

# **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”)

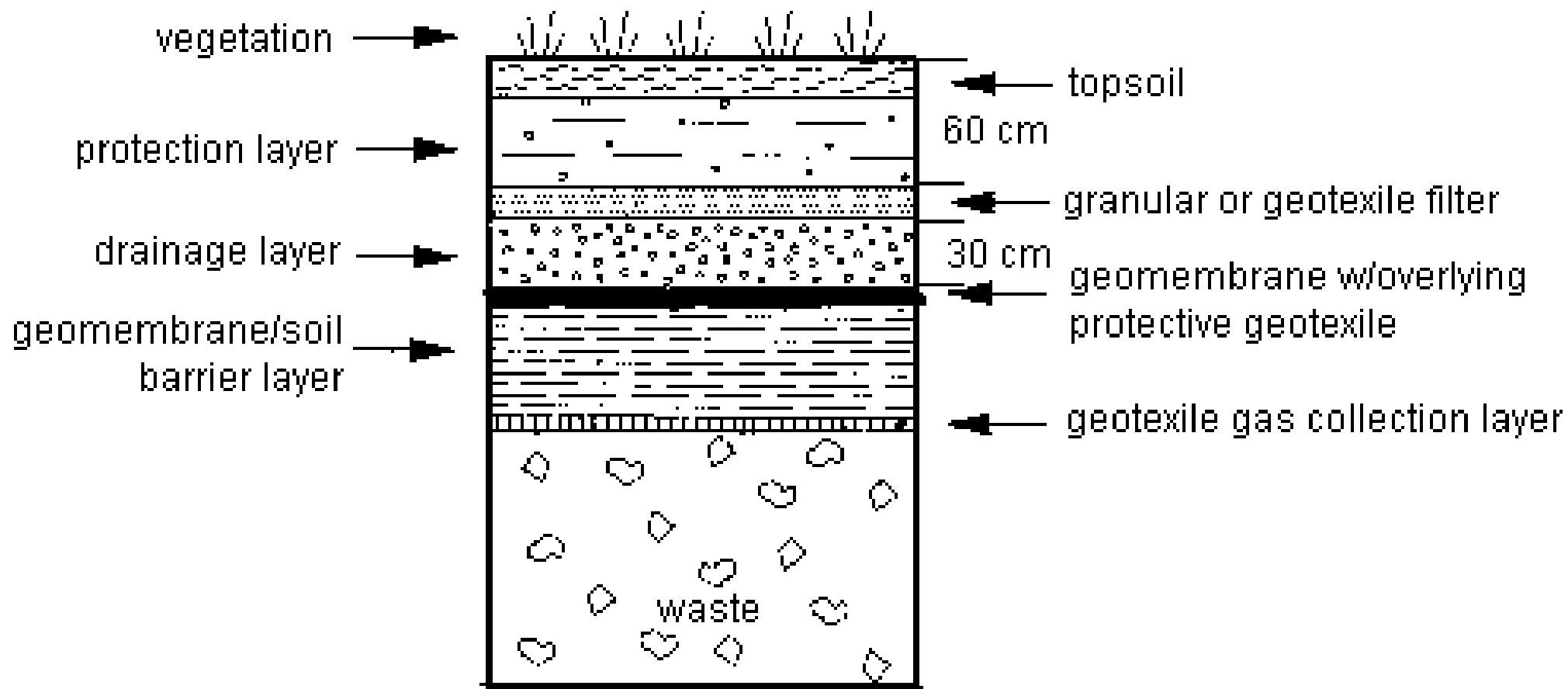
Prevent physical contact and exposure to waste

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](http://www.frtr.gov/matrix2/section4/4_30.html). Accessed February 26, 2003.

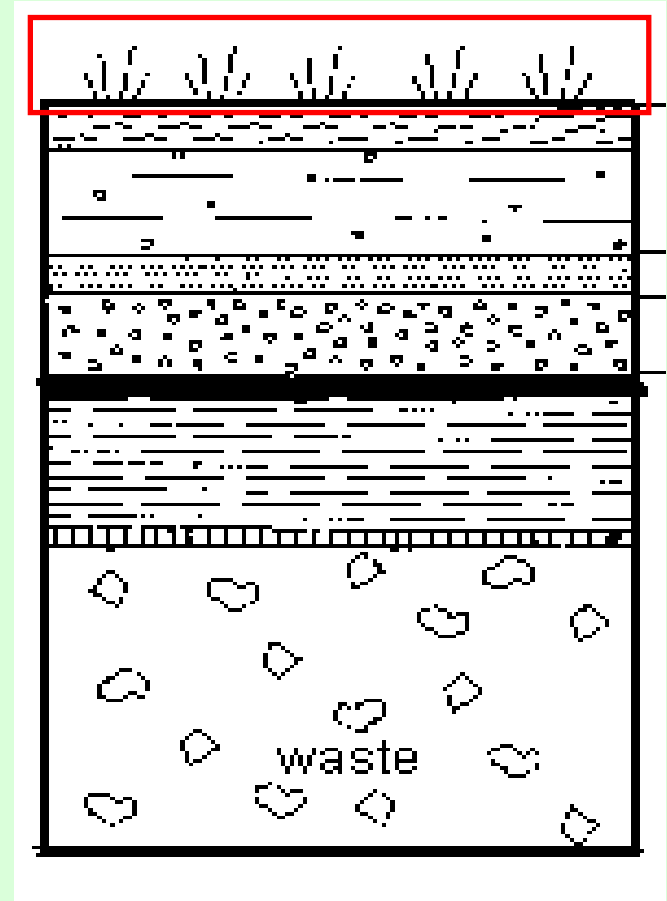
# Cap layers: Vegetation

## Purposes:

- Erosion control
- Infiltration reduction by evapotranspiration

## Characteristics:

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



# Cap layers: soil layer

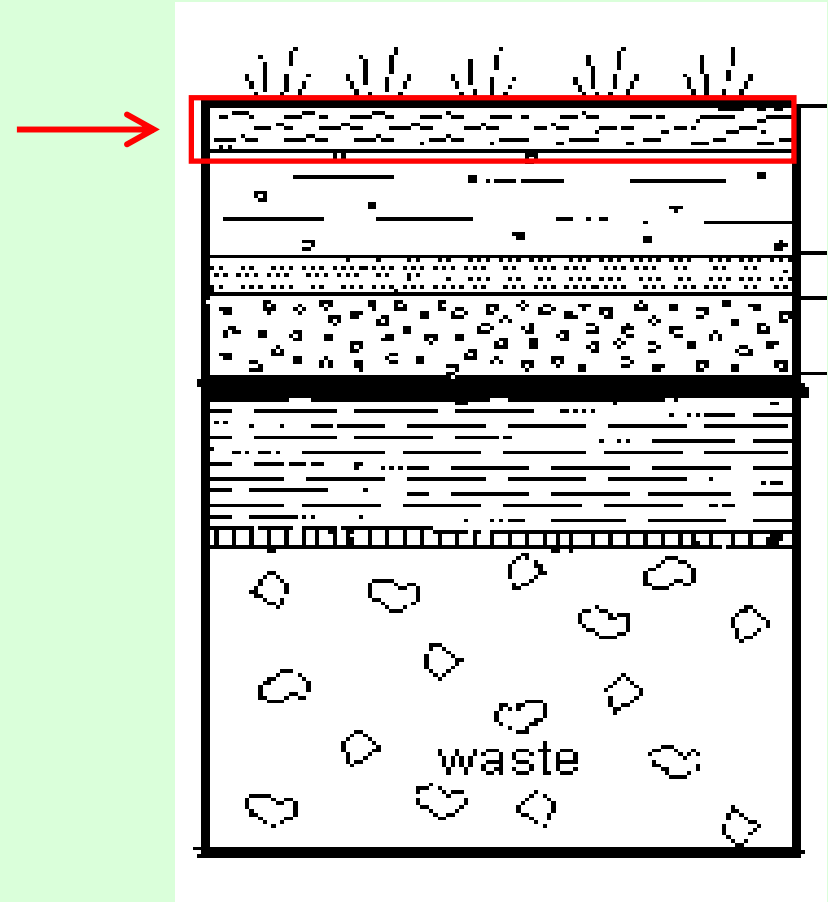
## Purposes:

Support vegetation

Protect underlying layers

Typically 60-cm thick

Crushed stone or cobbles  
may substitute in arid  
environments

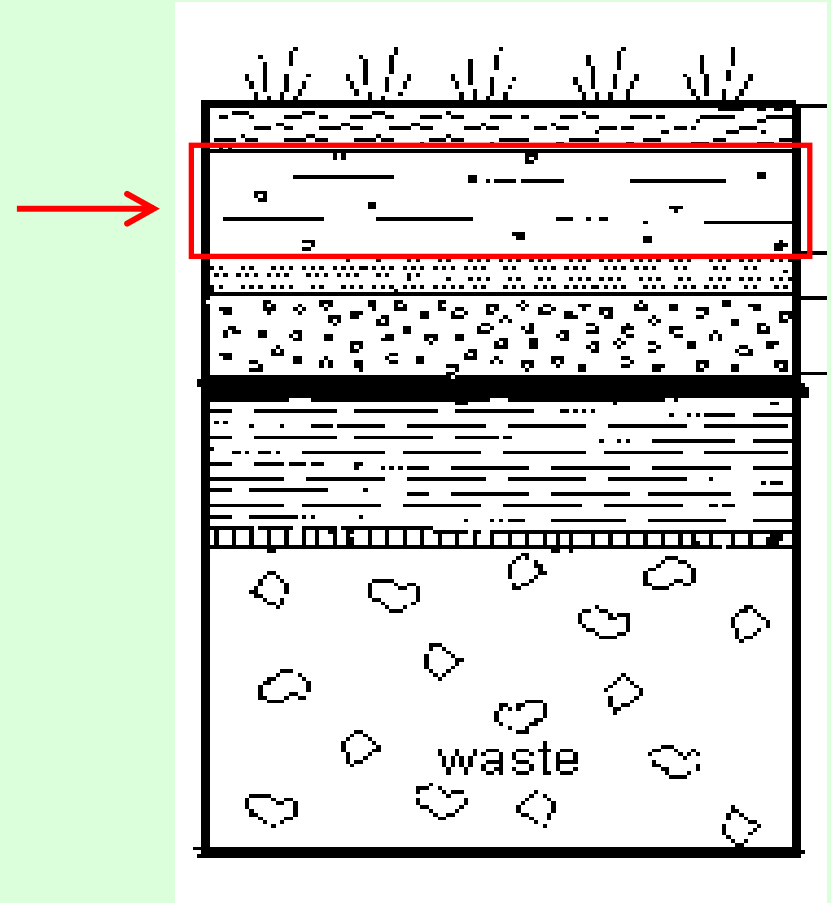


# Cap layers: Protection layer

Also called “biotic barrier”

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

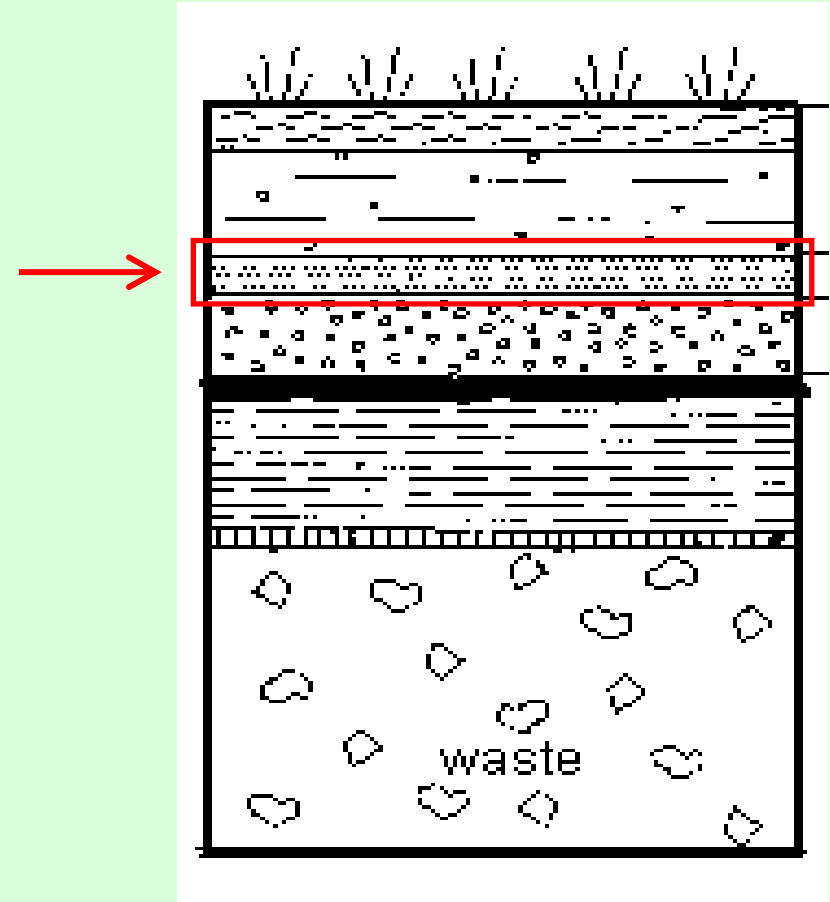
Not always included



# Cap layers: Filter layer

Prevents clogging of  
drainage layer by fines  
from soil layer

May be geosynthetic filter  
fabric or 30-cm sand





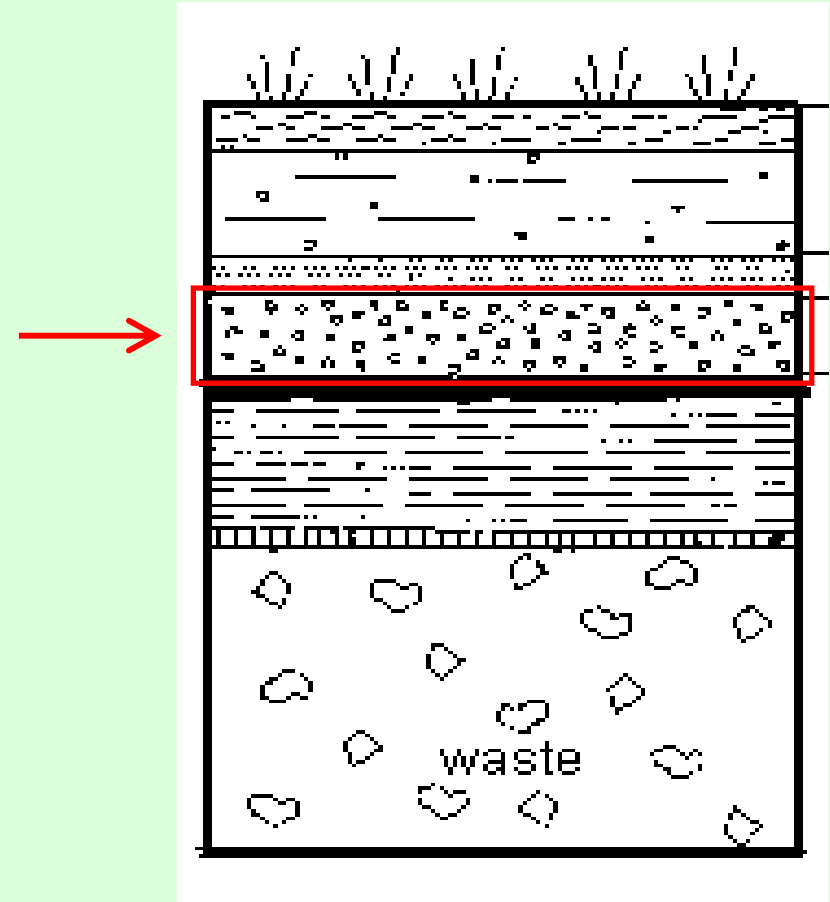
# Cap layers: Drainage layer

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



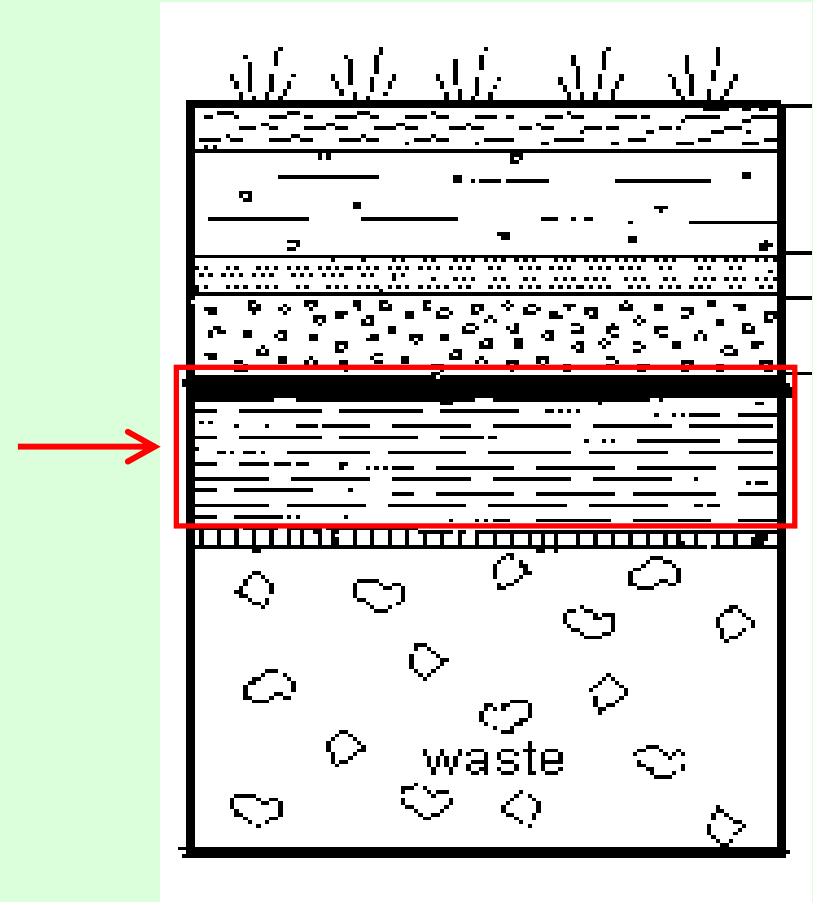
# Cap layers: Low K layer

“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

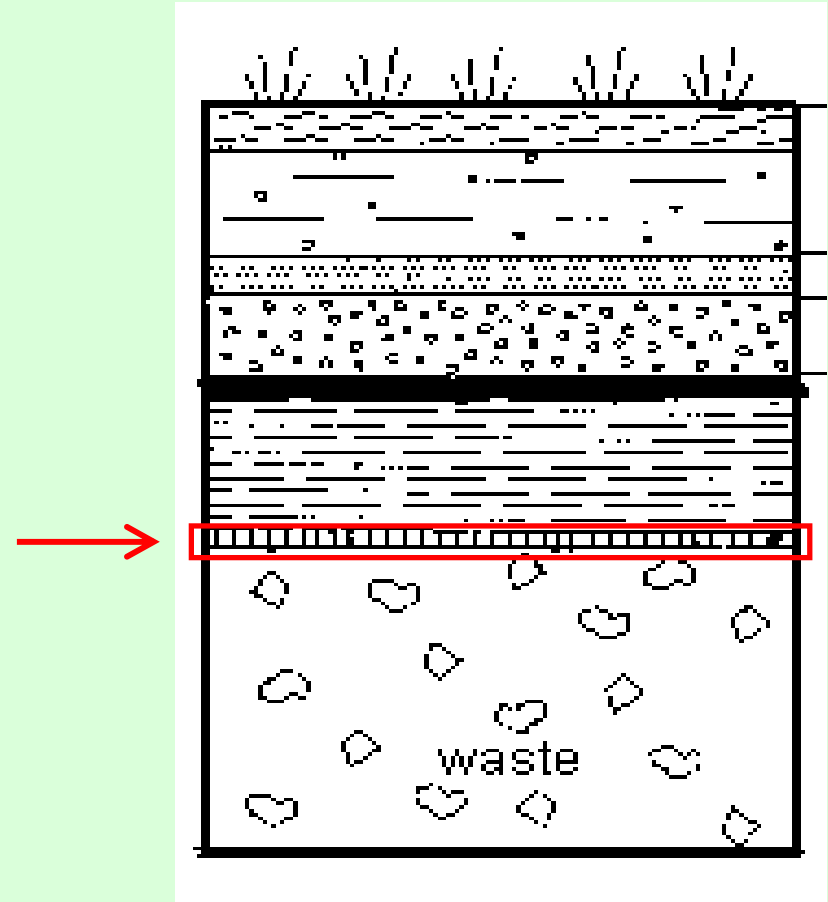


# Cap layers: Gas vent layer

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)

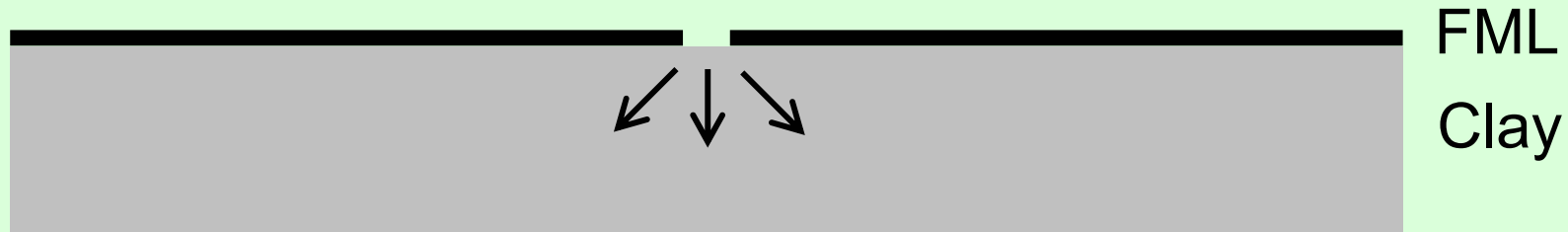
Impervious for practical purposes except at holes, tears, imperfectly sealed seams

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?

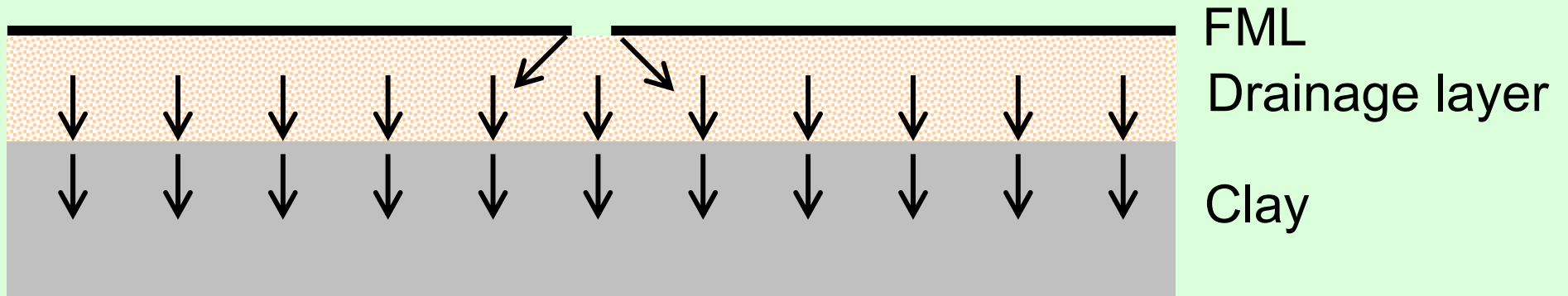
## Compacted clay liner

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 !!!

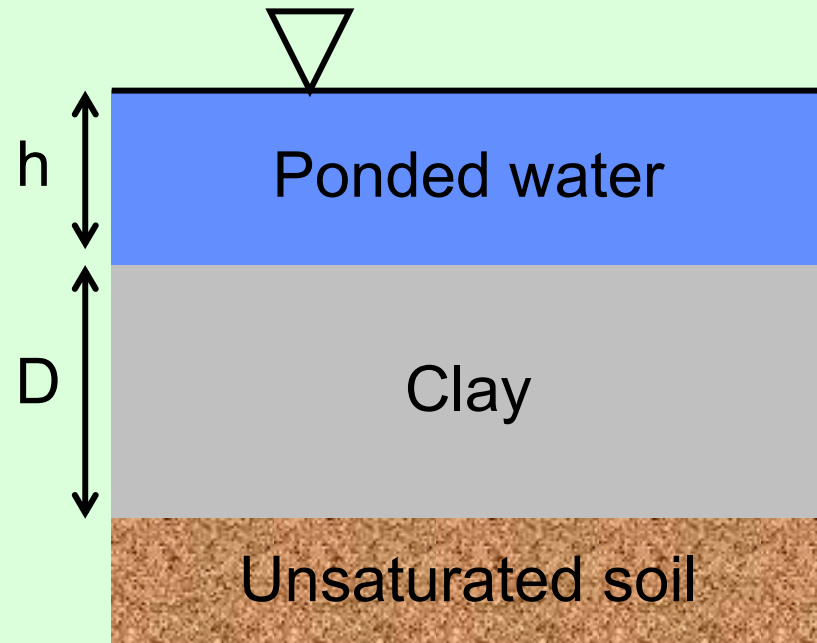
# Flow through clay liner

If clay is saturated and water is ponded to depth  $h$ :  
hydraulic gradient,  $i$ , through clay is:

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

$$Q = KiA$$

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



# 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	$1 \times 10^{-6}$	1,200	11,000
Good	$1 \times 10^{-7}$	120	1,100
Excellent	$1 \times 10^{-8}$	12	110



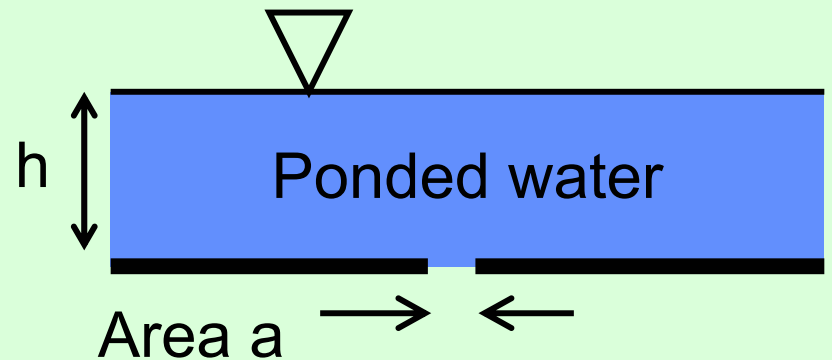
# Flow through hole in FML

Orifice equation:

$$Q = C_B a (2gh)^{0.5}$$

$C_B$  = orifice coefficient  $\approx 0.6$

$a$  = 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 <sup>2</sup>	10,000	93,000
Poor	1 @ 1 cm <sup>2</sup>	3,300	31,000
Good	1 @ 0.1 cm <sup>2</sup>	330	3,100
Excellent	none	0.01*	0.1

\* flow due to vapor transport

# Flow through composite liner

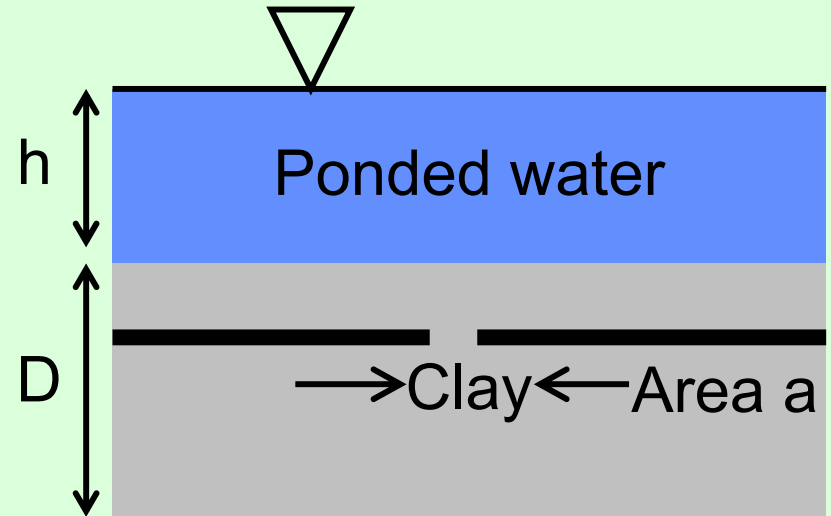
Empirical formula by  
Giroud et al.:

$$Q = C h^{0.9} a^{0.1} K^{0.74}$$

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 <sup>2</sup>	10,000	19
Poor	1 @ 1 cm <sup>2</sup>	3,300	0.8
Good	1 @ 0.1 cm <sup>2</sup>	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 <sup>2</sup>	330	3,100
Excellent clay	1 x 10 <sup>-8</sup>	12	110
Poor composite	30 @ 0.1 cm <sup>2</sup>	19	180
Poor composite	1 @ 1 cm <sup>2</sup>	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](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](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](http://www.bigdig.com/thtml/gw_sw.htm).

Accessed May 11, 2004.



# Hydromill for Deepest Slurry Walls

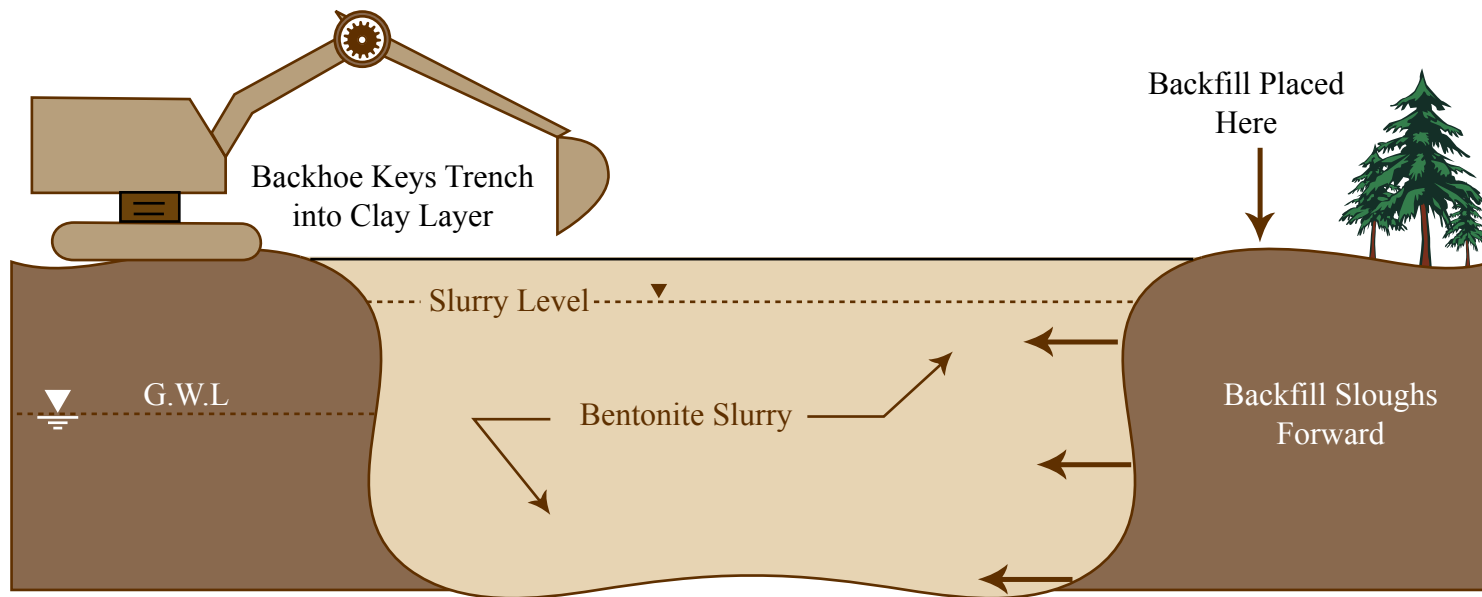
See image at the Web site of the Massachusetts Turnpike Authority, Central Artery/Tunnel Project.

[http://www.bigdig.com/thtml/gw\\_sw.htm](http://www.bigdig.com/thtml/gw_sw.htm).

Accessed May 11, 2004.

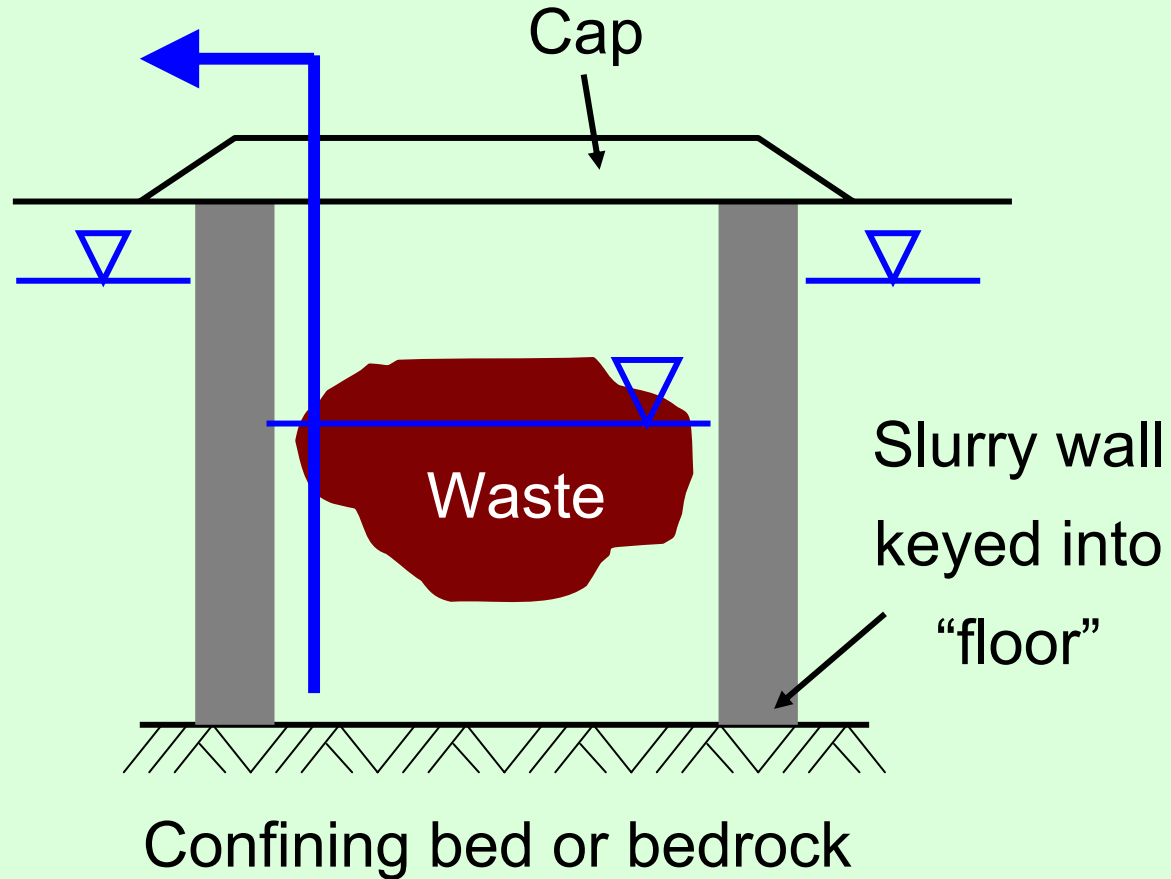
# Slurry wall construction

## Schematic of SB Slurry Wall Installation Process

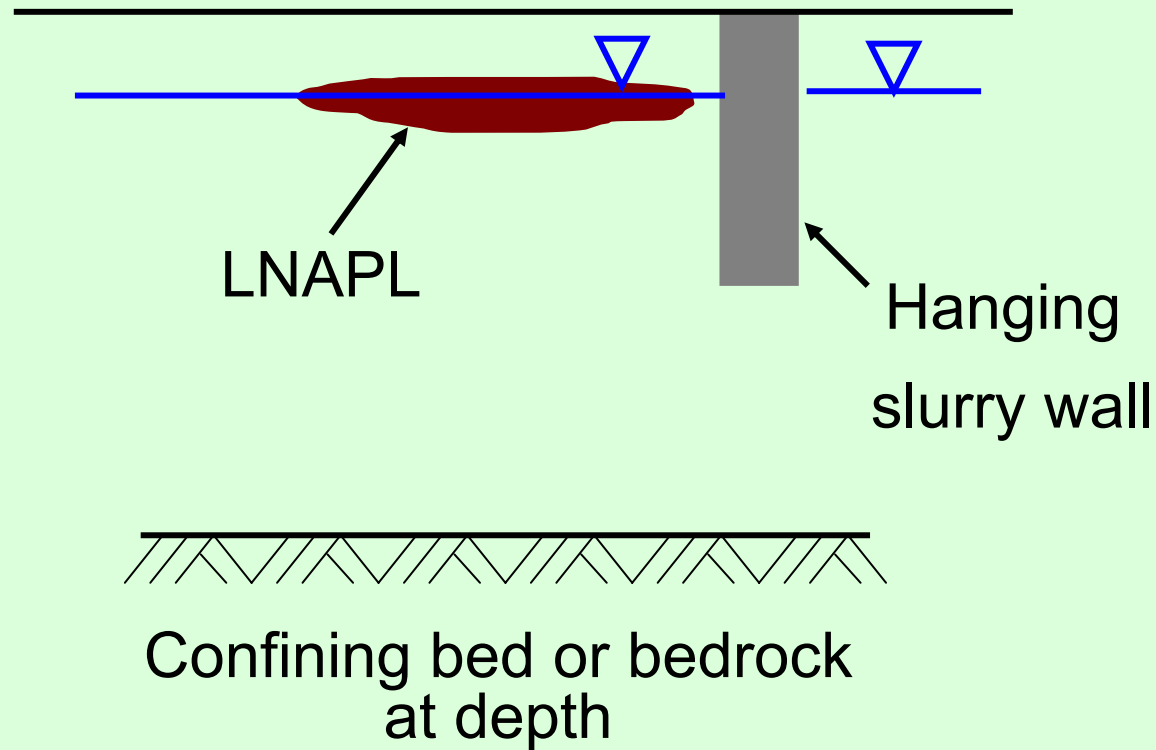


Adapted from: Grubb, D. G. and N. Sitar. "Evaluation of Technologies for In-situ Cleanup of DNAPL Contaminated Sites." Report Number EPA/600/R-94/120. NTIS Number PB94-195039. R.S. Kerr Environmental Research Laboratory, U.S. Environmental Protection Agency, Ada, Oklahoma, August 1994.

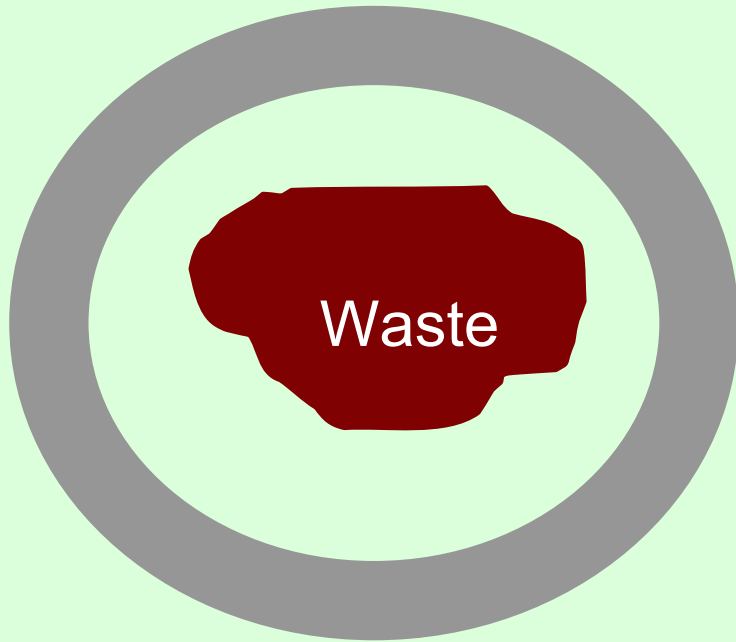
# Typical vertical section for slurry wall



# Alternative vertical section for “hanging” slurry wall for LNAPLs

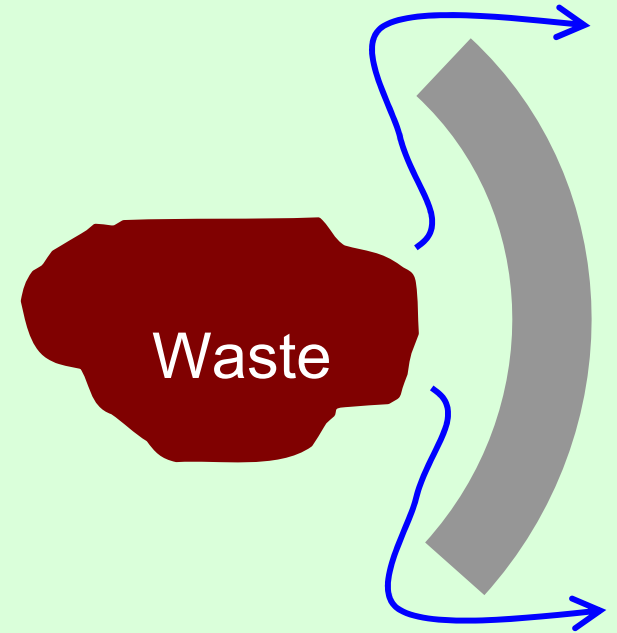
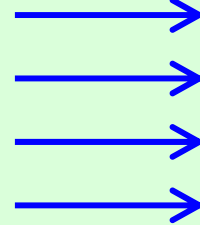


# Alternative horizontal plans



Slurry wall encircles and isolates waste

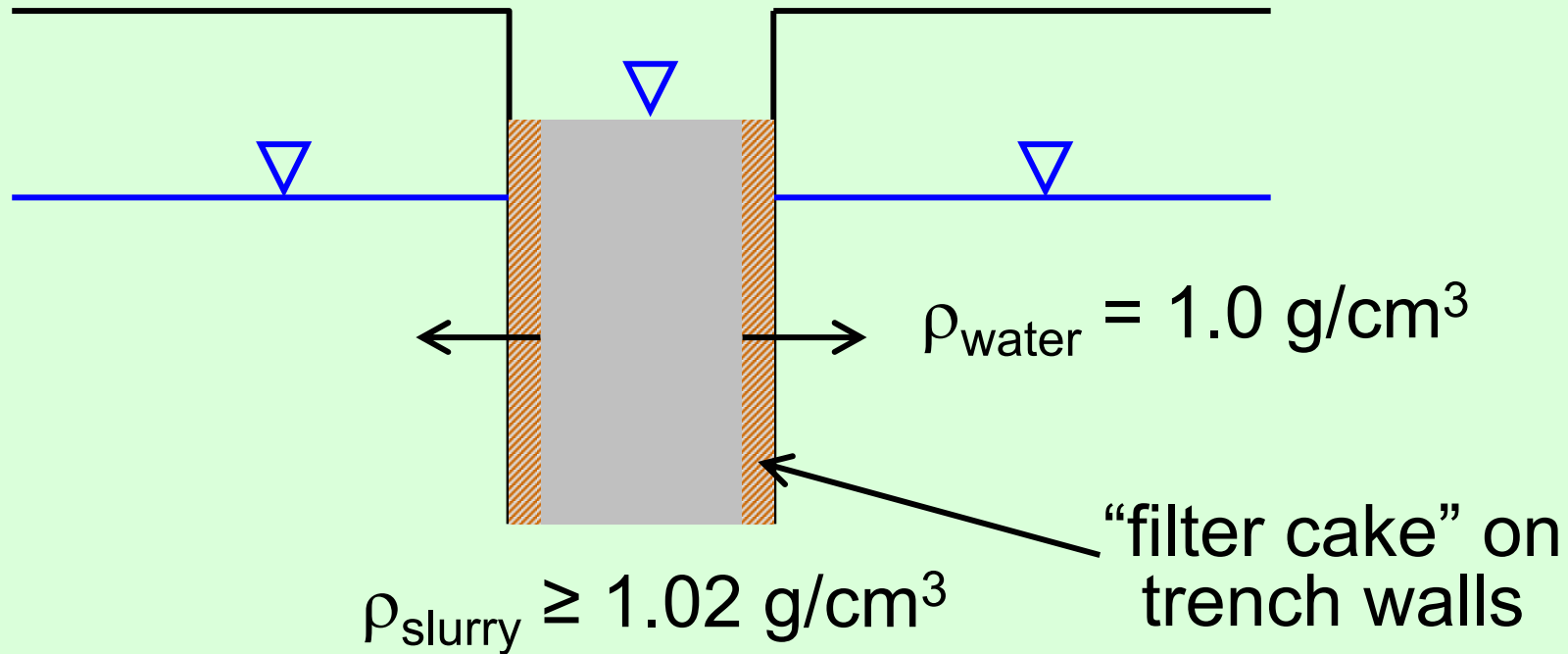
Ground-water flow



Slurry wall delays eventual migration

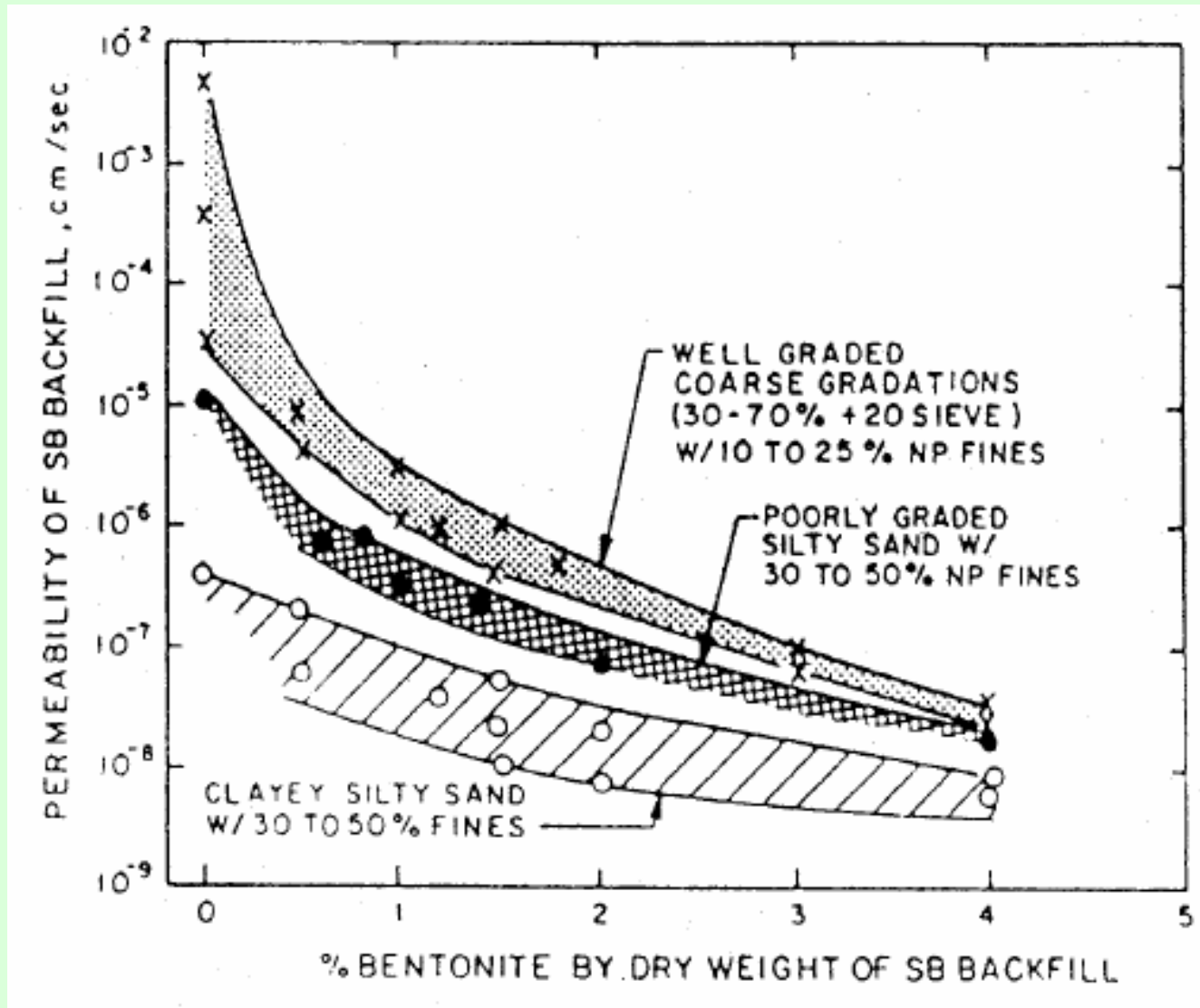
# Soil mechanics of slurry walls

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



Slurry density should be  $0.25 \text{ g/cm}^3$  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 m<sup>2</sup> (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

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

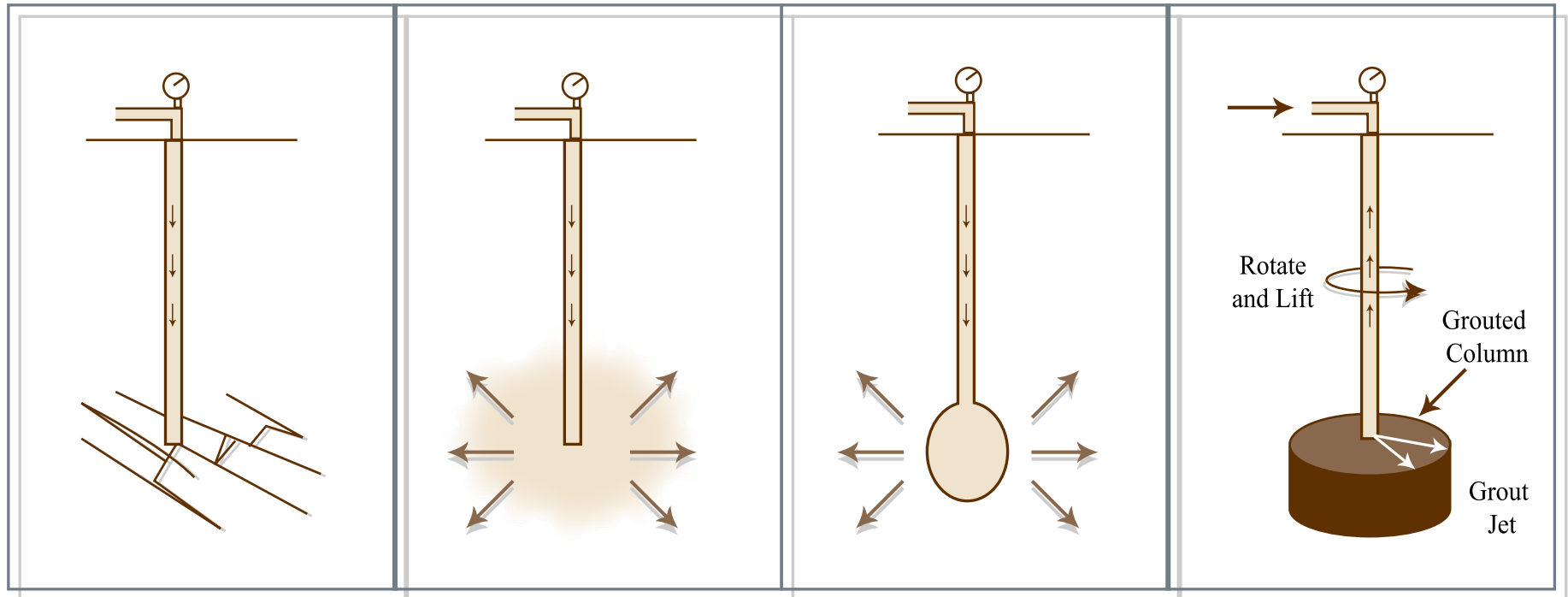
Pressure grouting – forces grout into fractures in rock

Deep-soil mixing – grout-bentonite slurry mixed into soils to create wall



# Grouting methods

## Schematic Showing Different Grouting Techniques



Penetration (Intrusion)

Penetration (Permeation)

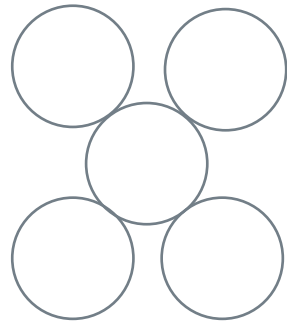
Displacement  
(Compaction Grouting)

Jet Grouting  
(Displacement, Replacement)

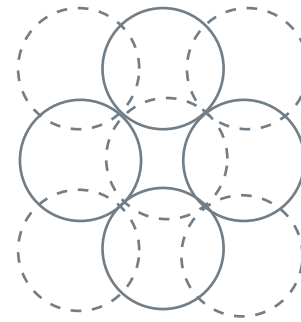
Adapted from: Grubb, D. G. and N. Sitar. "Evaluation of Technologies for In-situ Cleanup of DNAPL Contaminated Sites."  
Report Number EPA/600/R-94/120. R.S. Kerr Environmental Research Laboratory, U.S. Environmental  
Protection Agency, Ada, Oklahoma, August 1994.

# Grouting patterns

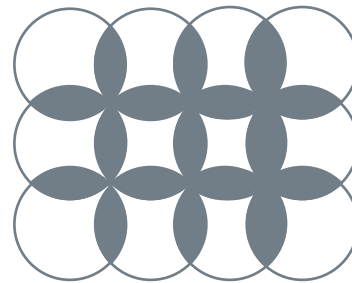
## Drilling Pattern



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%

# Wastes treated by S/S

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

# 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 = aluminosilicate 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:

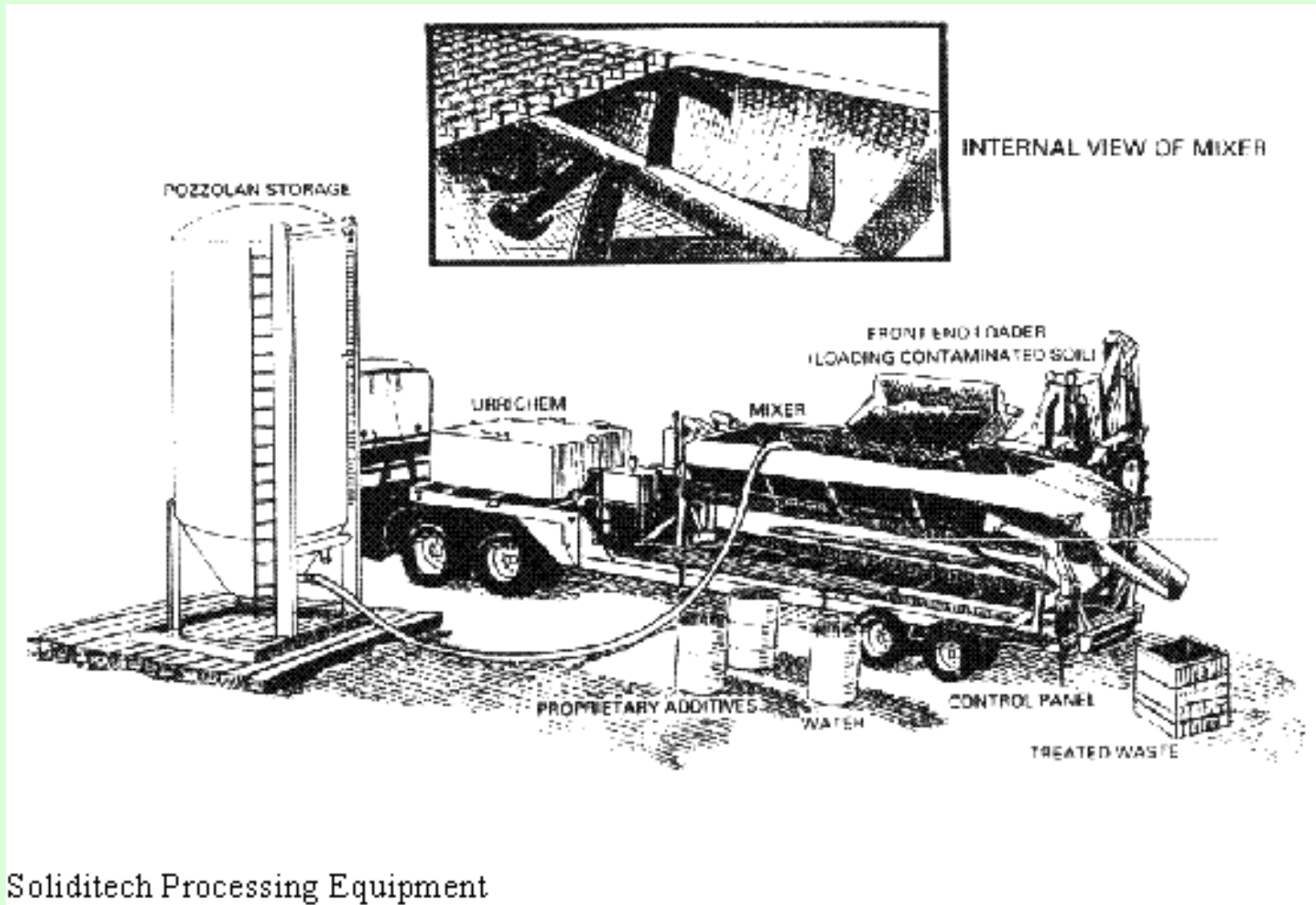
oil and grease, surfactants, chelating agents

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

# 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.

# In-situ methods

Shallow soil mixing – to about 10 meters deep

Cost: ~\$50-80/m<sup>3</sup> (per FRTR)

Backhoes can be used for small projects, shallow soil

Deep soil mixing

Cost: ~\$190-300/m<sup>3</sup>

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/In.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](http://cgpr.ce.vt.edu/photo_album_for_geotech/Ground%20improvement/DSM%20Port%20Oakland/DSM%20at%20Port%20-%20main.html).

Accessed May 11, 2004.



# 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<sup>3</sup> (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

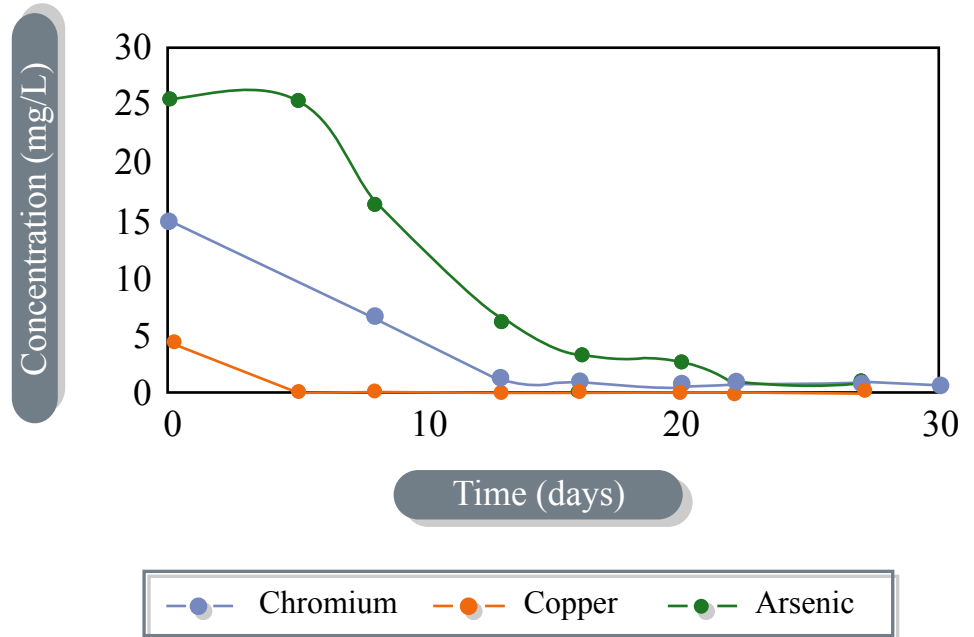
Electrodes advanced through soil as molten mass enlarges

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.