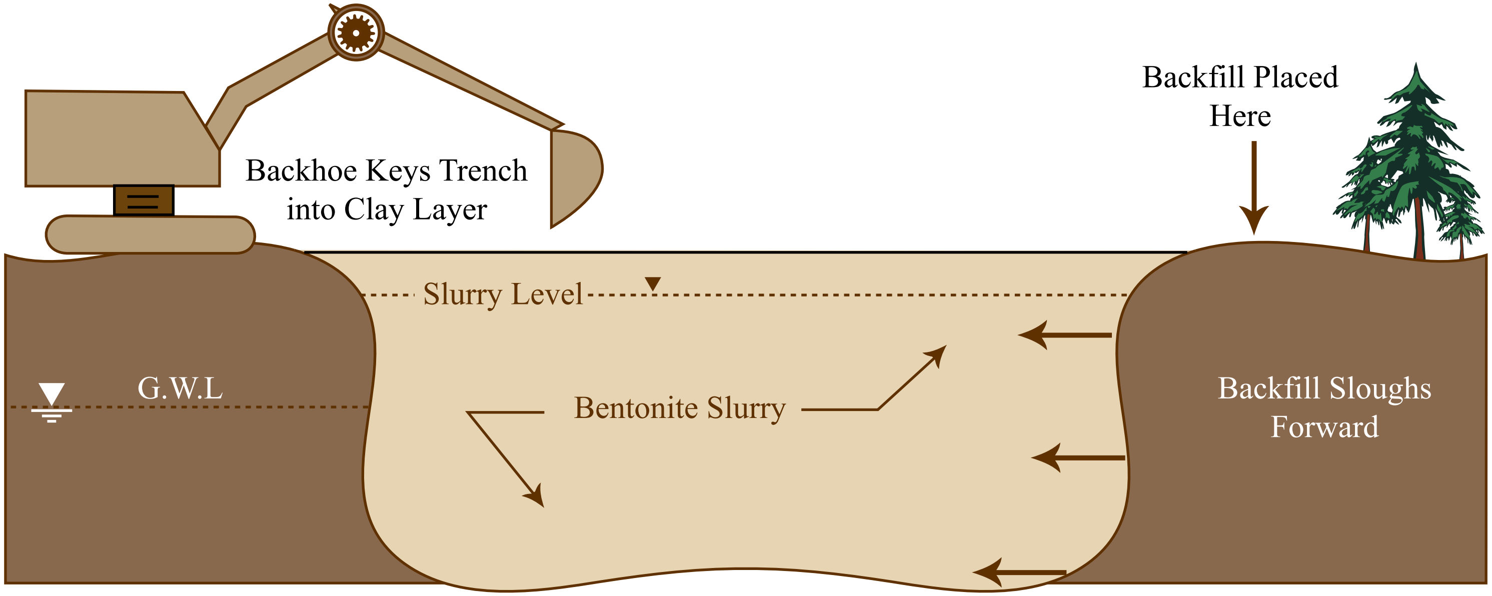
See image at the Web site of the Massachusetts Turnpike Authority, Central Artery/Tunnel Project. http://www.bigdig.com/thtml/gw_sw.htm. Accessed May 11, 2004.

Hydromill for Deepest Slurry Walls

See image at the Web site of the Massachusetts Turnpike Authority, Central Artery/Tunnel Project. http://www.bigdig.com/thtml/gw_sw.htm. Accessed May 11, 2004.

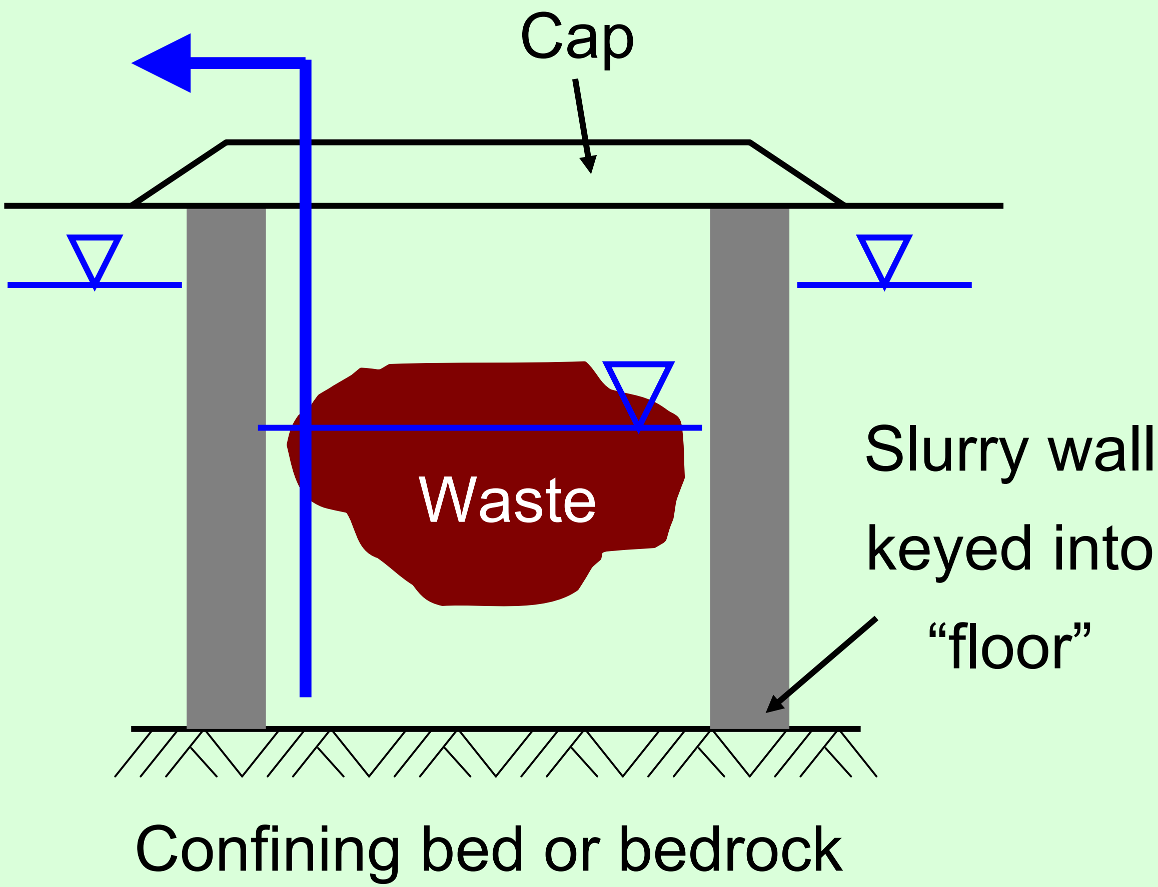
Slurry wall construction

Schematic of SB Slurry Wall Installation Process

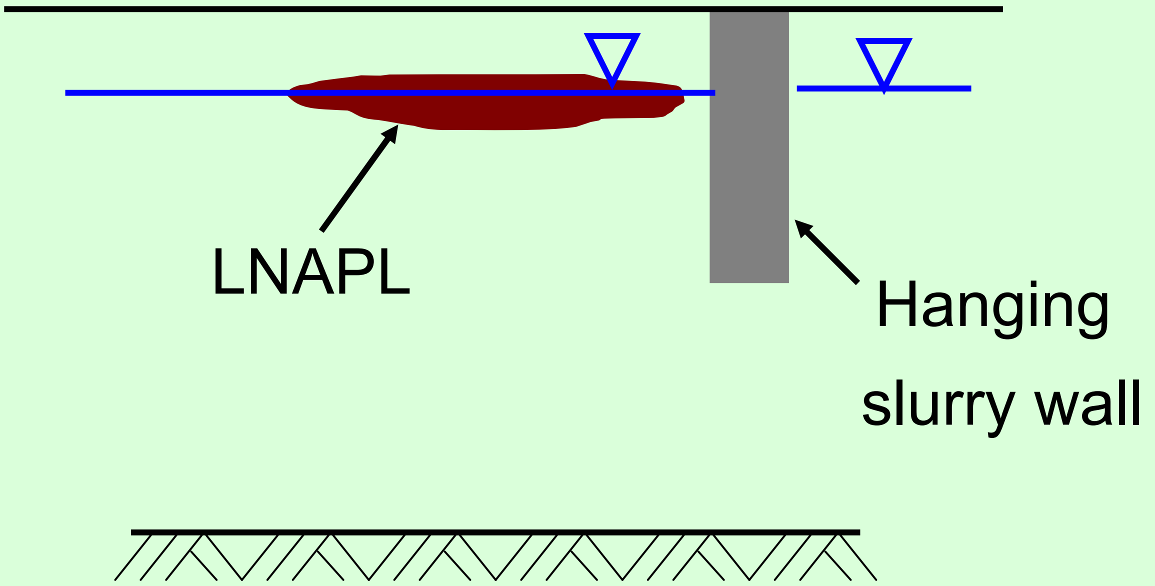


Adapted from: Grubb, D. G. and N. Sitar. "Evaluation of Technologies for In-situ Cleanup of DNAPL Contaminated Sites." Report Number EPA/600/R-94/120. NTIS Number PB94-195039. R.S. Kerr Environmental Research Laboratory, U.S. Environmental Protection Agency, Ada, Oklahoma, August 1994.

Typical vertical section for slurry wall



Alternative vertical section for "hanging" slurry wall for LNAPLS

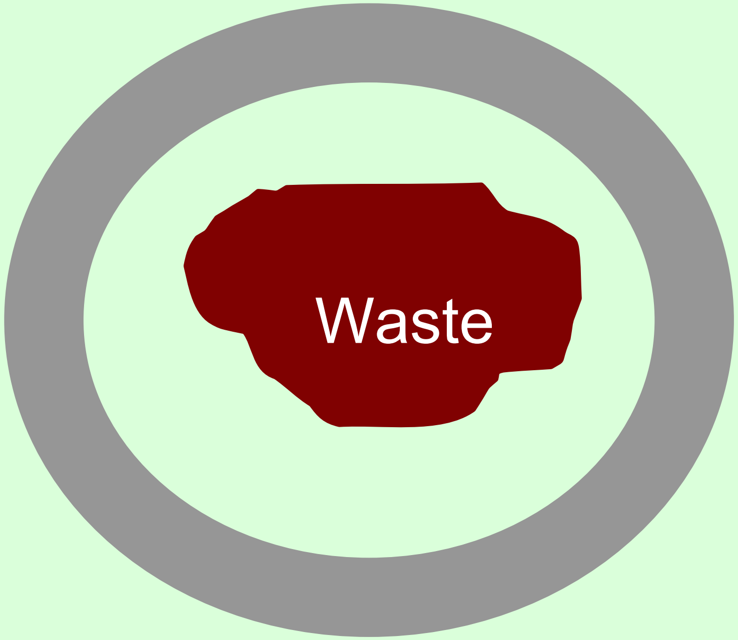


LNAPL

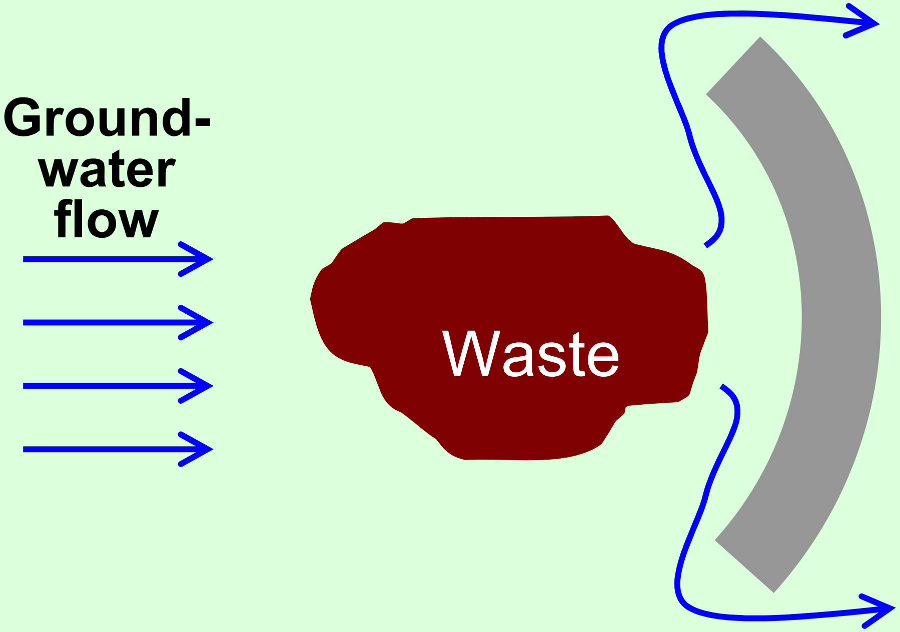
Hanging slurry wall

Confining bed or bedrock at depth

Alternative horizontal plans



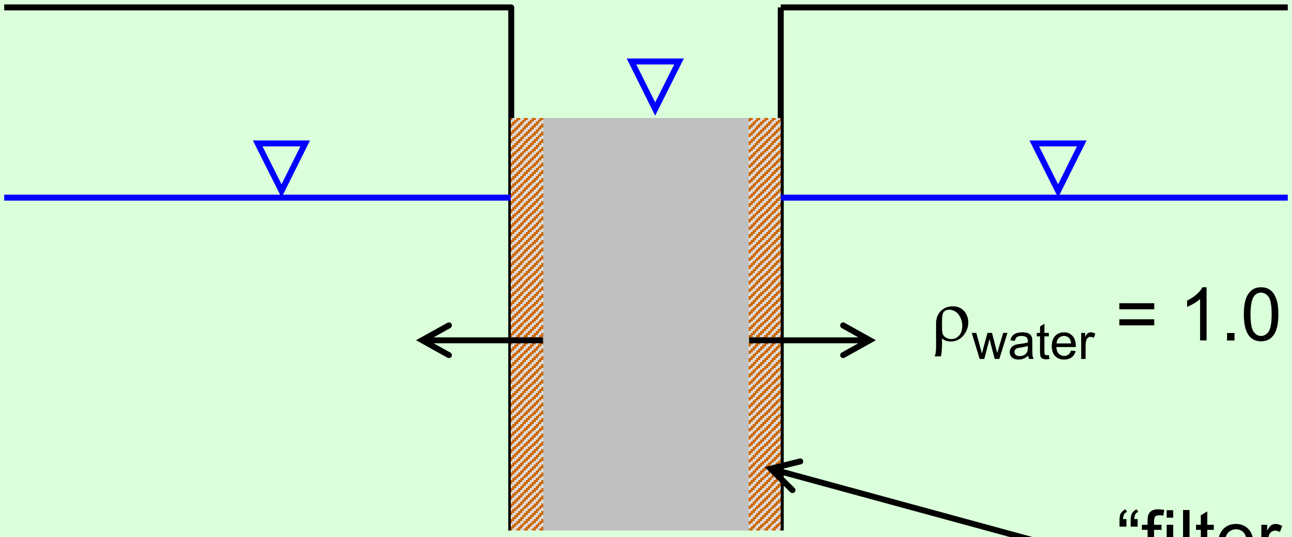
Slurry wall encircles
and isolates waste



Slurry wall delays
eventual migration

Soil mechanics of slurry walls

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



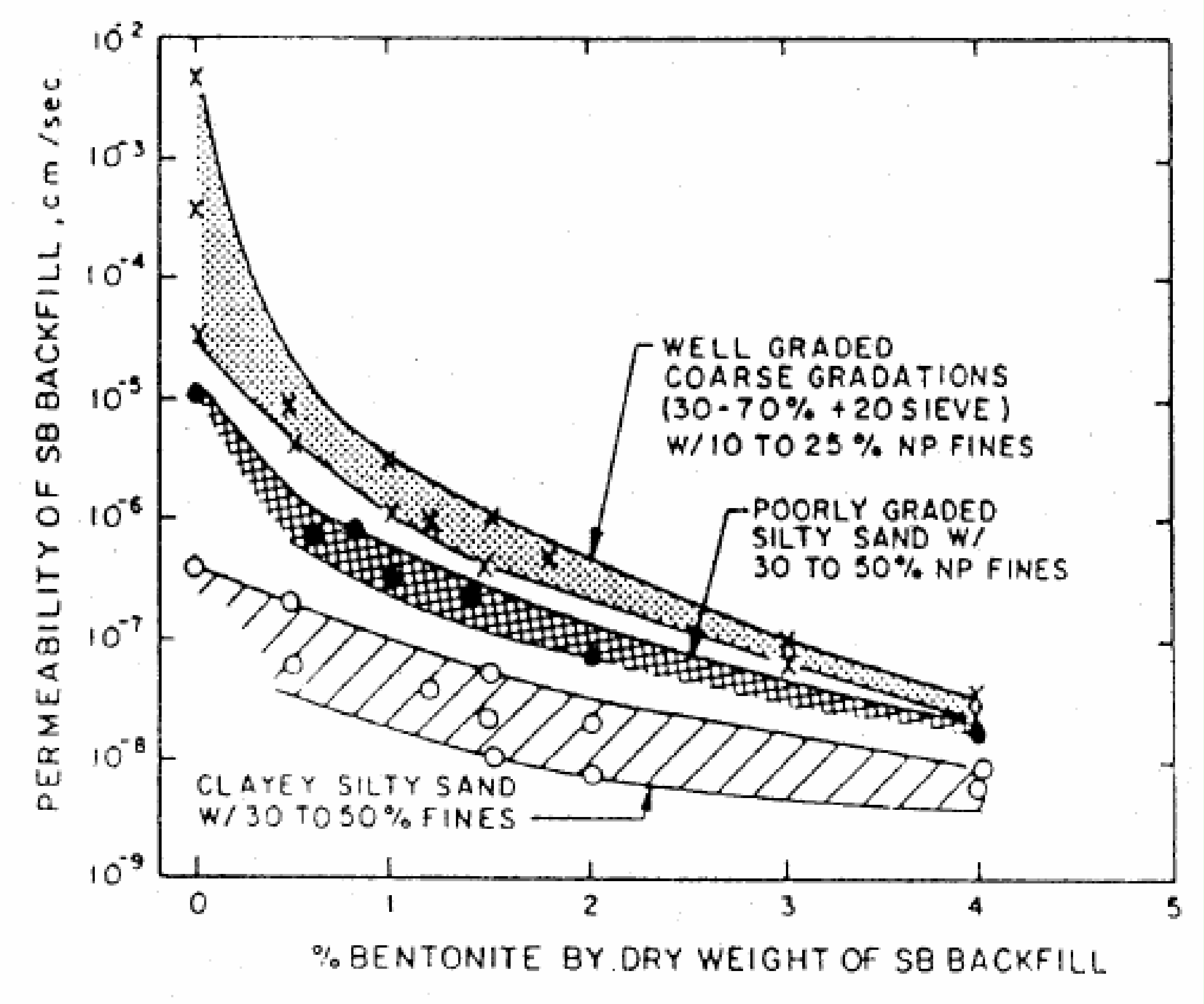
$\rho_{water} = 1.0\ g/cm^3$

"filter cake" on trench walls

$\rho_{slurry} \geq 1.02\ g/cm^3$

Slurry density should be 0.25 g/cm^3 lighter than emplaced backfill

Permeability of slurry walls



Source: Grubb, D. G., and N. Sitar, 1994. Evaluation of technologies for in-situ cleanup of DNAPL contaminated sites. Report Number EPA/600/R-94/120. R.S. Kerr Environmental Research Laboratory, U.S. Environmental Protection Agency, Ada, Oklahoma. August 1994.

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 5×10^{-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 m^2 (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)

Source: U.S. EPA, 1998. Evaluation of Subsurface Engineered Barriers at Waste Sites. Report No. EPA-542-R-98-005. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency, Washington, D.C. August 1998. (http://www.epa.gov/swertio1/download/remed/subsurf.pdf).

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

Source: Ross, R. R., and M. S. Beljin, 1998. Evaluation of Containment Systems Using Hydraulic Head Data. *Journal of Environmental Engineering, ASCE*. Vol. 124, No. 6, Pg. 575. June 1998.

Interlocking Sheet Piles

See image at the Web site of Waterloo Barrier Inc., sealable joint steel sheet piling (WZ 75 profile). http://www.waterloo-barrier.com/ Accessed May 11, 2004.

Sheet Pile Installation

See image at the Web site of Ontario Centre for Environmental Technology Advancement, Technology Profile Catalogue, Waterloo Barrier™ for Groundwater Containment. http://www.oceta.on.ca/profiles/wbi/barrier.html Accessed May 11, 2004.

Sheet Pile Grouting

See image at the Web site of Ontario Centre for Environmental Technology Advancement, Technology Profile Catalogue, Waterloo Barrier™ for Groundwater Containment. http://www.oceta.on.ca/profiles/wbi/barrier.html Accessed May 11, 2004.

Grout curtains

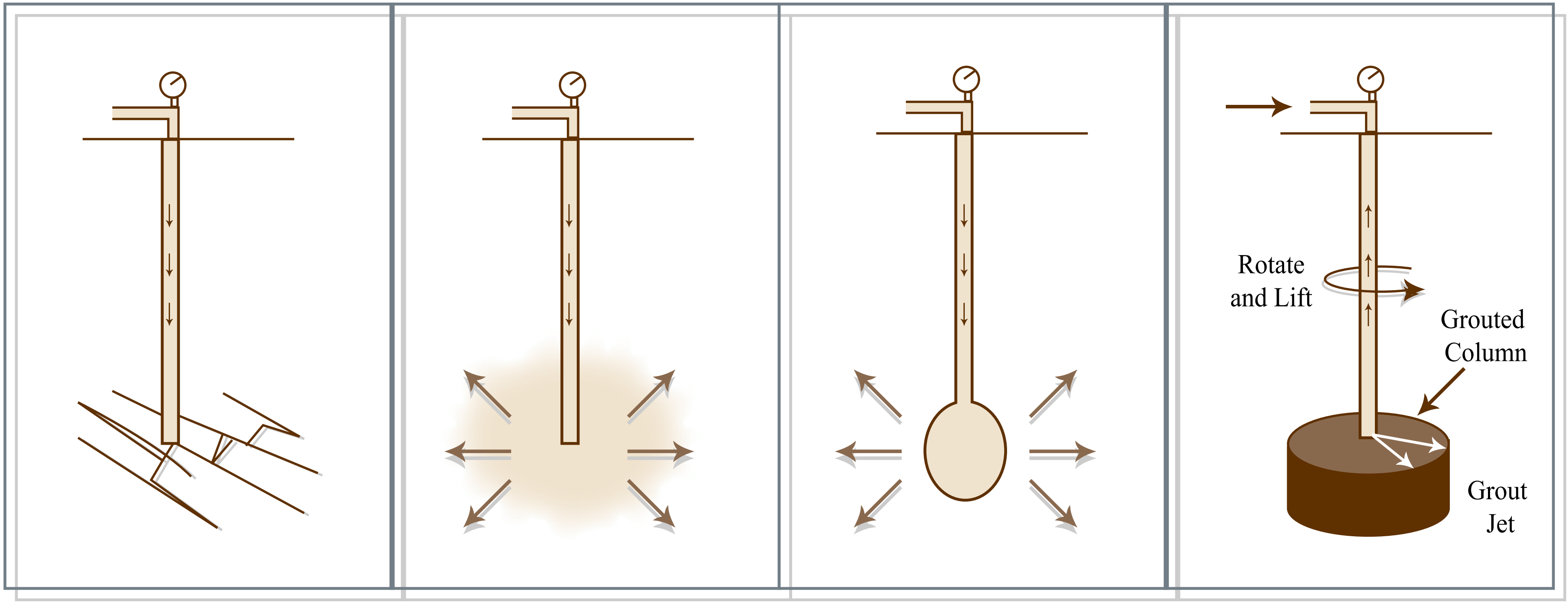
Subsurface emplacement of grout to form containment

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)

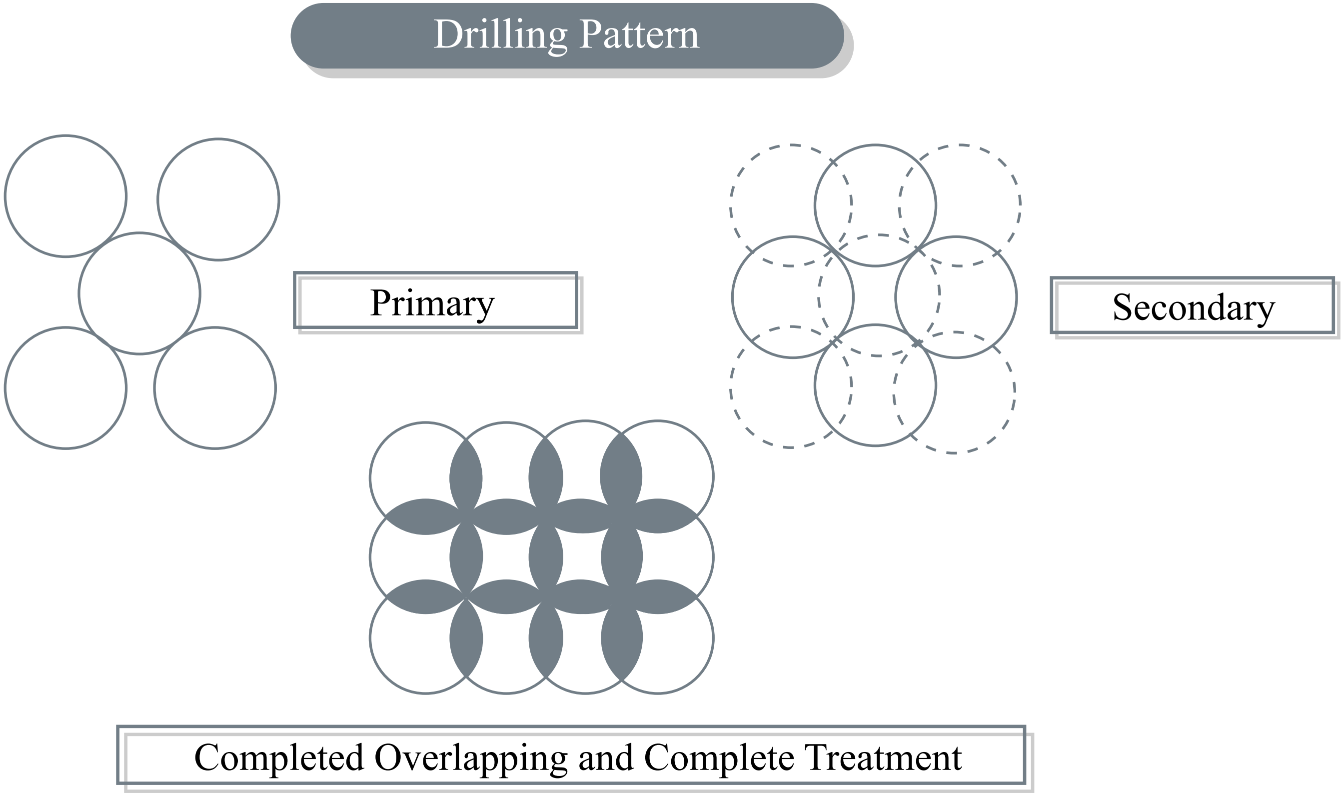
Penetration (Permeation)

Displacement
(Compaction Grouting)

Jet Grouting
(Displacement, Replacement)

Adapted from: Grubb, D. G. and N. Sitar. "Evaluation of Technologies for In-situ Cleanup of DNAPL Contaminated Sites."
Report Number EPA/600/R-94/120. R.S. Kerr Environmental Research Laboratory, U.S. Environmental
Protection Agency, Ada, Oklahoma, August 1994.

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].

Adapted from: Grubb, D. G. and N. Sitar. "Evaluation of Technologies for In-Situ Cleanup of DNAPL Contaminated Sites." Report Number EPA/600/R-94/120. R. S. Kerr Environmental Research Laboratory, U.S. Environmental Protection Agency, Ada, Oklahoma, August 1994.

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

Stablization: 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

Soil vapor extraction	28%
Solidification/stabilization (in-situ and ex-situ)	24%
Offsite incineration	13%
Bioremediation	11%
Thermal desorption	9%

Source: U.S. EPA, 2000. Solidification/Stabilization Use at Superfund Sites. Report No. EPA-542-R-00-010. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency, Washington, D.C. September 2000.

Wastes treated by S/S

Metals only	56%
Organics only	6%
Metals and organics	31%
Radioactive wastes	5%
Nonmetals with and without organics	2%

Source: U.S. EPA, 2000. Solidification/Stabilization Use at Superfund Sites. Report No. EPA-542-R-00-010. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency, Washington, D.C. September 2000. (http://www.clu-in.org/download/techdrct/tdss_sfund.pdf)

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:

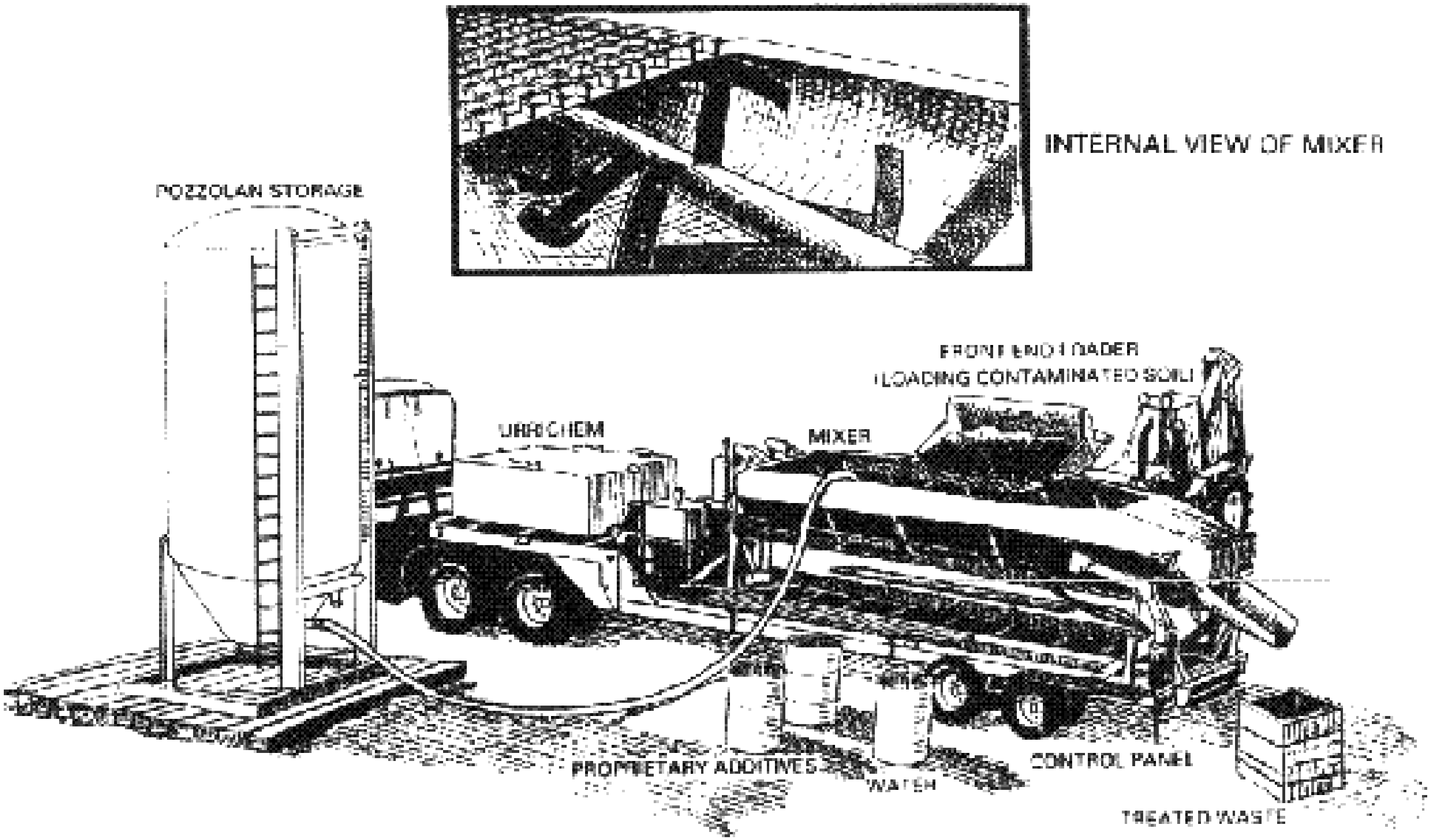
oil and grease, surfactants, chelating agents

Not likely to be effective with volatile organics

PCBs can be stabilized

(volatilization may be biggest removal factor)

Soliditech Ex-situ S/S Process



Soliditech Processing Equipment

Source: U.S. EPA, 1989. The Superfund innovative Technology Evaluation Program: Technology Profiles. Report No. EPA/540/5-89/013. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency, Washington, D.C. November 1989.

Ex-Situ Stabilization in Pug Mill

Screening soil prior to mixing in pug mill

Source: U.S. Environmental Protection Agency, November 14, 2001. Region 10: The Pacific Northwest, Northwest Pipe and Casing Photo Gallery. Washington D.C. http://yosemite.epa.gov/r10/cleanup.nsf/9f3c21896330b4898825687b007a0f33/3b3a728ac5f456f888256acb005f3273?OpenDocument. Accessed February 26, 2003.

Ex-Situ Stabilization in Pug Mill

See images at the Web sites of C-shops.com (http://www.roadsolutionsinc.com/photogallery.asp) and Trans World Equipment Sales, Soil Remediation Equipment (http://www.twequip.com/Equipment/soil.htm). Accessed May 11, 2004.

(1/2-left):C-shops.com, undated. Photo Gallery, Road Solutions, Inc. Indianapolis, IN. http://www.roadsolutionsinc.com/photogallery.asp. Accessed February 27, 2003.

(1/2-right): Trans World Equipment Sales, February 12, 2003. Soil Remediation Equipment. Trans World Equipment Sales. Moberly, MO. http://www.twequip.com/Equipment/soil.htm. Accessed February 26, 2003.

In-situ methods

- Shallow soil mixing – to about 10 meters deep
  - Cost: ~\$50-80/m^3 (per FRTR)
  - Backhoes can be used for small projects, shallow soil
- Deep soil mixing
  - Cost: ~\$190-300/m^3
- Vacuum hoods may be needed to control vapor and dust
- Volume increase is typically about 15%

Shallow Soil Mixing

See image of Lechmere Square MGP Site at the Web site of Geo-Con, Environmental Construction and Remediation, In-Situ Soil Stabilization, Shallow Soil Mixing, http://www.geocon.net/envssm4.asp. Accessed May 11, 2004.

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 Accessed May 11, 2004.

Soil Mixing Machine for Deep Soil Mixing

See images at the Web site of the Department of Civil and Environmental Engineering, Virginia Tech, Center for Geotechnical Practice and Research, Deep Soil Mixing for Reinforcement & Strengthening of Soils at Port of Oakland, CA. http://cgpr.ce.vt.edu/photo_album_for_geotech/Ground%20improvement/DSM%20Port%20Oakland/DSM%20at%20Port%20-%20main.html. Accessed May 11, 2004.

Center for Geotechnical Practice and Research, February 11, 2003. Deep Soil Mixing for Reinforcement & Strengthening of Soils at Port of Oakland, CA. Center for Geotechnical Practice and Research, Geotechnical Engineering, Department of Civil and Environmental Engineering, Virginia Tech. Blacksburg, VA. http://cgpr.ce.vt.edu/photo_album_for_geotech/Ground%20improvement/DSM%20Port%20Oakland/DSM%20at%20Port%20-%20main.html. Accessed February 26, 2003.

Deep Soil Mixer

Source: Kennedy Space Center, undated. Enhanced In-Situ Zero Valent Metal Permeable Treatment Walls. Kennedy Space Center, Technology Commercialization Office. KSC, FL. http://technology.ksc.nasa.gov/WWWaccess/techreports/98report/03-ee/ee05.html. Accessed February 26, 2003.

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

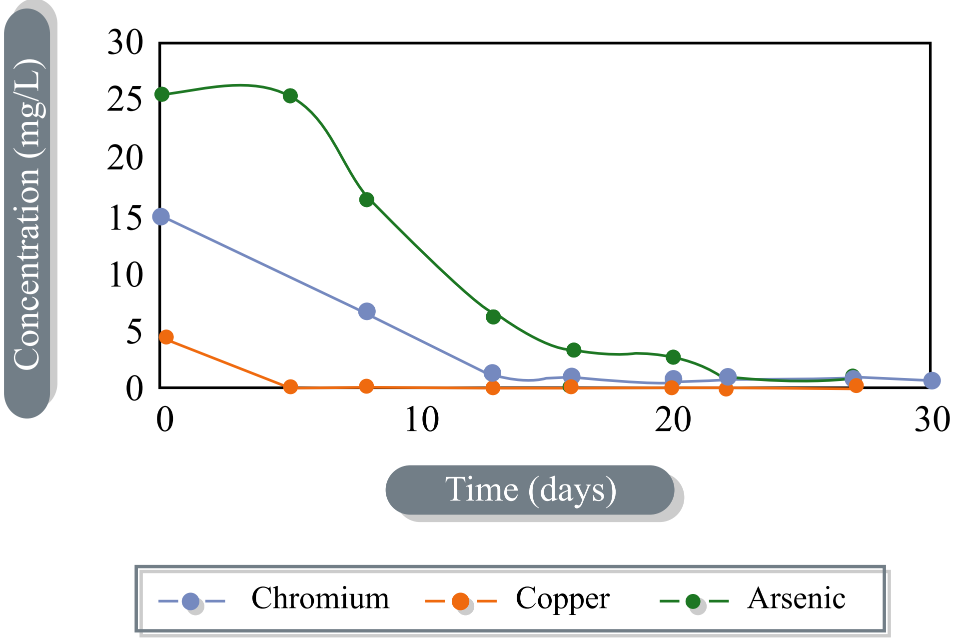
Chemical containment

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).

Adapted from: Willett, A., B. Vigue, and S. Koenigsberg. "All Locked Up." *Environmental Protection* 14, no. 9 (November/December 2003): 50-54.