Lecture 17

Landfill operation and construction

References on landfill

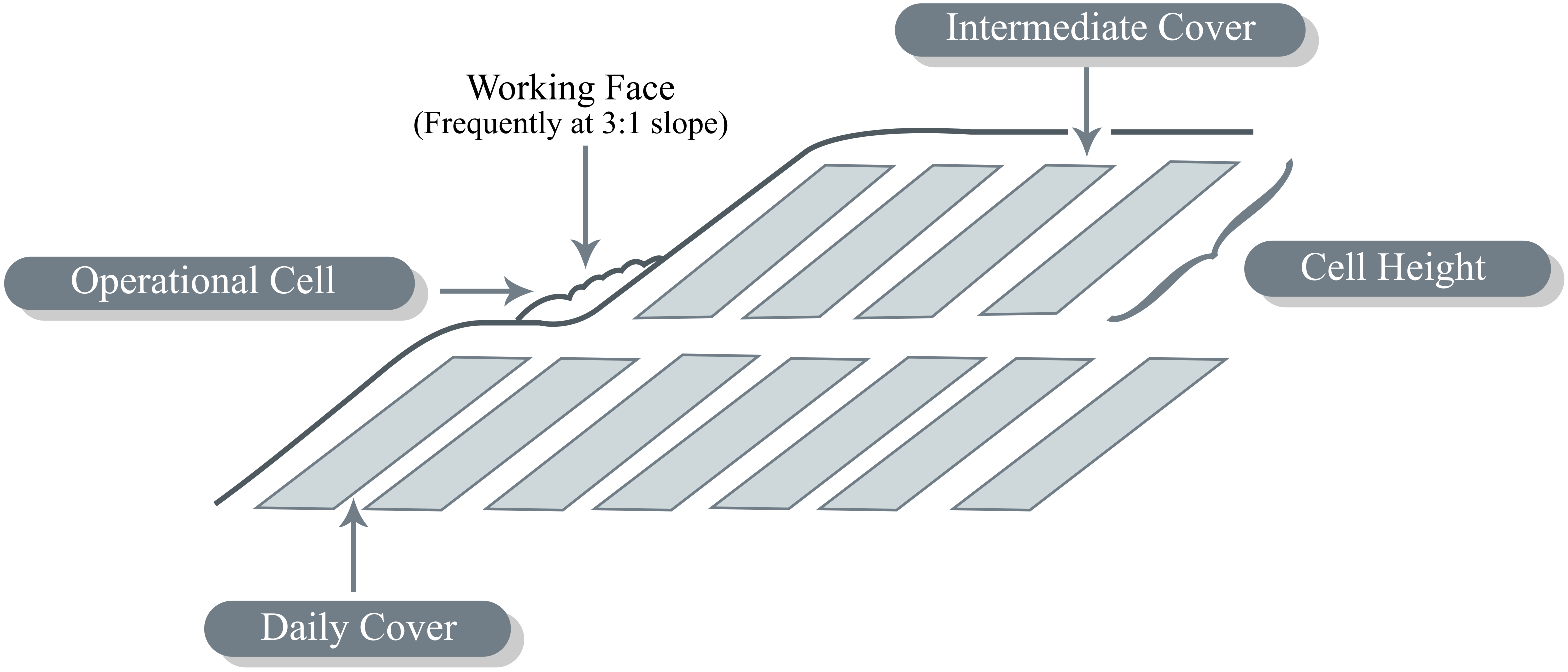
McBean, E.A., F.A. Rovers and G.J. Farquhar, 1995. *Solid Waste Landfill Engineering and Design*. Prentice Hall PTR, Englewood Cliffs, New Jersey.

Qian, X., R. M. Koerner, and D. H. Gray, 2002. *Geotechnical Aspects of Landfill Design and Construction*. Prentice Hall, Upper Saddle River, New Jersey.

Bagchi, A., 1994. *Design, Construction, and Monitoring of Sanitary Landfill, Second Edition*. John Wiley & Sons, New York.

Daniel,D.E., and R.M. Koerner, 1995. *Waste Containment Facilities, Guidance for Construction, Quality Assurance and Quality Control of Liner and Cover Systems*. American Society of Civil Engineers, New York.

MSW landfill cell construction



Configuration of Daily Cell and Lifts

Adapted from: McBean, E. A., F. A. Rovers, and G. J. Farquhar. *Solid Waste Landfill Engineering and Design*. Englewood Cliffs, New Jersey: Prentice Hall PTR, 1995.

MSW landfill operations

Waste cell is typically 3 to 5 meters high

Slope of working face controls area to volume of landfill and compaction of waste

- Best compaction at 10:1 (horizontal: vertical)
- Usual slope is 3:1 to reduce landfill surface area

MSW landfill operations

“Working face” = area of active waste placement

- Approximately 60-cm (2-ft) thickness of waste placed on slope
- Compacted by 2 to 5 passes of steel-wheel compactor
  - (Compacting is lighter at bottom, near liner, to avoid puncture)
- Multiple lifts placed to complete a cell
- Cell is covered by 15 cm (6 inches) of daily cover

Steel-wheeled compactor

See image at the Web site of MSW Management Magazine, Bolton, N., Compactonomics, January/February 2000. http://www.forester.net/msw_0001_compactonomics.html.

Accessed May 11, 2004.

Waste density

Residential waste at curbside	150 kg/m^3
After compaction in garbage truck	300 kg/m^3 (range: 180 to 415 kg/m^3)
In landfill after compaction	590 to 830 kg/m^3
Typical soil (for comparison)	1,800 kg/m^3 (1.5 tons/yd^3)

Source: McBean, E.A., F.A. Rovers and G.J. Farquhar, 1995. *Solid Waste Landfill Engineering and Design*. Prentice Hall PTR, Englewood Cliffs, New Jersey.

MSW daily cover

Materials:

- Usually soil
- Sometimes:
  - shredded vegetation
  - chipped wood
  - compost
  - spray-on proprietary mixes

Cover-to-waste ratio is typically 1 to 4 for soil

→ Substantial volume of landfill goes to daily cover!

Spray-on daily cover

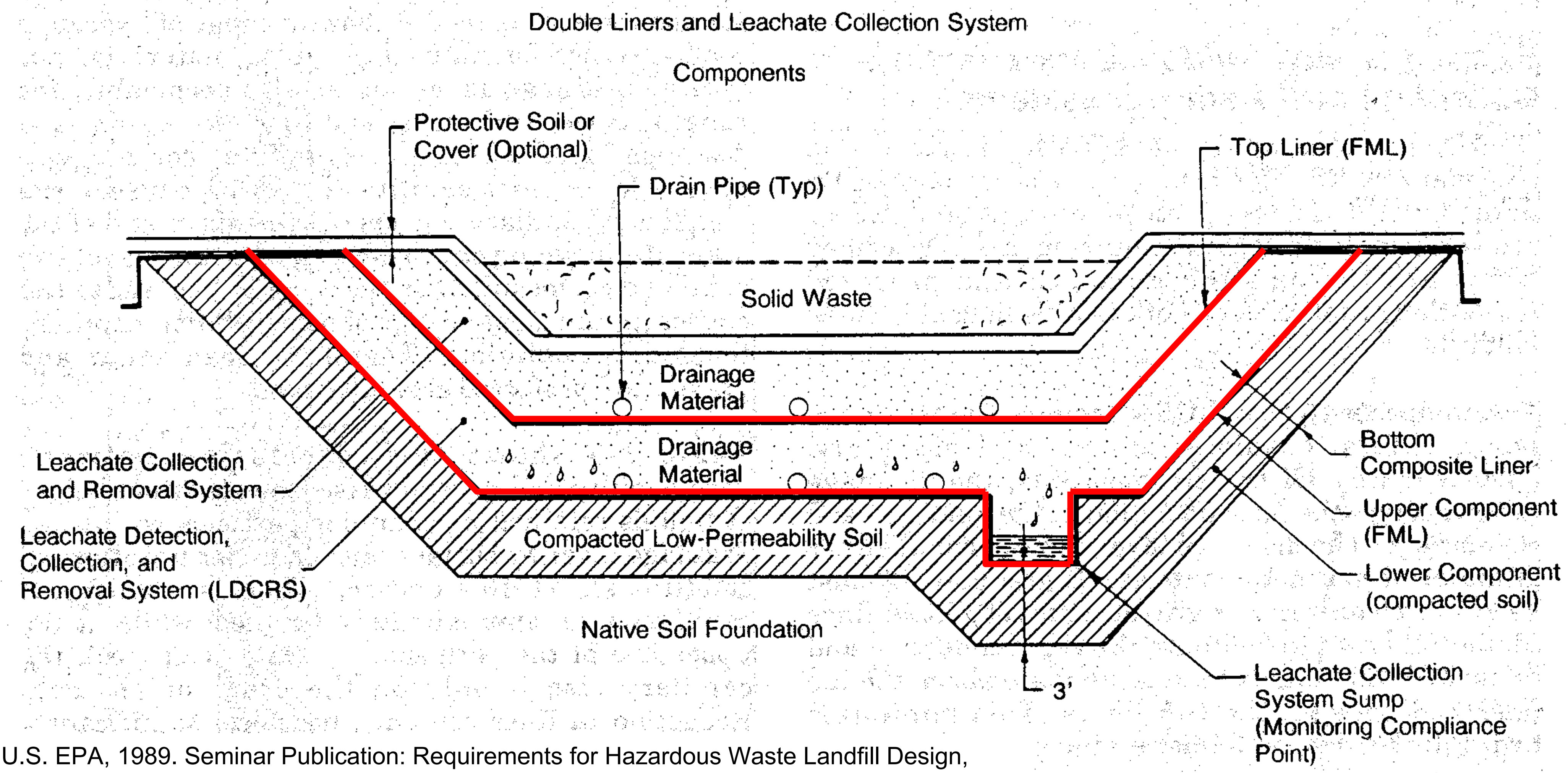
See images at the Web site of Source: Emerald Seed and Supply, WASTE-COVER™ Landfill Mulch, http://www.emeraldseedandsupply.com/hydroseeding/mulch_wastecover.html.

Accessed May 11, 2004.

Purposes of daily cover

- Reduce moisture entering waste
  - Most moisture enters waste during filling
- Control litter
- Reduce odors
- Limit access to rodents and birds
- Reduce fire risk
- Provide vehicle access to active face
- Improve aesthetics

Liner systems



U.S. EPA, 1989. Seminar Publication: Requirements for Hazardous Waste Landfill Design, Construction, and Closure. Report Number EPA/625/4-89/022. Center for Environmental Research Information, U.S. Environmental Protection Agency, Cincinnati, Ohio. August 1989.

Alternative liner materials

1. Soil liner

   Also called compacted clay liner (CCL)

2. Flexible membrane liner (FML)

   Also called geomembrane

3. Geosynthetic clay liner (GCL)
4. Composite liners

Liner systems

Single-liner systems:

- Typical for municipal solid waste
- Compacted low-K soil, geomembrane, or composite

Double-liner systems:

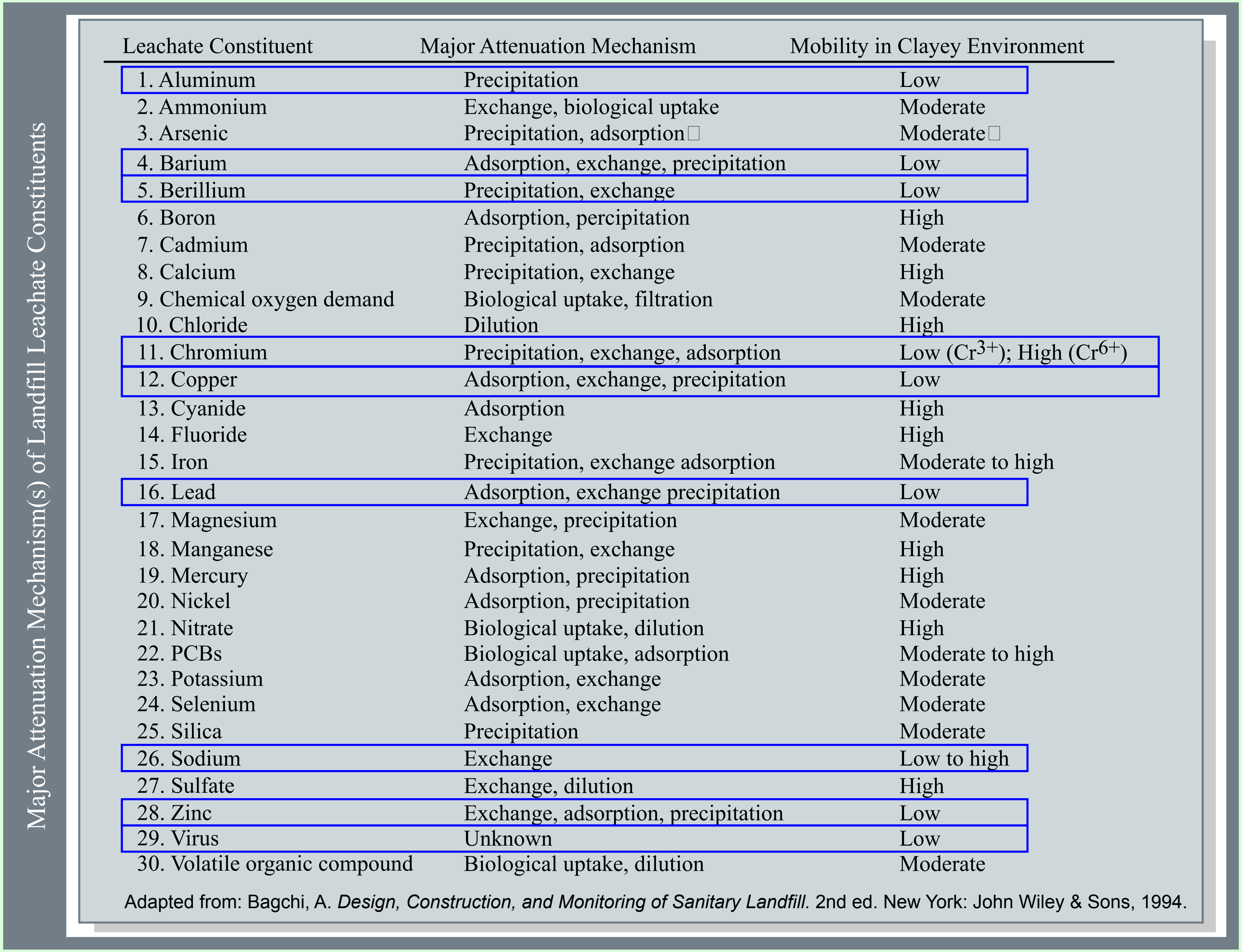
- Typical for hazardous waste, often for MSW
- Two liners with high-K drainage layer in between to intercept leachate
- Design recognizes that liners leak!

Liner materials – soil

Advantages:

- Clay can attenuate pollutants
- Thickness provides redundancy, resistance to penetration
- Long-lived, self-healing
- Inexpensive if locally available

Soil attenuation capacity



Major Attenuation Mechanism(s) of Landfill Leachate Constituents

Leachate Constituent	Major Attenuation Mechanism	Mobility in Clayey Environment
1. Aluminum	Precipitation	Low
2. Ammonium	Exchange, biological uptake	Moderate
3. Arsenic	Precipitation, adsorption	Moderate
4. Barium	Adsorption, exchange, precipitation	Low
5. Berillium	Precipitation, exchange	Low
6. Boron	Adsorption, percipitation	High
7. Cadmium	Precipitation, adsorption	Moderate
8. Calcium	Precipitation, exchange	High
9. Chemical oxygen demand	Biological uptake, filtration	Moderate
10. Chloride	Dilution	High
11. Chromium	Precipitation, exchange, adsorption	Low (Cr^{3+}); High (Cr^{6+})
12. Copper	Adsorption, exchange, precipitation	Low
13. Cyanide	Adsorption	High
14. Fluoride	Exchange	High
15. Iron	Precipitation, exchange adsorption	Moderate to high
16. Lead	Adsorption, exchange precipitation	Low
17. Magnesium	Exchange, precipitation	Moderate
18. Manganese	Precipitation, exchange	High
19. Mercury	Adsorption, precipitation	High
20. Nickel	Adsorption, precipitation	Moderate
21. Nitrate	Biological uptake, dilution	High
22. PCBs	Biological uptake, adsorption	Moderate to high
23. Potassium	Adsorption, exchange	Moderate
24. Selenium	Adsorption, exchange	Moderate
25. Silica	Precipitation	Moderate
26. Sodium	Exchange	Low to high
27. Sulfate	Exchange, dilution	High
28. Zinc	Exchange, adsorption, precipitation	Low
29. Virus	Unknown	Low
30. Volatile organic compound	Biological uptake, dilution	Moderate

Adapted from: Bagchi, A. *Design, Construction, and Monitoring of Sanitary Landfill.* 2nd ed. New York: John Wiley & Sons, 1994.

Liner materials – soil

Disadvantages:

- Construction is difficult – requires heavy equipment
- Thickness reduces volume for waste
- Subject to freeze/thaw and desiccation cracking
- Low tensile and shear strength – may shear or crack due to settlement
- May be degraded by chemicals
- Expensive if not available locally
- Extensive field testing required

Liner materials – soil

Usual design standard: $K \leq 10^{-7}$ cm/sec

- Origin of this standard is unclear
- Probably* selected as an achievable K
- Turns out to be very difficult to achieve $K \leq 10^{-7}$ cm/sec

---

* Daniel,D.E., and R.M. Koerner, 1995. *Waste Containment Facilities, Guidance for Construction, Quality Assurance and Quality Control of Liner and Cover Systems*. American Society of Civil Engineers, New York.

Liner materials – geomembranes

Advantages:

- Easily installed – needs only light equipment
- Very low leakage rates if free of holes
- Has high tensile and shear strength, flexibility – accommodates settlement
- Thin – leaves volume for waste

Liner materials – geomembranes

Disadvantages

- Photodegrades
- Slopes on geomembranes may be unstable
- High leakage if punctured or poorly seamed
- Some chemicals may be incompatible, permeable
- Thin – subject to puncturing
- No sorptive capacity
- Unknown lifetime
- Less field quality testing required

Liner materials – geosynthetic clay

Manufactured composite of bentonite and geotextile

Advantages:

- Easily installed
- Self sealing – no seams required
- Some sorptive capacity
- Low leakage rates

Liner materials – geosynthetic clay

Disadvantages

- Thin – easily punctured
- Slopes on geosynthetic clay liners may be unstable
- Limited experience

Liner materials – composite liners

Composite liner ≠ double liner

Composite liner = two or more materials

- Usually clay and geomembrane

Combines desirable properties of two materials

Liner materials – composite liners

Advantages:

- Low leakage rates
- Low contaminant mass flux
- Provides sorptive capacity
- Acceptable loss of waste storage space
- Acceptable ground-water protection

Liner materials – composite liners

Disadvantages:

- Difficult to construct
- Expensive

Liner materials – composite liners

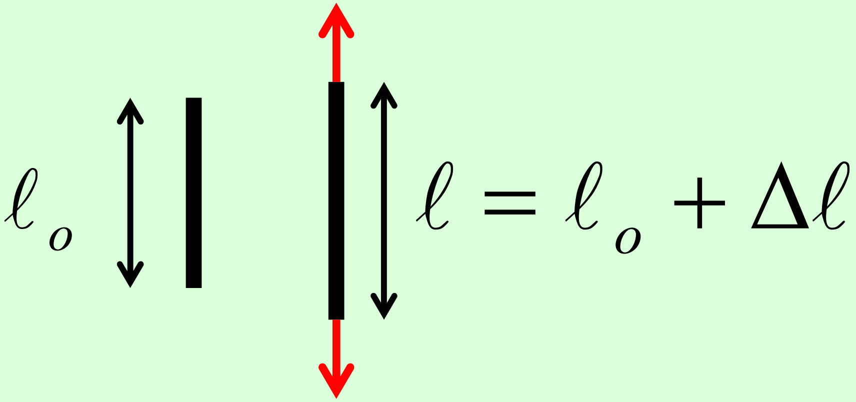
	Geomembrane	**Clay**
Hydraulic properties	Decreases leakage	Delays travel time
Physical properties	Thin: can be torn or punctured Retains continuity under stress or strain	Thick: cannot be torn or punctured May crack under stress or strain
Endurance properties	Subject to aging Not self-healing Chemically resistant	Does not age Self-healing May be affected by chemicals

Liner failure modes

Tension failure
Liner slippage
“Blowout” from water pressure
Liner uplift by water pressure
Liner uplift by wind
At pipes, access ways, other structural details

Tensile failure

- Flexible membrane liners (FMLs) have finite tensile strength
  - Measured in laboratory by increasing stress on sample and measuring strain
  - Stress = force per unit area = σ
  - Strain = elongation under stress / original length = ε



$$\ell = \ell_o + \Delta\ell$$

$$\varepsilon = \frac{\Delta\ell}{\ell_o}$$

Units

Stress has units of pressure

- Metric system: 1 Pa = 1 N/m^2
- Possible alternatives:
  - 1 kg-force/m^2 = 9.8 Pa
  - 1 dyn/cm^2 = 0.1 Pa
- English units: 1 psi = 1 pound-force / in^2
  - 1 psi = 6895 Pa
- Also used:
  - 1 psf = 1 pound-force / ft^2

Units continued

Density vs. unit weight

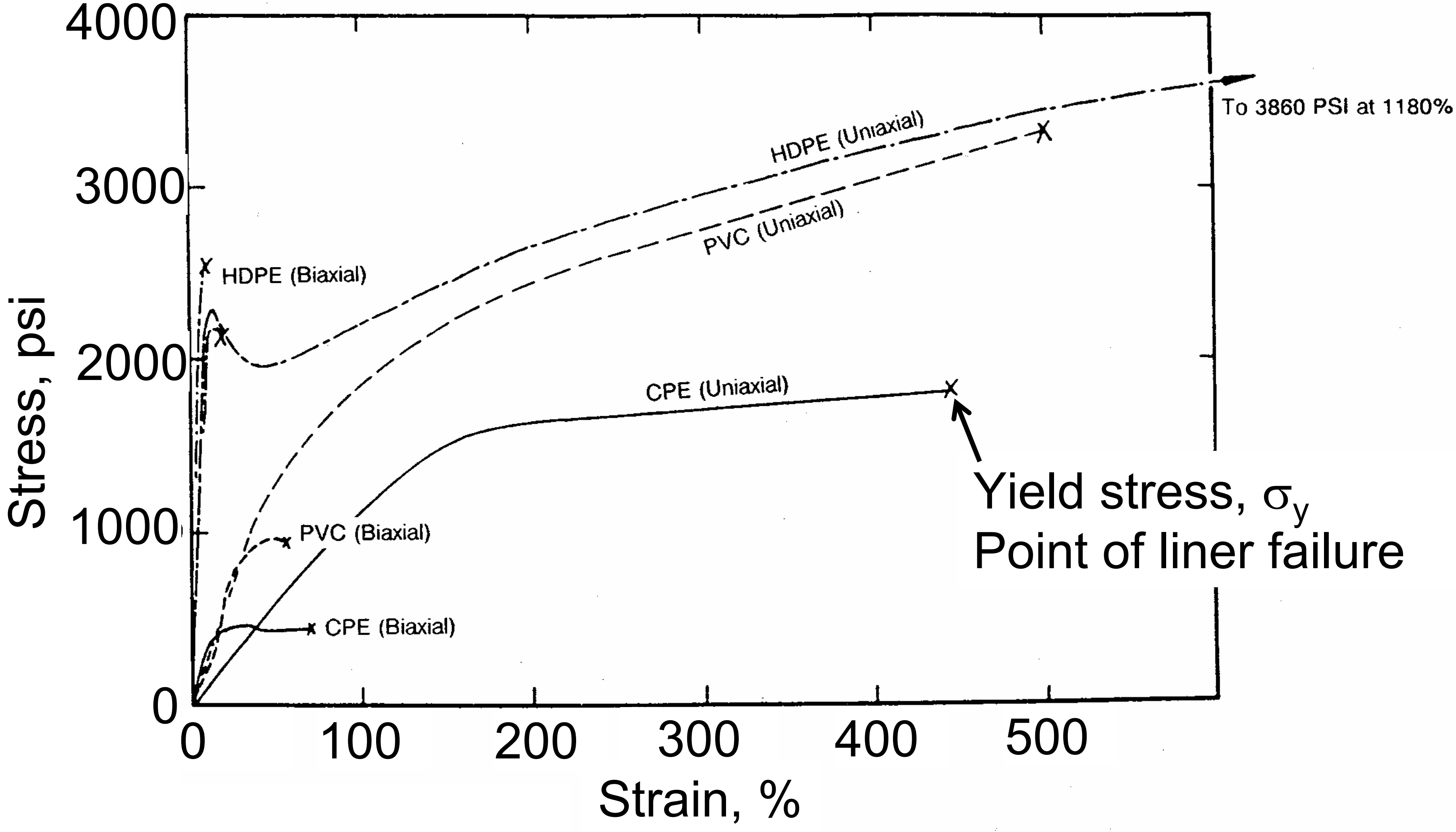
Density ρ = mass / unit volume

e.g. $\rho_{WATER} = 1\ g/cm^3 = 1\ kg/L$

Unit weight γ = weight / unit volume = $\rho\ g$

e.g. $\gamma_{WATER} = 9.8\ N/L = 1$ kg-force/L

Stress-strain tests of FMLs



Yield stress, σ_y
Point of liner failure

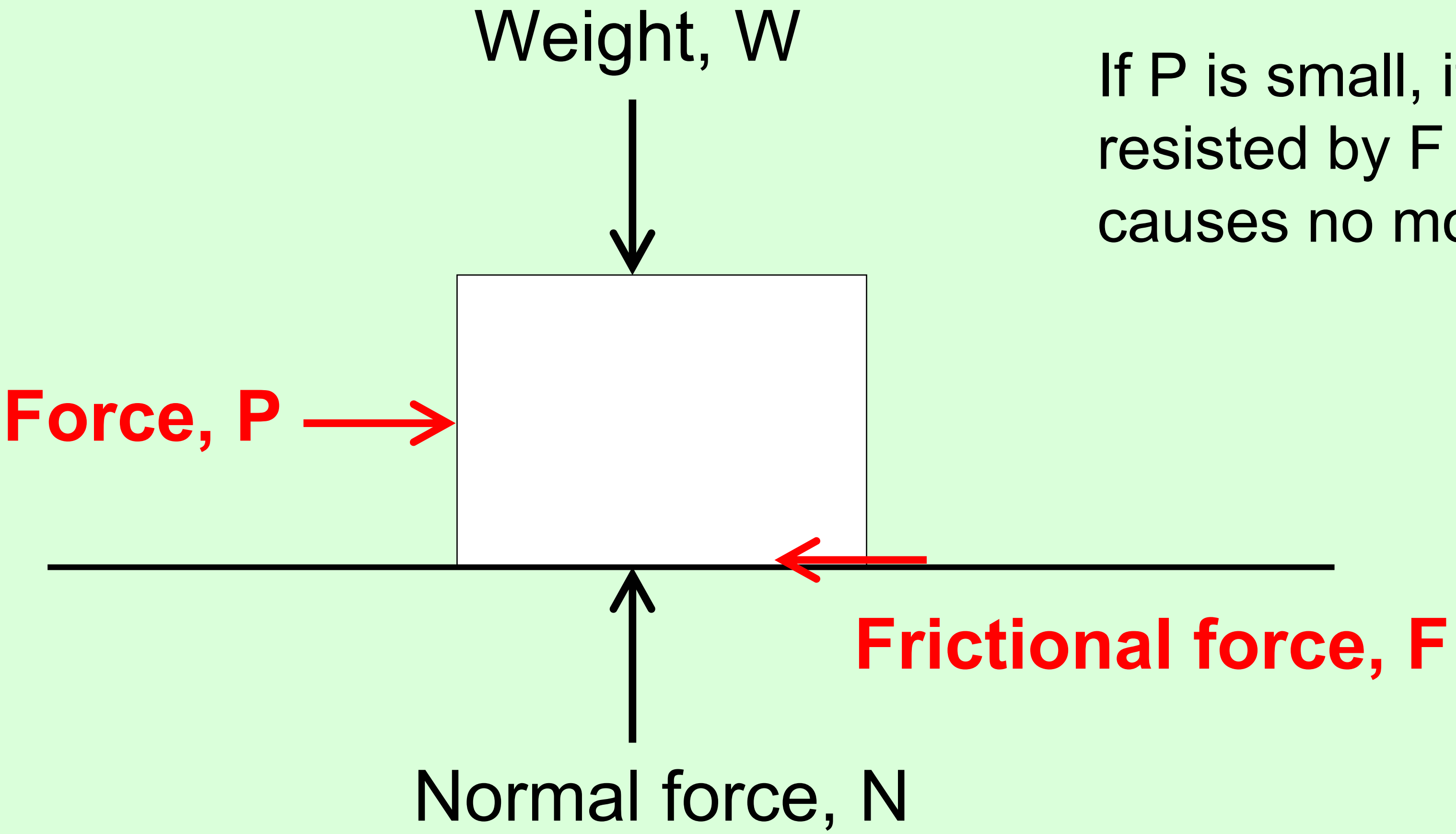
U.S. EPA, 1989. Seminar Publication: Requirements for Hazardous Waste Landfill Design, Construction, and Closure. Report Number EPA/625/4-89/022. Center for Environmental Research Information, U.S. Environmental Protection Agency, Cincinnati, Ohio. August 1989.

FML tensile strength

Typical FML yield stress = 1000 to 5000 psi

Manufacturers provide tensile strength data for their products

Review of statics



Weight, W

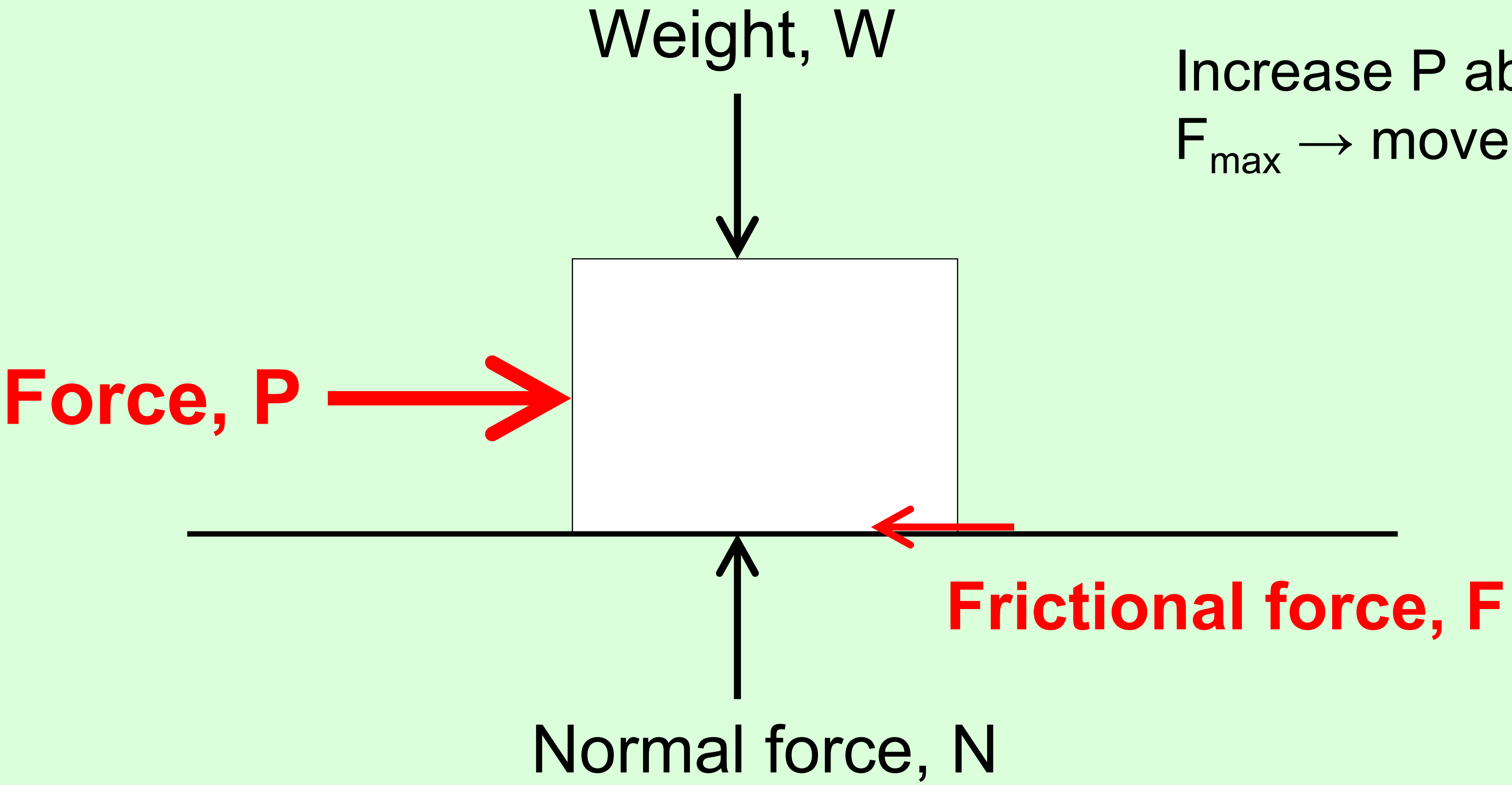
Force, P

Frictional force, F

Normal force, N

If P is small, it is resisted by F and causes no movement

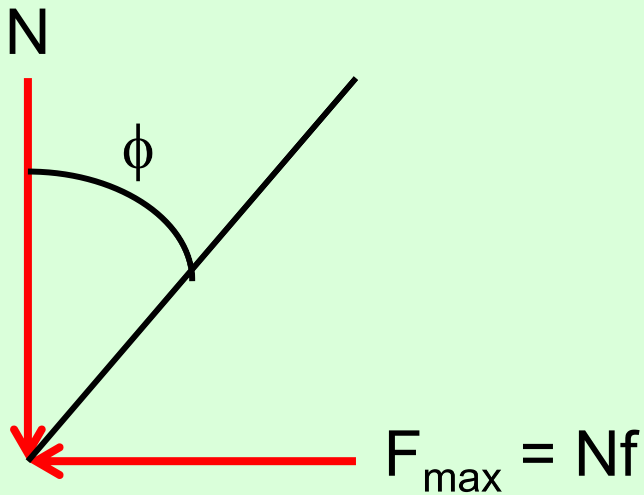
Review of statics



Increase P above $F_{max} \rightarrow$ movement

Friction force

F_{max} is maximum friction force = Nf where f is friction factor



ϕ = friction angle

$$\tan\phi = \frac{F_{max}}{N}$$

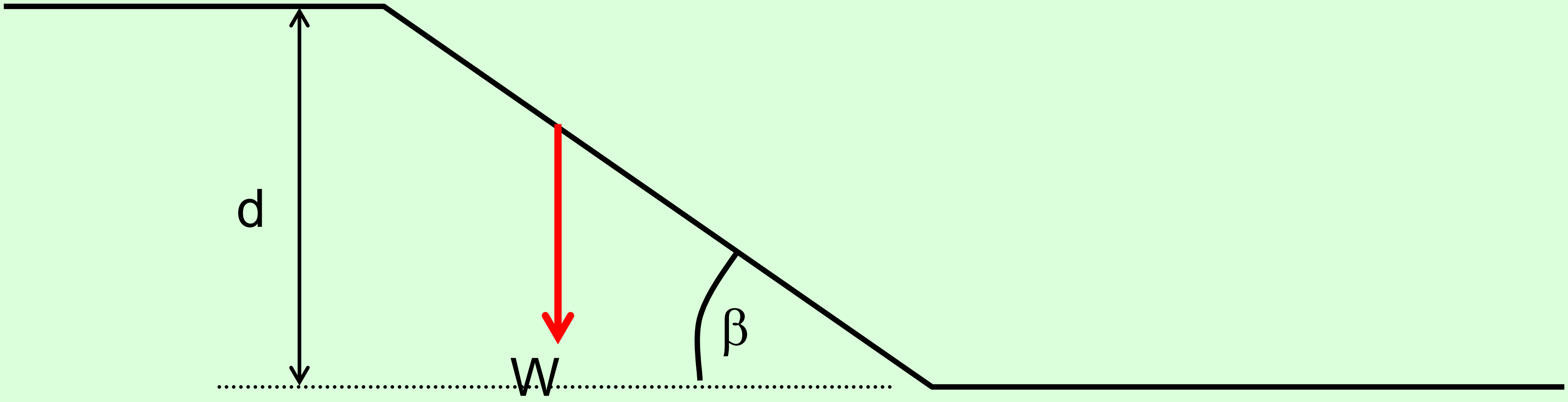
Forces on FML due to its own weight

W = weight of FML (per unit width)

F = force of friction (per unit width)

d = depth of landfill

β = angle of landfill side slope



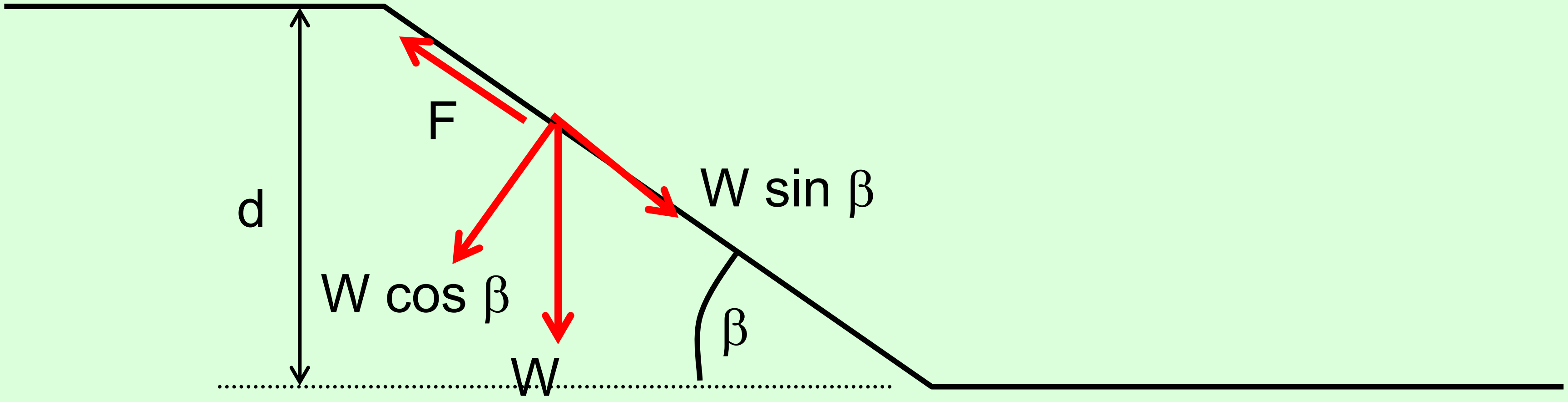
Weight of liner, W

$W = g\rho_L\ t\ (d / \sin\beta)$

t = liner thickness

ρ_L = density of liner = 0.92 to 1.4 g/cm^3

Forces on FML due to its own weight

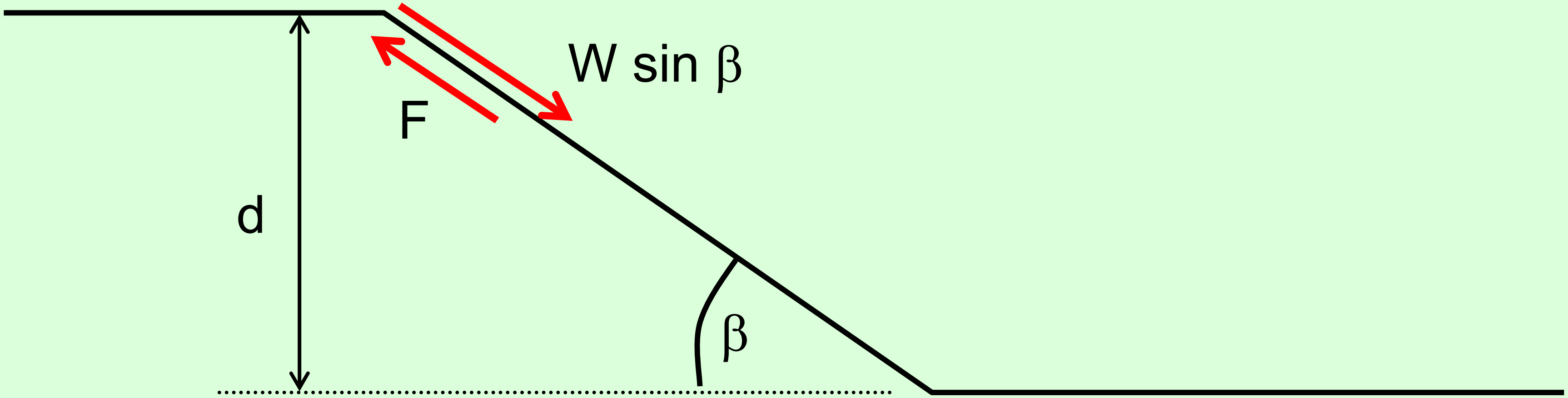


Friction force on liner

Normal force N = W cos β

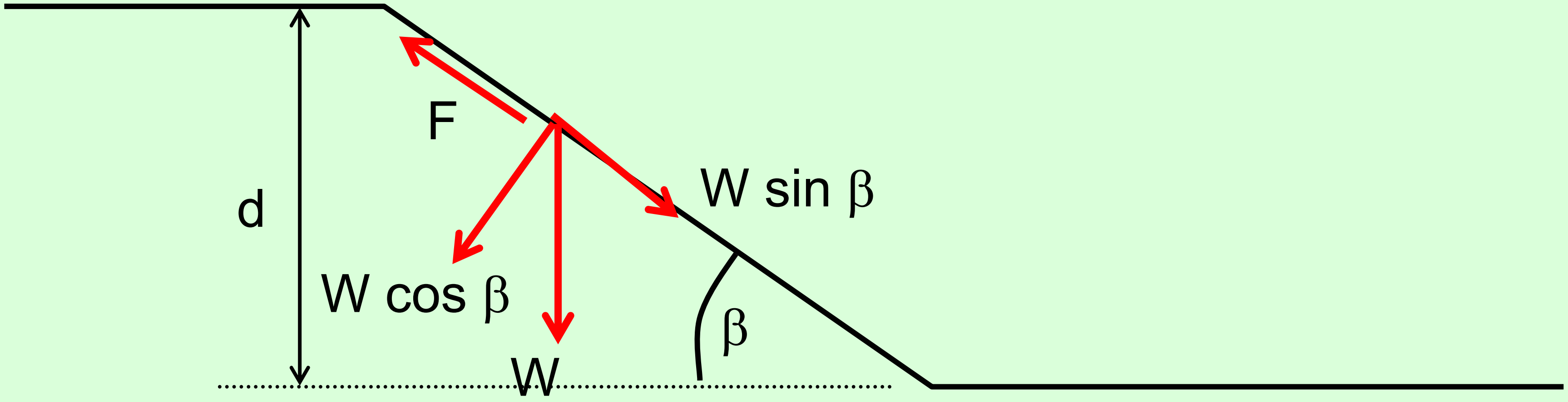
F = N tan ϕ = W cos β tan ϕ

Tensile forces on FML



Tensile force on liner: $T = W \sin \beta - F$

Forces on FML due to its own weight



Tensile force on liner: $T = W \sin\beta - F = W \sin\beta - W \cos\beta \tan\phi$

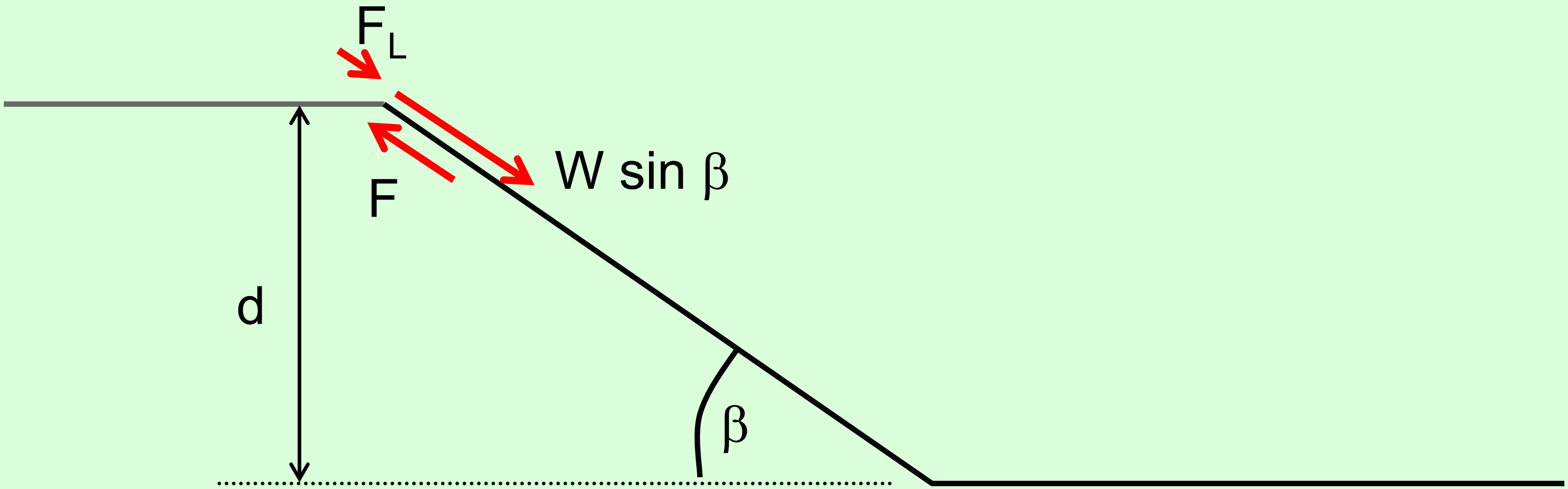
Tensile stress on liner = $\dfrac{\text{tensile force}}{\text{x - section area}} = \sigma$

For unit liner width, $\sigma = T/t$ $\sigma < \sigma_y$ to avoid liner failure!

Liner slippage

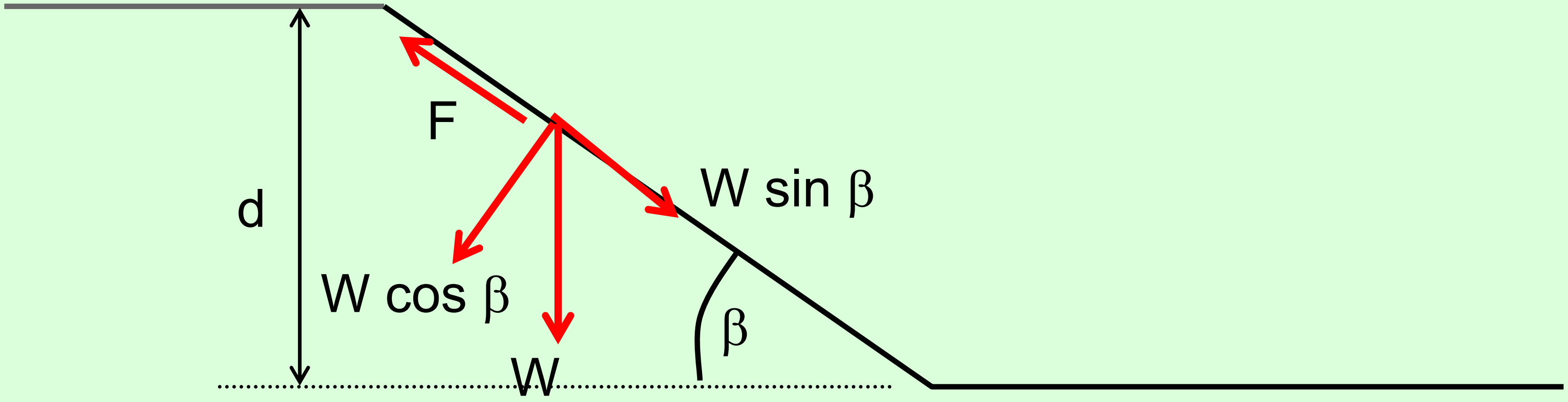
Net force on liner at top of slope =

$F_L = W \sin\beta - F = W \sin\beta - W \cos\beta \tan\phi$



Liner will slip down landfill slope if $F < W \sin\beta$

Liner slippage



Friction force on liner

Normal force $N = W \cos \beta$

Liner slips unless:

$F = N \tan \phi = W \cos \beta \ \tan \phi > W \sin \beta$

$\tan \phi > W \cos \beta / W \sin \beta = \tan \beta$

Liner slippage

Typical values of ϕ:

	Friction angle, ϕ	Horizontal:vertical
Soil to FML	17 to 27°	3.3:1 to 2:1
Soil to geotextile	23 to 30°	2.3:1 to 1.7:1
FML to geotextile	6 to 23°	9.5:1 to 2.4:1

Typical design is 3:1 = 19.5°

Liner slippage

Factor of safety for liner slippage:

$$FS = \frac{\tan\phi}{\tan\beta} = 1.25 \text{ to } 1.5$$

A higher factor of safety is needed when outcome endangers public or environment!

Liner slippage

Simple analysis does not necessarily suffice for design

Example: Kettleman Hills hazardous waste landfill in California had liner slip failure in 1988

Pre-filling analysis indicated liner would be stable

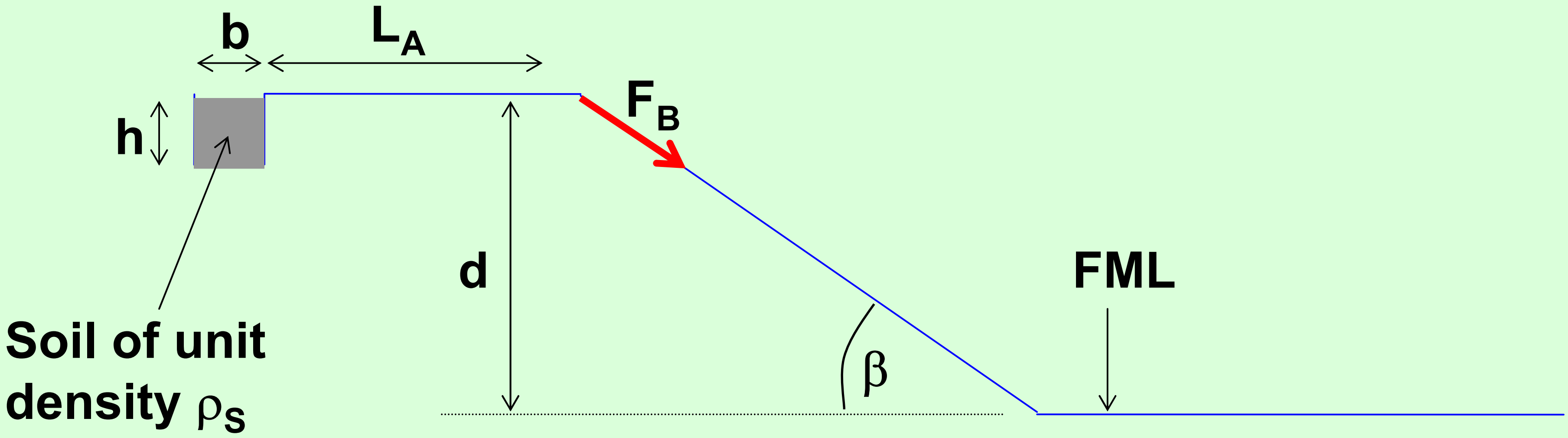
Subsequent multi-dimensional analysis showed instabilities

Anchorage to resist liner slippage

F_B is the net force on the liner at the top of the slope

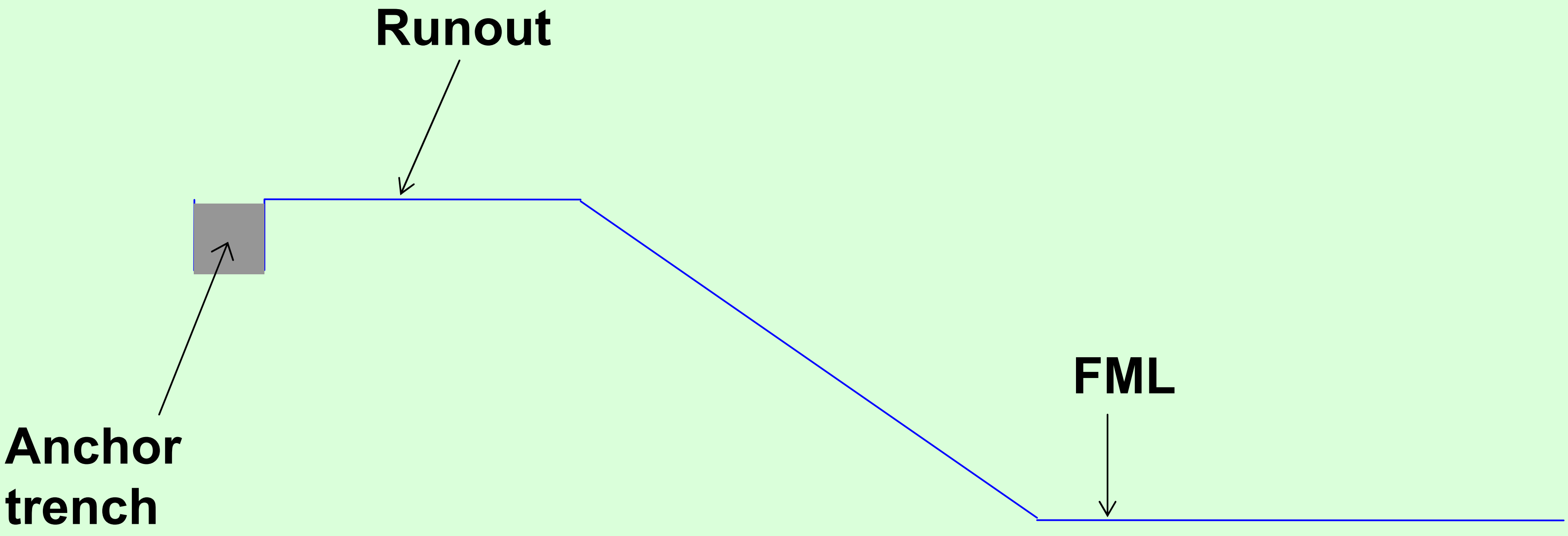
$$= W \sin \beta - W \cos \beta \tan \phi$$

F_B is resisted by F_A, the anchorage force



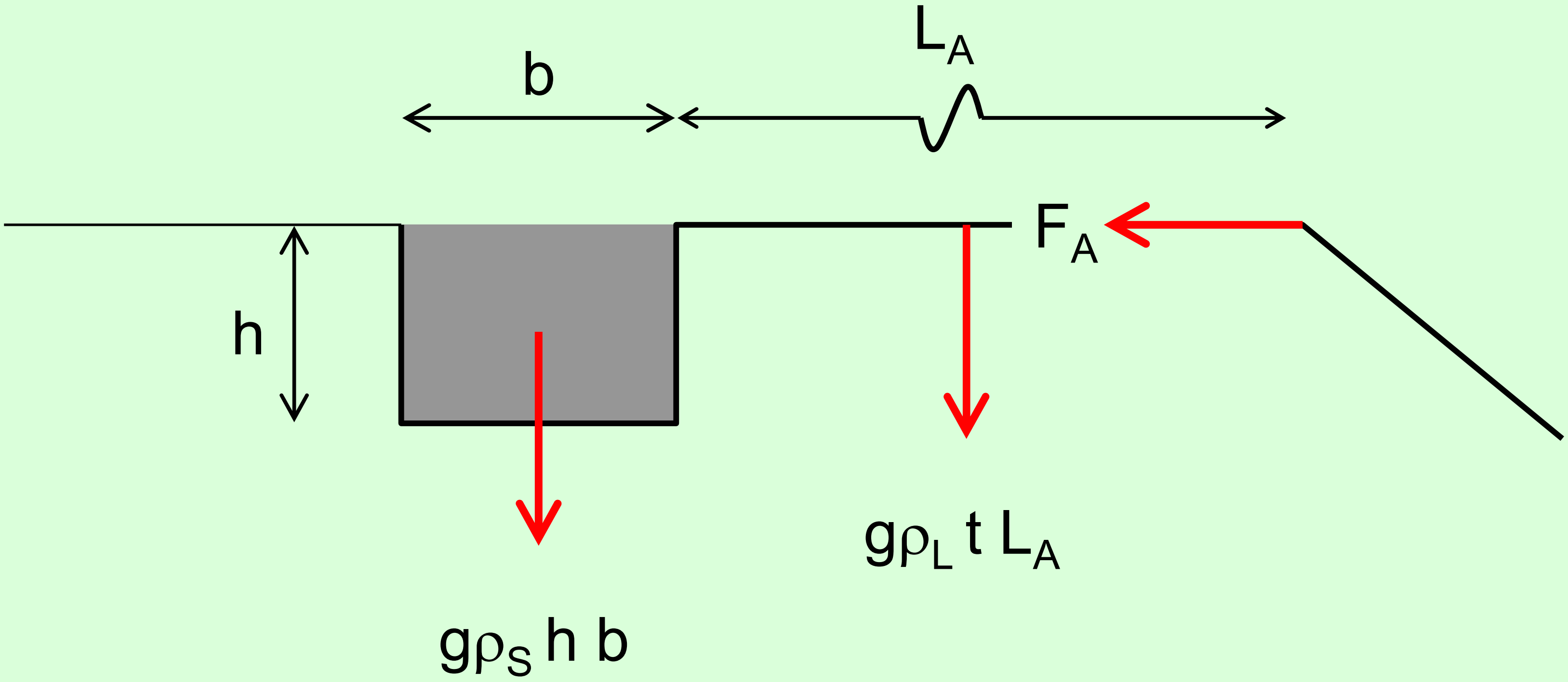
Anchorage to resist liner slippage

Terminology:



Anchorage design

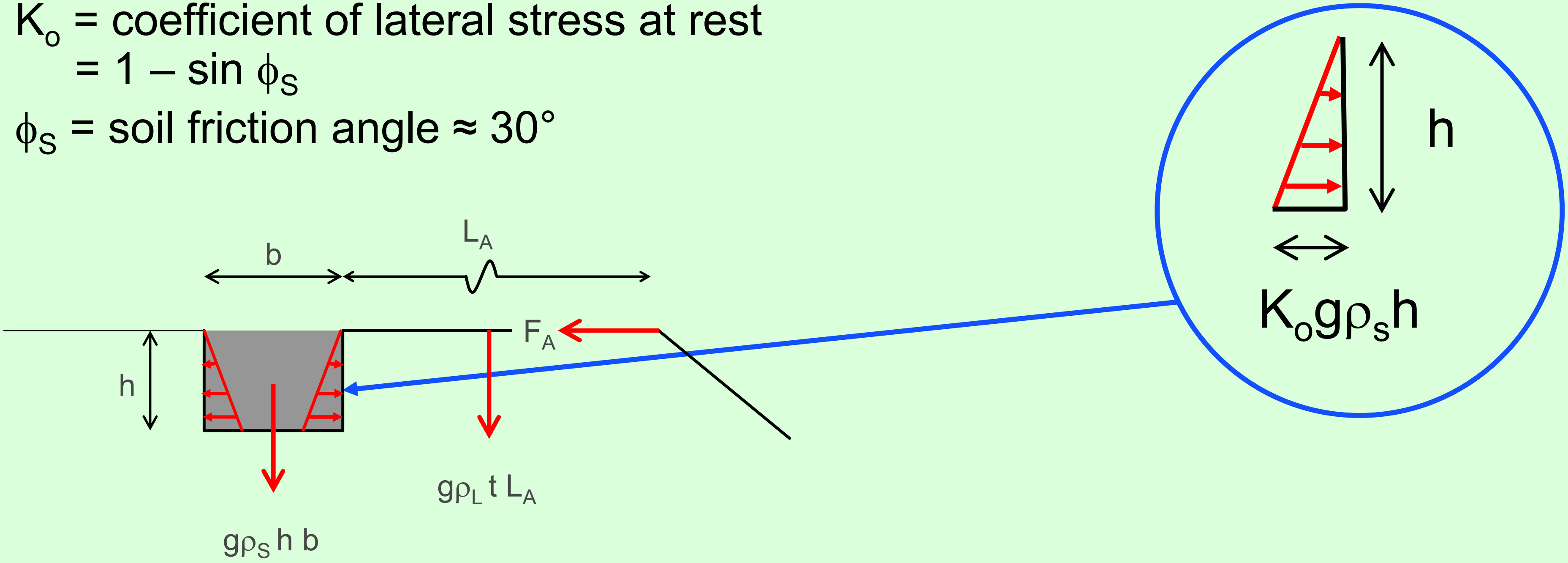
$$F_A = g\rho_S\ h\ b\ \tan\phi + g\rho_L t\ \ L_A\ \tan\phi$$



This equation ignores sidewall friction in anchor trench

Anchorage design

K_o = coefficient of lateral stress at rest
$= 1 - \sin \phi_S$
ϕ_S = soil friction angle ≈ 30°

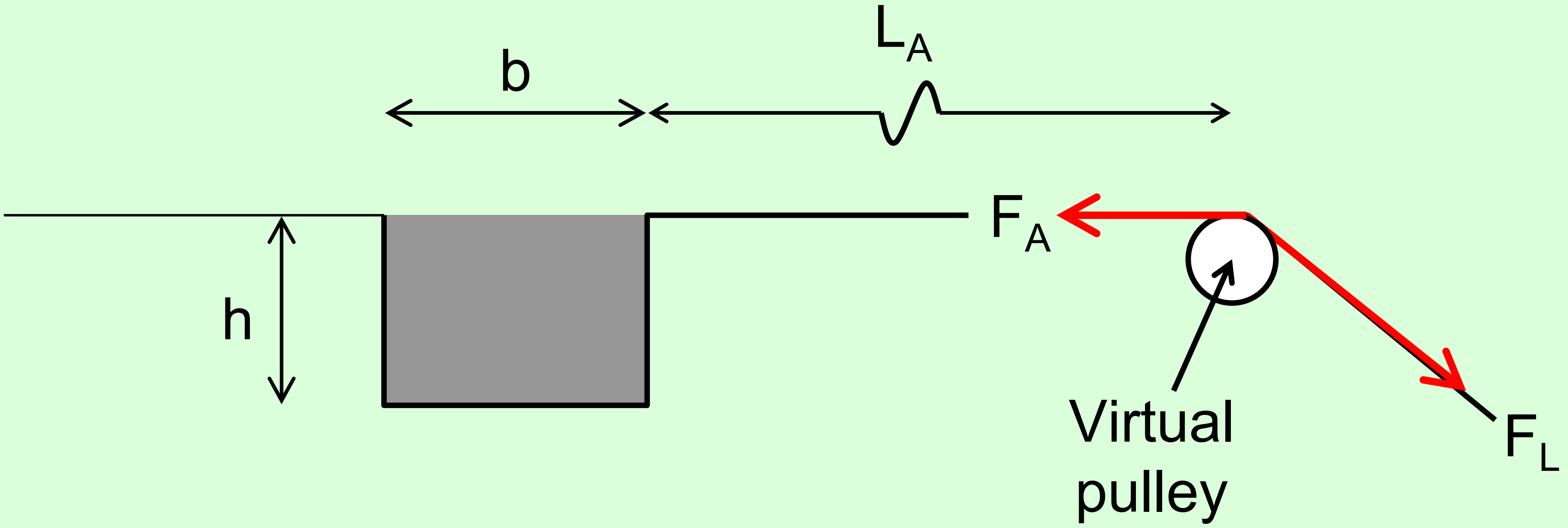


$$F_A = g\rho_S\, h\, b \tan\phi + g\rho_L t\, L_A \tan\phi + 2K_o g\rho_S\, h^2/2 \tan\phi$$

Including sidewall friction in anchor trench

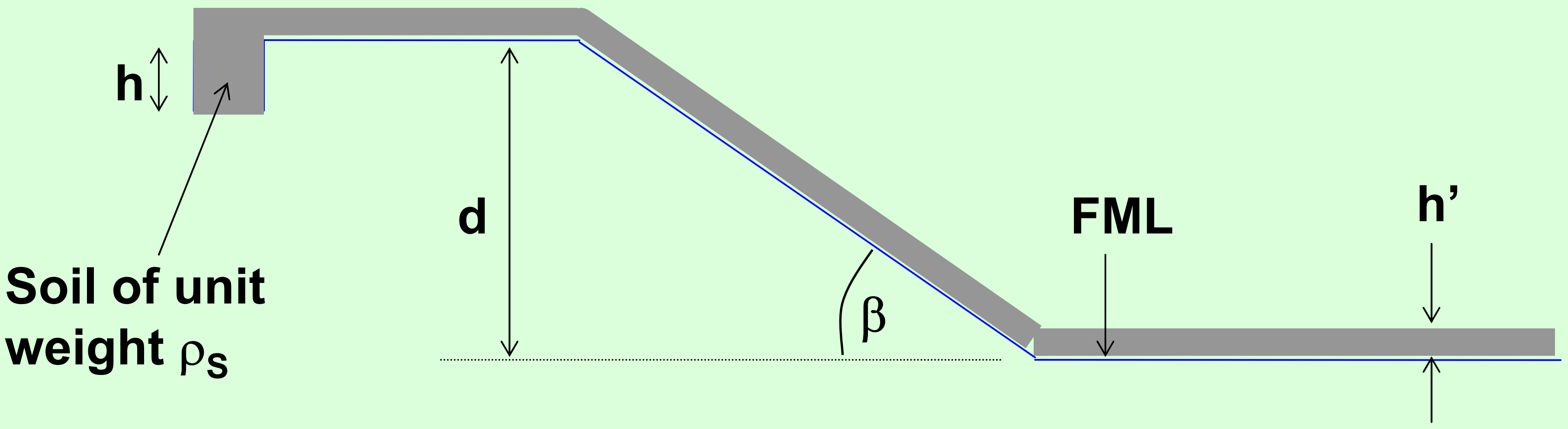
Anchorage design

Anchorage force, F_A, resists pull by liner, F_L



Factor of safety = $FS_A = F_A/F_L$ should be 1.2 to 1.5

Anchorage with soil cover



$F_A = g\rho_S\,(h + h')\,b \tan\phi + (g\rho_L\,t + g\rho_S\,h')\,L_A \tan\phi$

(Does not include anchor trench sidewall friction)

Other forces to be considered

Weight of soil on liner = $g\rho_S\ h'\ d \cos\beta$

Weight of vehicle
= $T \sin\beta$ for vehicle of weight T

Force of equipment braking $\simeq$ 0.3 T

Seepage (weight of water on liner)

Force of anchorage at base if any

Wind forces on liner

Requires analysis of potential maximum wind, uplift associated with that wind

Design needs to determine spacing of sand bags to weigh down empty liner

Structural details as source of failure

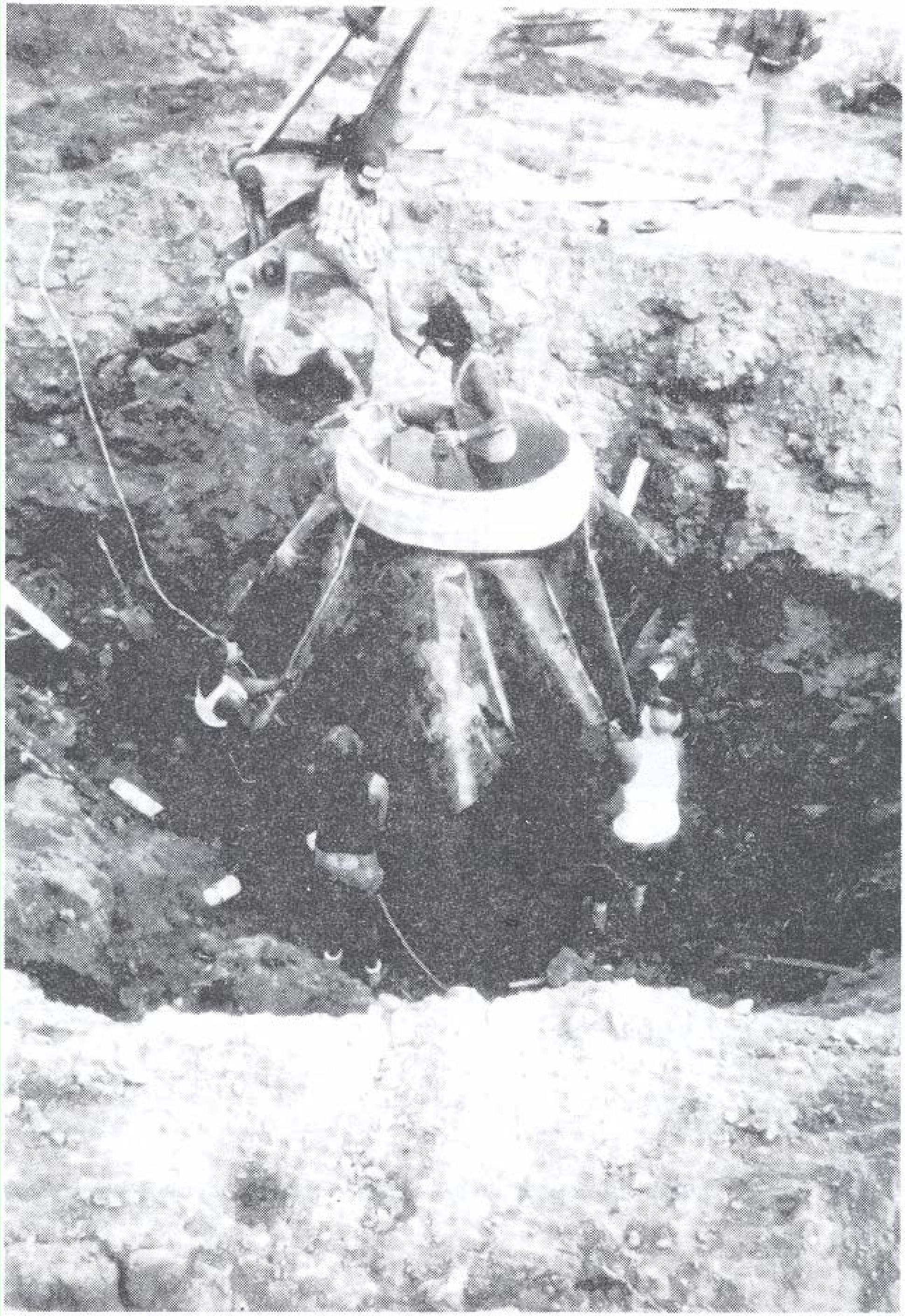
Standpipes are installed to provide access to leachate collection system

Consolidating waste exerts downward pull on standpipe

Frictional pull can punch standpipe through liner if forces get too great

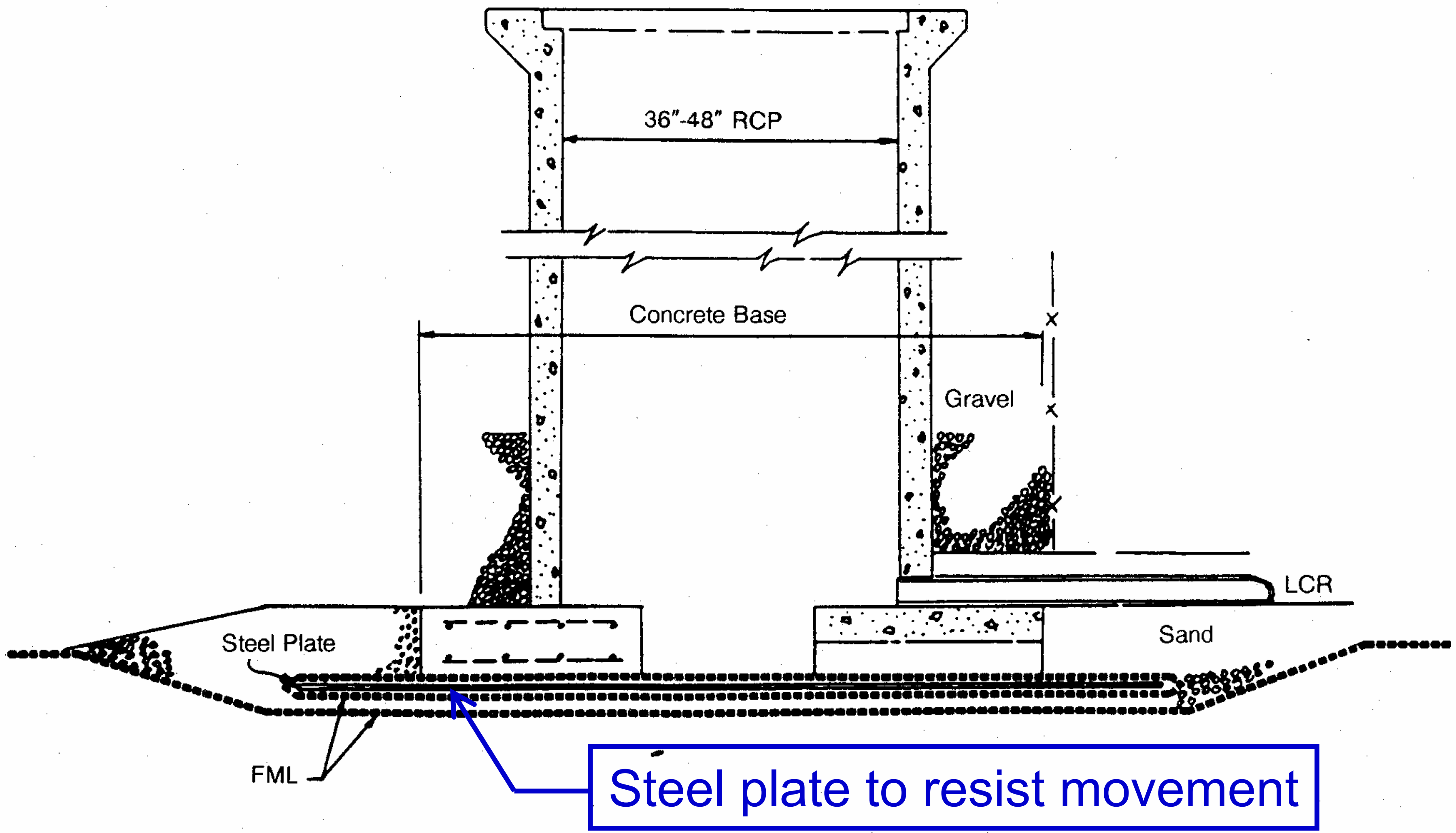
Remedy is to cover standpipe with liner or other low-friction material to reduce pull of waste, and to strengthen below standpipe

FML to reduce friction on standpipe



U.S. EPA, 1989. Seminar Publication: Requirements for Hazardous Waste Landfill Design, Construction, and Closure. Report Number EPA/625/4-89/022. Center for Environmental Research Information, U.S. Environmental Protection Agency, Cincinnati, Ohio. August 1989.

Standpipe structural elements

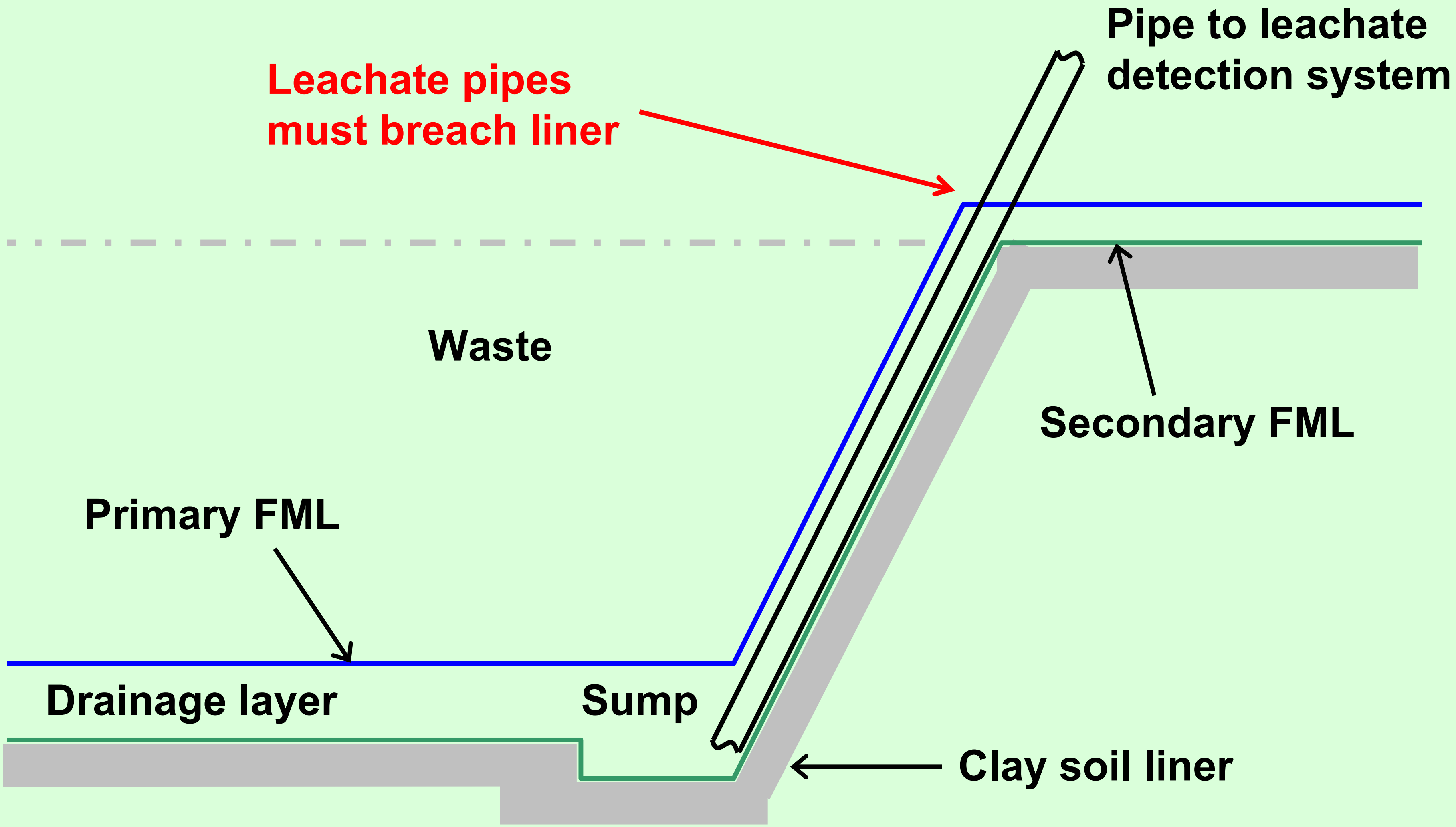


Steel plate to resist movement

Figure 3-15. Details of standpipe/drain.

U.S. EPA, 1989. Seminar Publication: Requirements for Hazardous Waste Landfill Design, Construction, and Closure. Report Number EPA/625/4-89/022. Center for Environmental Research Information, U.S. Environmental Protection Agency, Cincinnati, Ohio. August 1989.

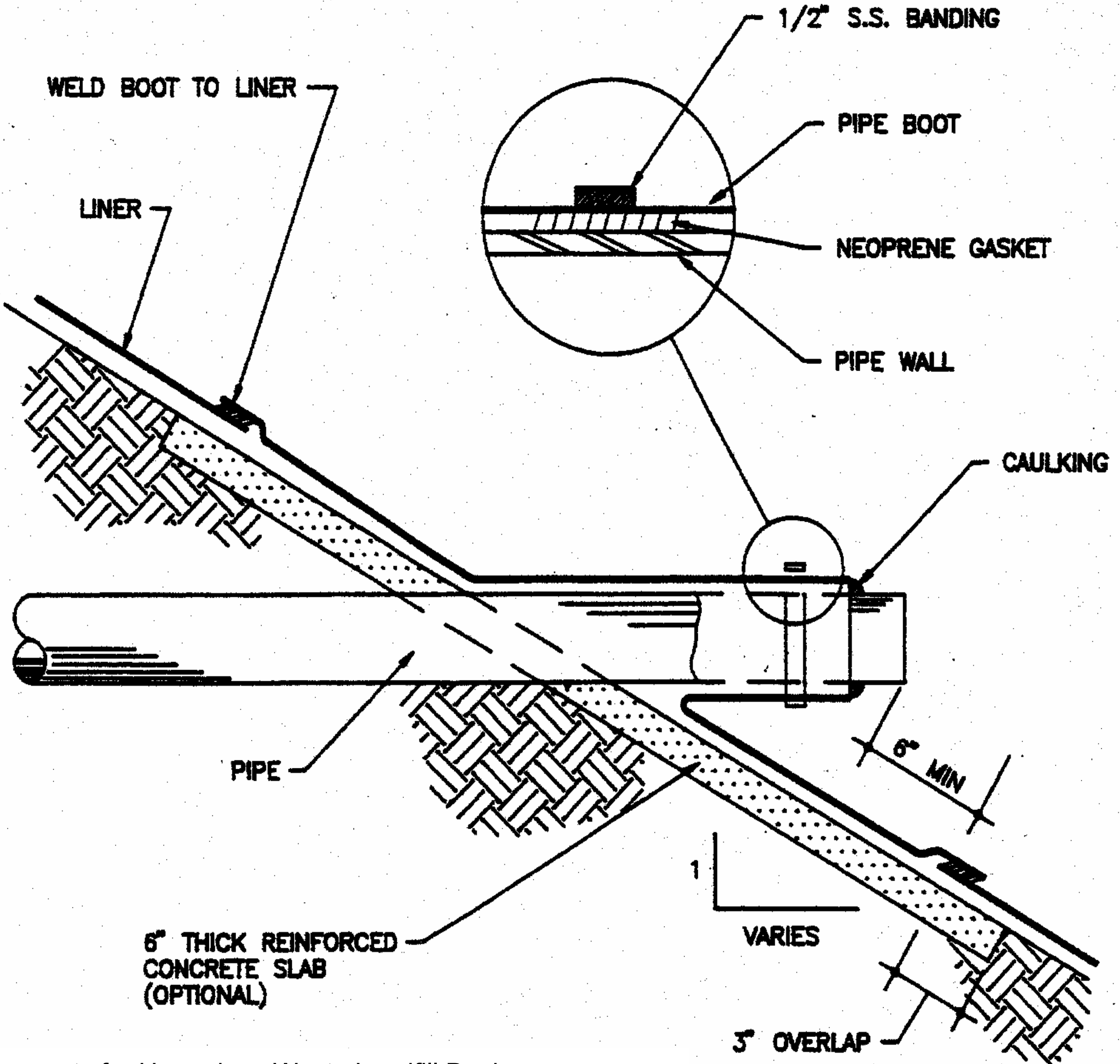
Pipes to leachate collection



Leachate pipe detail

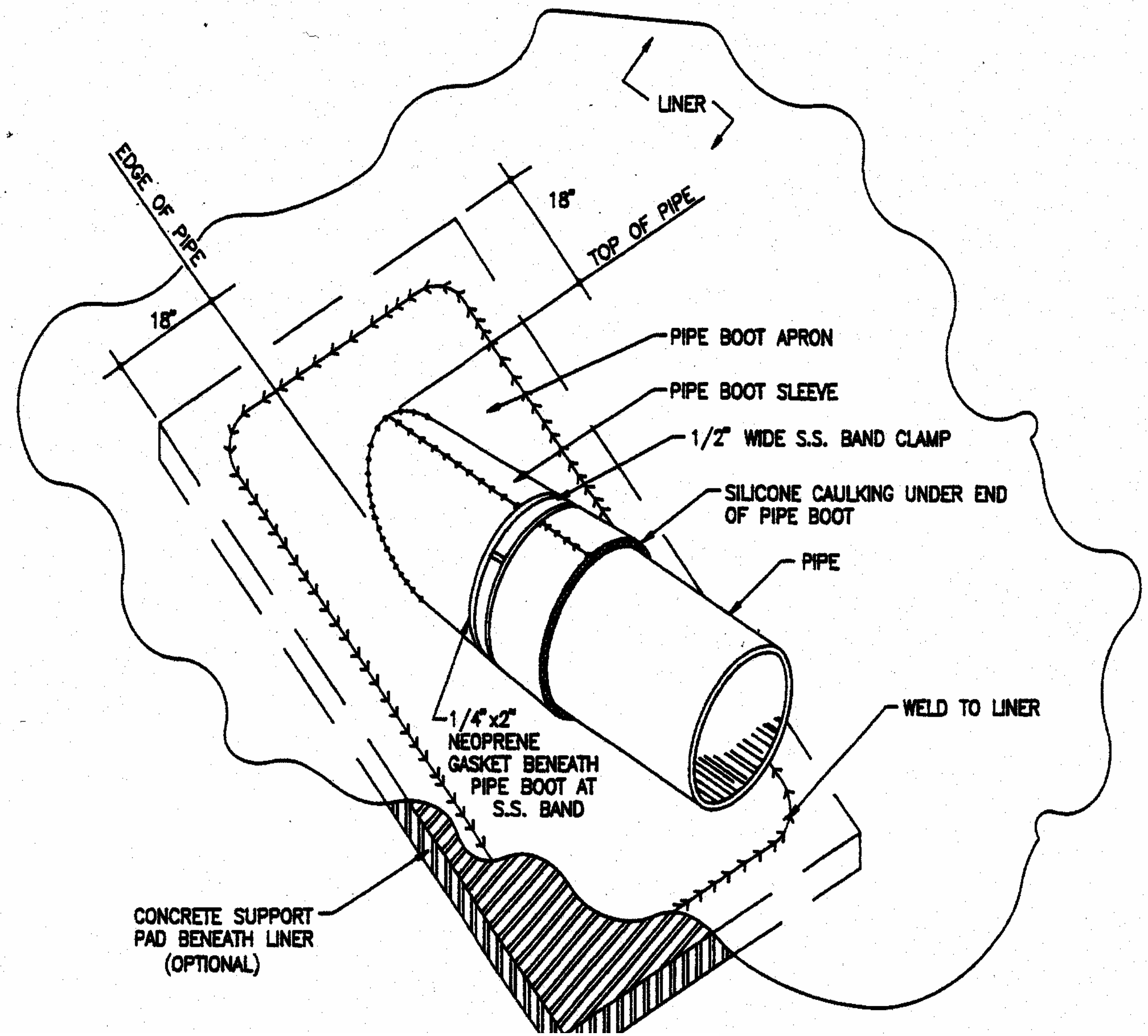
If leachate pipe is firmly fixed to liner, then if the pipe gets hit by a vehicle or similar, liner can tear

Need instead to construct flexible penetrations, to avoid damage



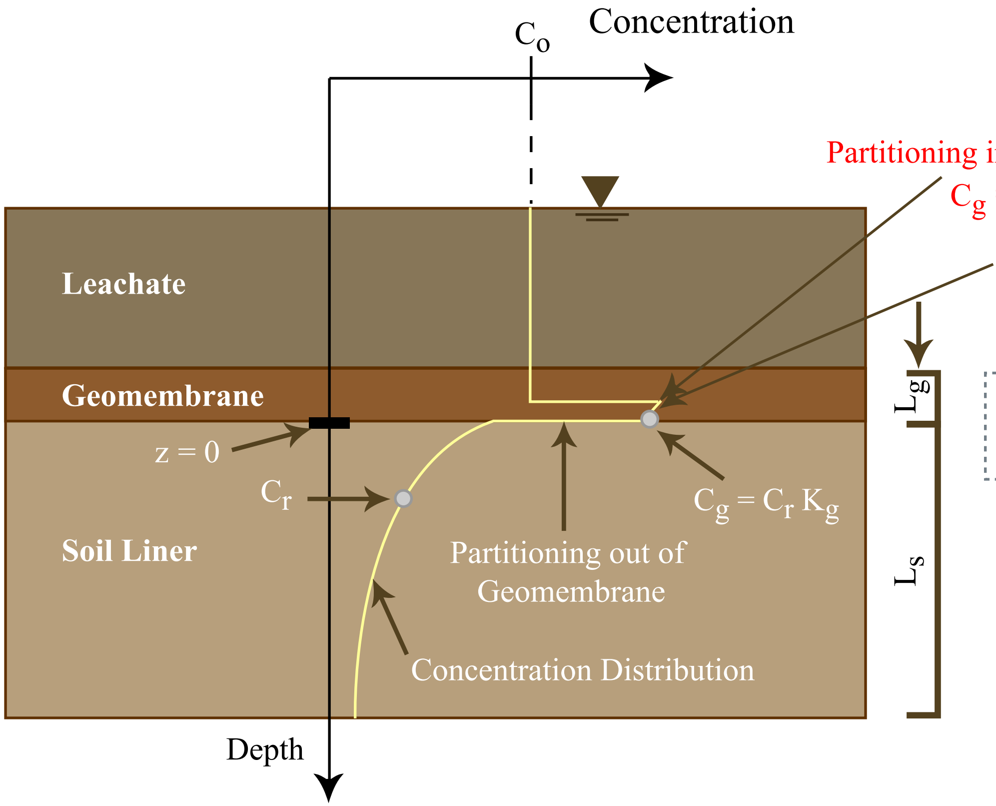
Source: U.S. EPA, 1989. Seminar Publication: Requirements for Hazardous Waste Landfill Design, Construction, and Closure. Report Number EPA/625/4-89/022. Center for Environmental Research Information, U.S. Environmental Protection Agency, Cincinnati, Ohio. August 1989.

Leachate pipe detail



Source: U.S. EPA, 1989. Seminar Publication: Requirements for Hazardous Waste Landfill Design, Construction, and Closure. Report Number EPA/625/4-89/022. Center for Environmental Research Information, U.S. Environmental Protection Agency, Cincinnati, Ohio. August 1989.

Organic chemical transport through composite liner



K_g= 135 for Toluene
(K_g is dimensionless [$(M/L^3)/(M/L^3)$])

C_o= Leachate Concentration	C_g= Partition Coefficient of Geomembrane	C_r= Soil Pore Water Concentration
L_g= Geomembrane Thickness	K_g= Partition Coefficient of Geomembrane	L_s= Soil Liner Thickness

Adapted from: Foose, G. J. "Transit-Time Design for Diffusion through Composite Layers." *Journal of Geotechnical and Geoenvironmental Engineering, ASCE* 128, no. 7 (July 2002): 590-601.

Foose, G. J., C. H. Benson, and T. B. Edil. "Comparison of Solute Transport in Three Composite Liners." *Journal of Geotechnical and Geoenvironmental Engineering, ASCE* 128, no. 5 (May 2002): 391-403.

Partition coefficients for HDPE

Chemical	$\mathbf{K_g}$
Methylene chloride	1.7 - 2.9
Toluene	63 – 150
TCE	44 – 82
m-Xylene	190 - 310

Source: Park, J. K., and M. Nibras, 1993. Mass flux of organic chemicals through polyethylene geomembranes. *Water Environment Research*. Vol. 65, No. 3, Pg. 227-237. May/June 1993.

$$K_g = \frac{\dfrac{M_{SORBED}}{M_{FML}}\rho_{FML}}{C_W} \times 10^6$$

K_g = FML partition coefficient (-)

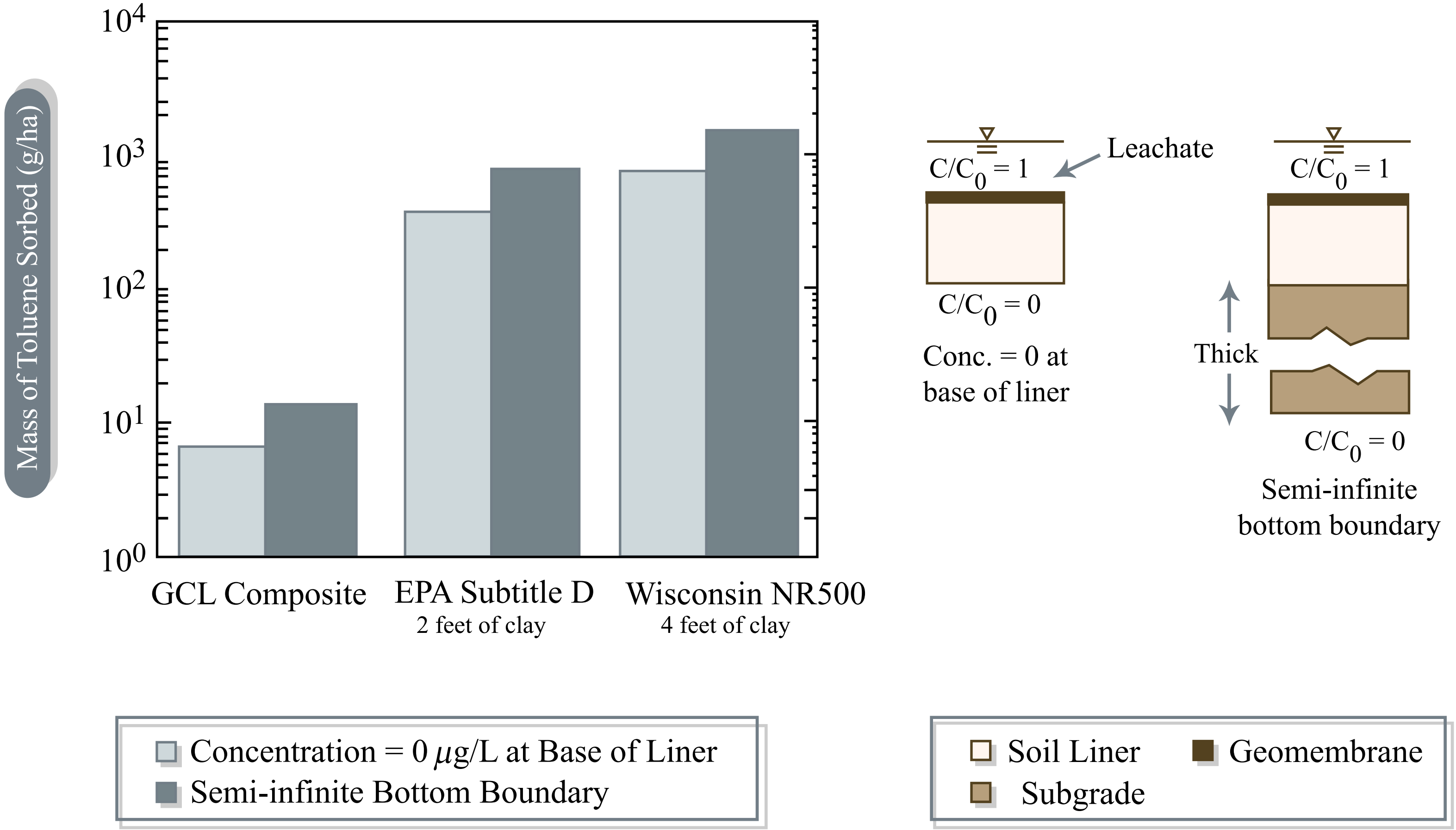
M_{SORBED} = mass sorbed to FML (g)

M_{FML} = mass of FML (g)

ρ_{FML} = density of FML (g/cm^3)

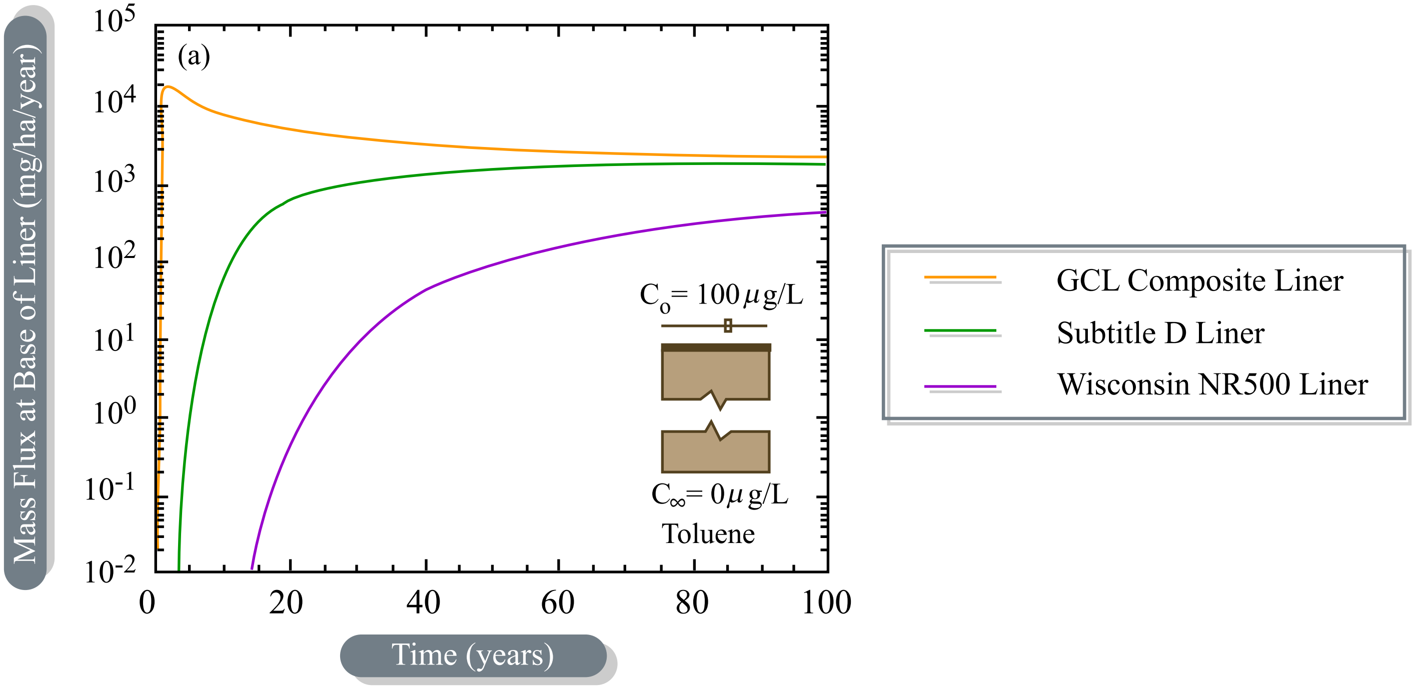
C_W = conc. in water (mg/L)

Toluene sorption by liners



Adapted from: Foose, G. J., C. H. Benson, and T. B. Edil. "Comparison of Solute Transport in Three Composite Liners." *Journal of Geotechnical and Geoenvironmental Engineering, ASCE* 128, no. 5 (May 2002): 391-403.

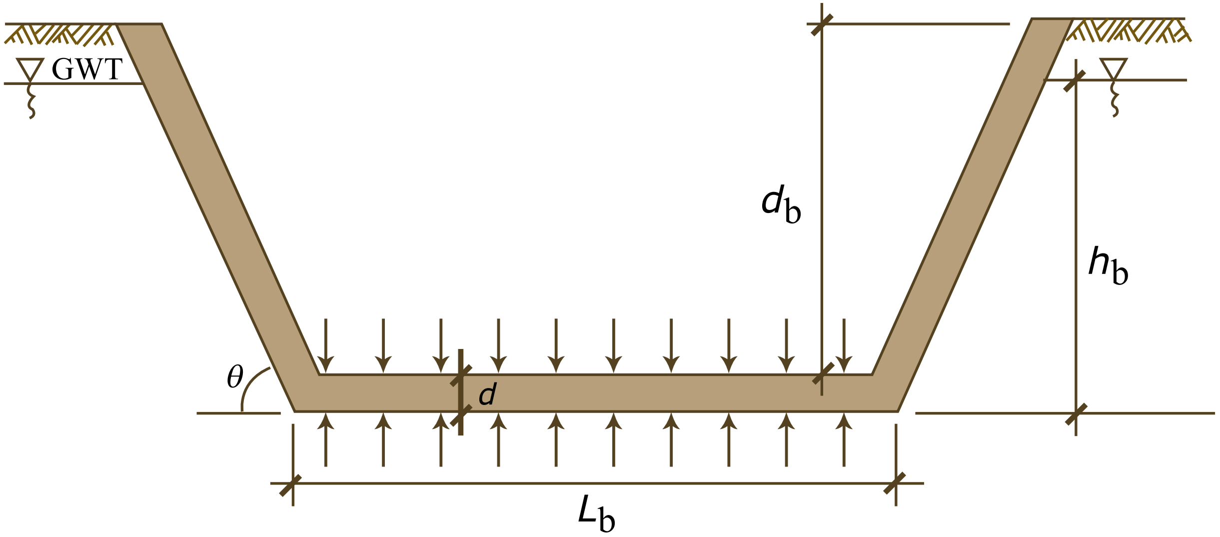
Toluene transport through liners



Adapted from: Foose, G. J., C. H. Benson, and T. B. Edil. "Comparison of Solute Transport in Three Composite Liners." *Journal of Geotechnical and Geoenvironmental Engineering, ASCE* 128, no. 5 (May 2002): 391-403.

Liner blowout

Empty landfill, with liner, below the water table:



Possible Liner Blowout Situation

Adapted from: Bagchi, A. *Design, Construction, and Monitoring of Sanitary Landfill.* 2nd ed.
New York: John Wiley & Sons, 1994.

Critical hydraulic head for liner base

h_b = critical head (relative to landfill base elevation) [L]

$$h_b = \frac{4}{3}\frac{K_b C_u}{\rho_w}\left(\frac{d}{L_b}\right)^2 + \frac{\rho_s}{\rho_w} d$$

Critical hydraulic head for liner base

h_b = critical head (relative to landfill base elevation) [L]

K_b = empirical constant $\cong$ 0.25

γ_w = unit weight of water [M/L^3] = $g\rho_W$

γ_s = unit weight of soil [M/L^3] = $g\rho_s$

C_u = unit shear strength of clay [M/L^2]
$\cong$ 7500-10,000 kg-force/m^2
$\cong$ 1500-2000 psf

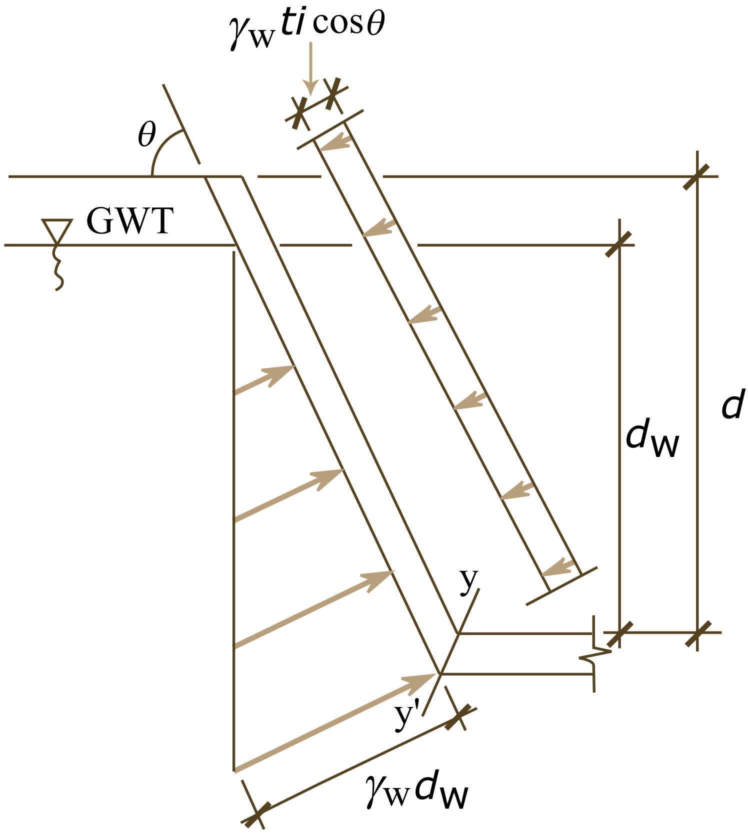
d = liner thickness [L]

L_b = length of base of landfill [L]

Sidewall blowout

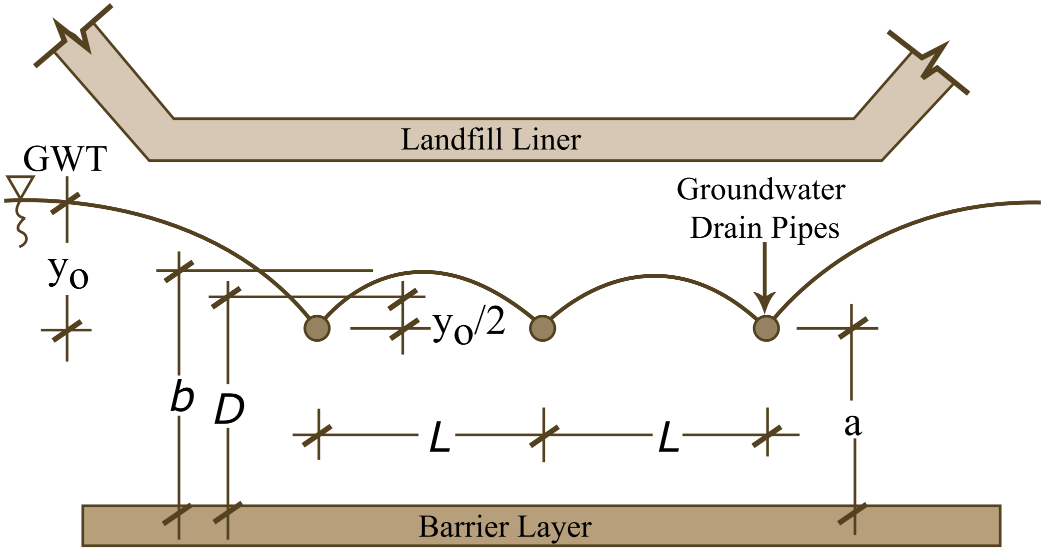
h_b = critical head (relative to landfill base elevation) [L]

$$h_b = \sqrt{\left(\frac{2C_u}{\gamma_w} + \frac{\gamma_s}{\gamma_w} d_b\right) d \sin^2\theta}$$



Adapted from: Bagchi, A. *Design, Construction, and Monitoring of Sanitary Landfill.* 2nd ed. New York: John Wiley & Sons, 1994.

Ground-water drains to prevent blowout



Adapted from: Bagchi, A. *Design, Construction, and Monitoring of Sanitary Landfill.* 2nd ed.
New York: John Wiley & Sons, 1994.