3.0 GS Design and Testing (Selected Problems)

3.1 Geomembranes
- thickness
- side slope tension
- anchorage

3.2 Geonets/Geocomposites
- leak detection
- leachate collection
- surface water drainage

3.3 Geotextiles
- filter for leachate collection
- separator for GN drainage
- protection for GM's
- gas collection layer

3.4 Geogrids
- veneer stability
- vertical expansion

3.5 Geopipe
- leachate collection spacing
- pipe diameter
- load capacity

3.1(a) GM Thickness

<u>First</u>, select minimum for installation

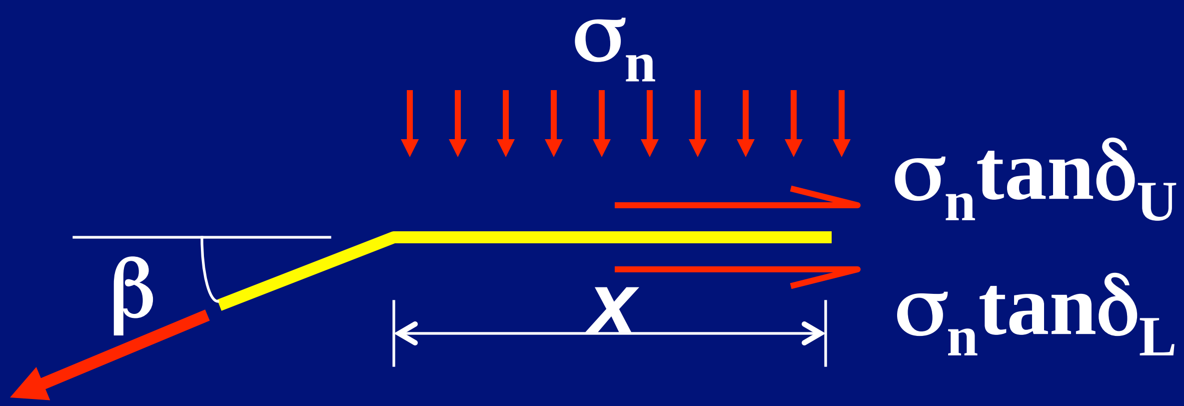
Recommended Minimum Properties for General Geomembrane Installation Survivability, after Koerner (1998)

Property and	Required Degree of Installation Survivability			
ASTM Test Method	Low	Medium	High	Very High
Thickness (D1593) (mm)	0.63	0.75	0.88	1.00
Tensile D882 (25 mm strip) (kN/m)	7	9	11	13
Tear (D1004 Die C) (N)	33	45	67	90
Puncture (D4833) (N)	110	140	170	200
Impact (D3998 mod.) (J)	10	12	15	20

<u>Second</u>, check against governing regulations

<u>Third</u>, verify against technical based design (follows)

Technical Based Thickness Design

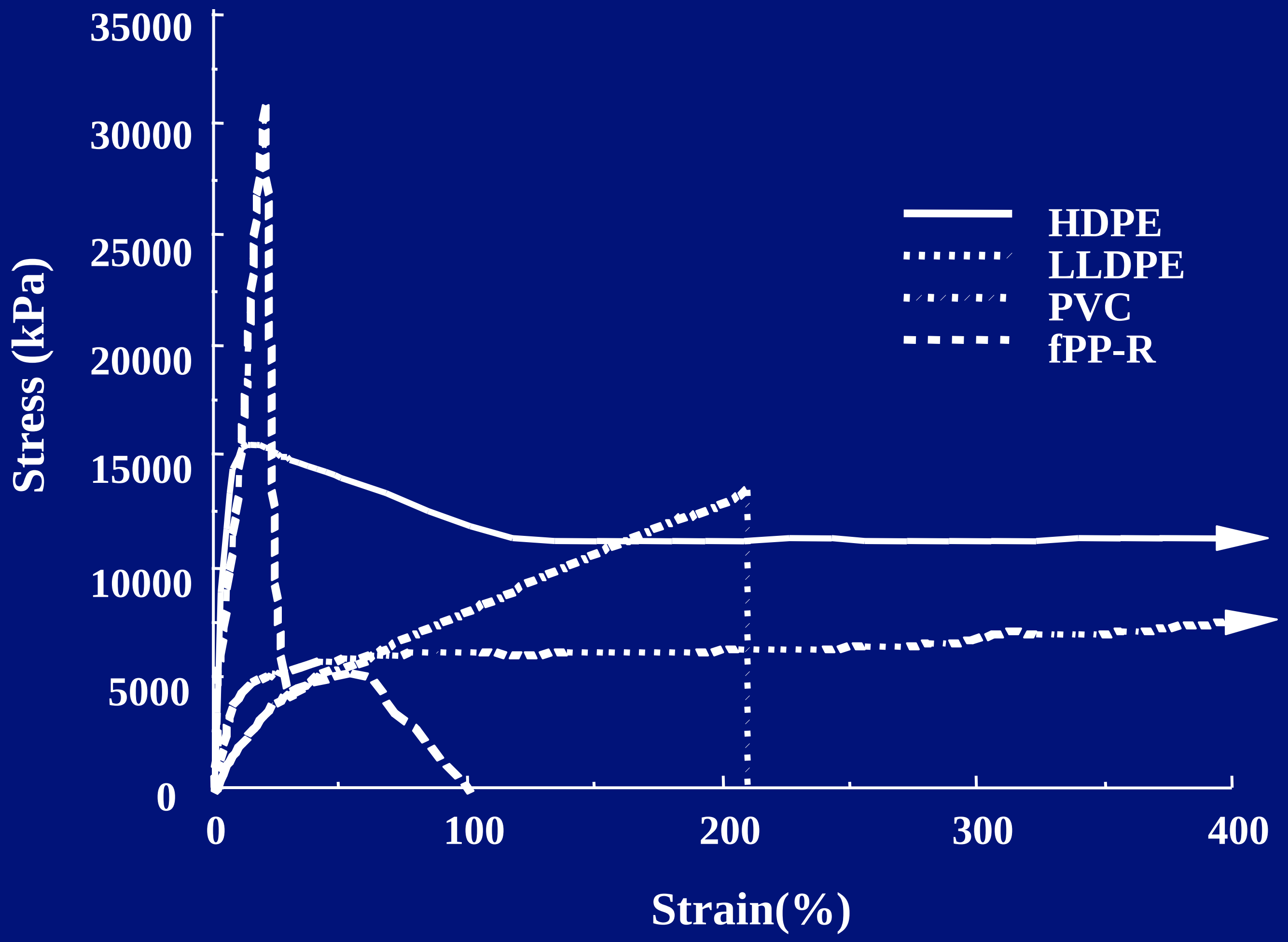


$$T = \sigma_{allow} t_{reqd}$$

$$t_{reqd} = \frac{\sigma_n x(\tan\delta_U + \tan\delta_L)}{\sigma_{allow}(\cos\beta - \sin\beta\tan\delta_L)}$$

and $$FS = \frac{t_{reg.} \text{ or } t_{instal.}}{t_{reqd}}$$

Tensile Strength Behavior of HDPE, LLDPE, PVC, and fPP-R



Tensile Strength Behavior of HDPE, LLDPE, PVC, and fPP-R

	Wide-Width Tension Test				
Test Property	Unit	HDPE	LLDPE	PVC	fPP-R
Maximum stress and	(kPa)	15,900	7,600	13,800	31,000
corresponding strain	(%)	15	400+	210	23
Modulus	(MPa)	450	69	20	300
Ultimate stress and	(kPa)	11,000	7,600	13,80	2,800
corresponding strain	(%)	400+	400+	210	79

GM Thicknesses are: HDPE 1.5 mm, LLDPE 1.0 mm, PVC 0.75 mm, fPP-R 0.91 mm

Example:

What is the required thickness of HDPE beneath 50 m waste at 12.5 kN/m³ under 20° subsidence. Use σ_{allow} = 15,900 kPa; x = 80 mm; δ_U = 18°; δ_L = 10°.

Solution:

$$t_{reqd} = \frac{(50)(12.5)(0.080)\left[\tan 18 + \tan 10\right]}{15{,}900\left[\cos 20 - (\sin 20)(\tan 10)\right]}$$

$$= 0.00179 \text{ m}$$

$$t_{reqd} = 1.79 \text{ mm}$$

Thus for U.S.

$$FS = \frac{t_{reqd}}{t_{reg.}} = \frac{1.79}{1.5} = 1.19, \quad \text{OK}$$

But for Germany

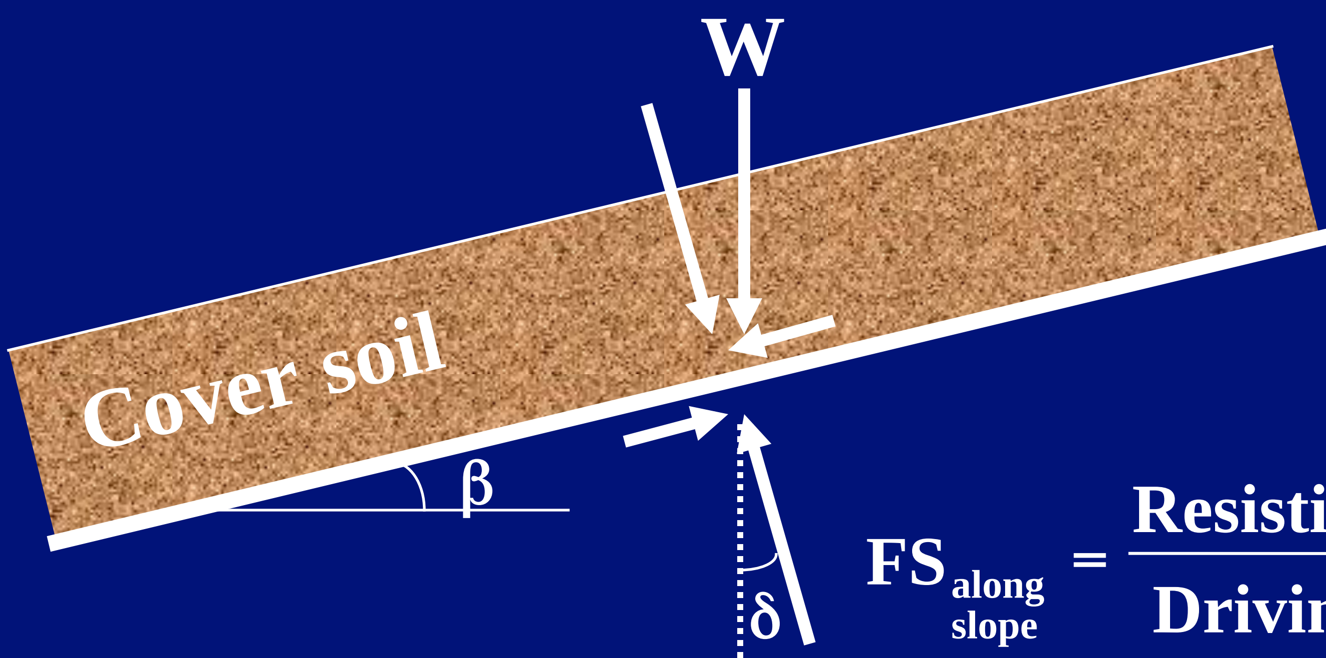
$$FS = \frac{t_{reqd}}{t_{reg.}} = \frac{1.79}{2.0} = 0.89, \quad \text{NG}$$

3.1(b) Geomembrane Cover Soil and GM Tension Design

(multiple layers come later)

- Cover soil stability
- Geomembrane tension
  - limit equilibrium
  - FEM
- Veneer reinforcement
  - (later in GG design section)

Cover Soil Stability (above GM)



$$FS_{\substack{along\\slope}} = \frac{\text{Resisting Forces}}{\text{Driving Forces}}$$

$$FS = \frac{(W\cos\beta)(\tan\delta)}{(W\sin\beta)}\frac{L}{L} \quad (1) \quad \text{or} \quad FS = \frac{\tan\delta}{\tan\beta} \quad (2)$$

Example (a) - Cover soil against GM

For 450 mm cover soil at 18 kN/m^3 on a GM with δ = 14°, what is FS-value for a 30 m long slope at 3(H)-to-1(V), i.e., β = 18.4°?

Solution:

$W = (0.450)(18) = 8.10 \text{ kN/m}^2$

$W \cos\beta = 7.69 \text{ kN/m}^2$

$W \sin\beta = 2.56 \text{ kN/m}^2$

Using Eq. 1

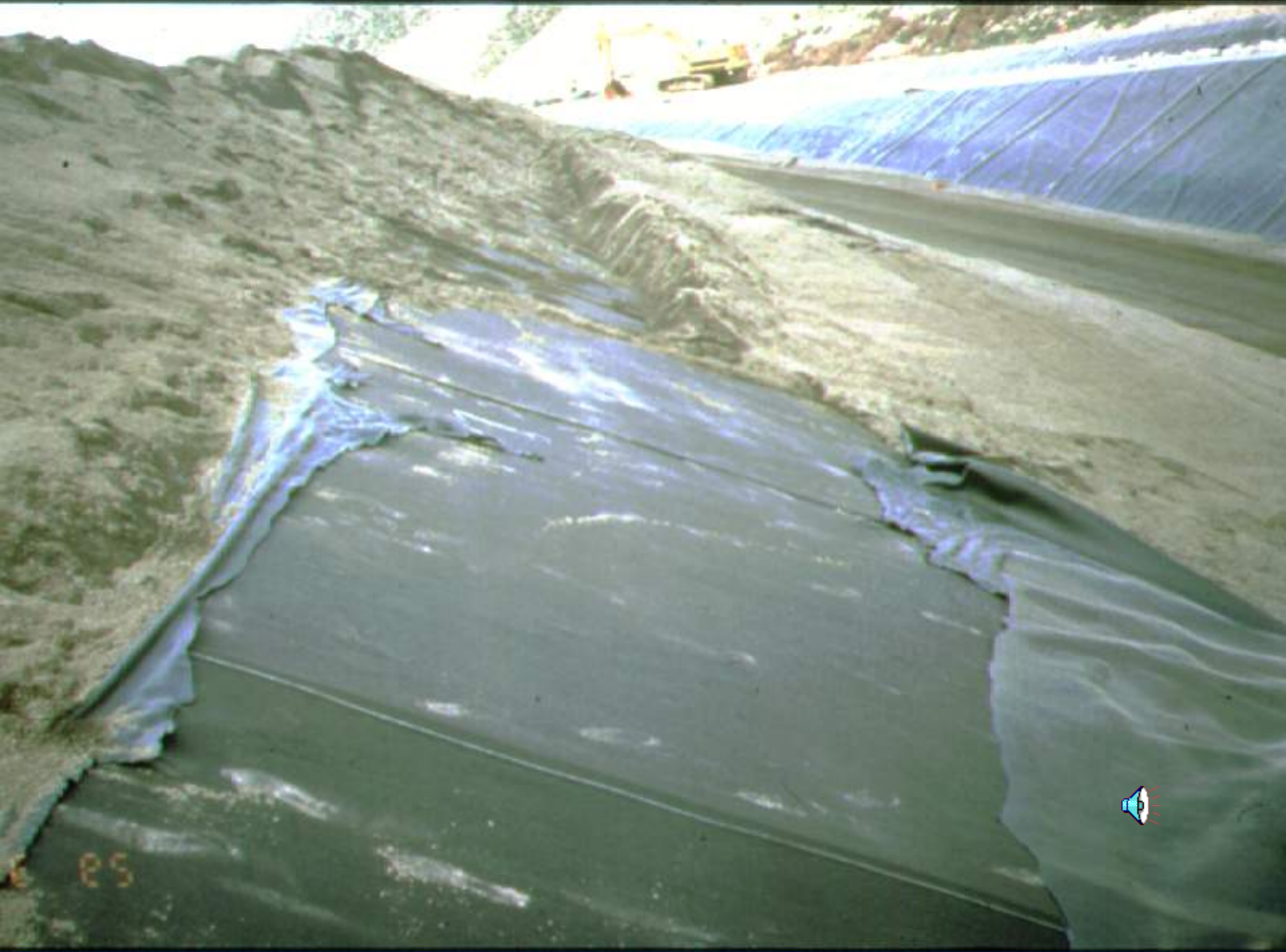
$$FS = \frac{7.69 \tan 14 (30)}{2.56 (30)}$$

$= 0.75$

Using Eq. 2

$$FS = \frac{\tan 14}{\tan 18.3}$$

$= 0.75$

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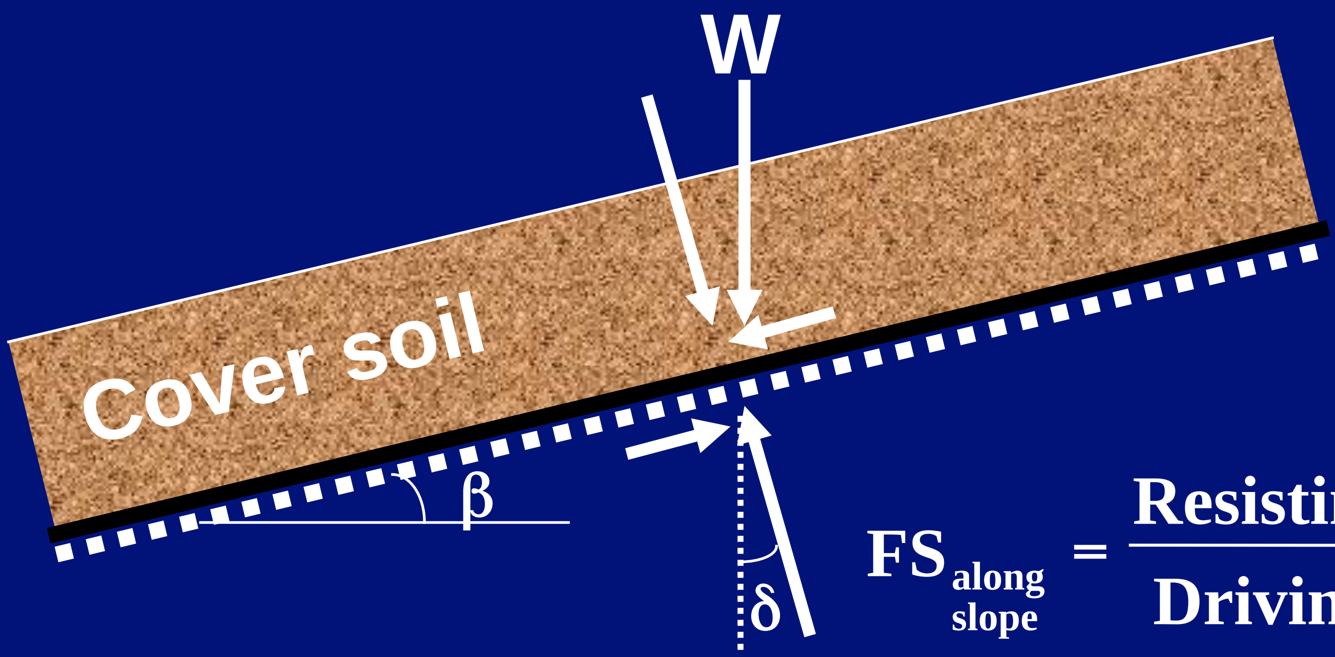
Cover Soil Stability (with GM)



$$FS_{\substack{along \\ slope}} = \frac{\text{Resisting Forces}}{\text{Driving Forces}}$$

$$FS = \frac{(W\cos\beta)(\tan\delta)(L) + T_{GM}}{(W\sin\beta)(L)}$$

Example (b) - Cover soil and GM against underlying GT (e.g., a GM placed above a GT)

Same problem as before, but δ_U = 19° and δ_L = 14°. The GM is 1.5 mm HDPE with T_{allow} = 15,900 kPa. Vary slope length and find the resulting FS-values.

$$FS = \frac{(W\cos\beta)\tan\delta(L) + T_{GM}}{W\sin\beta(L)} \qquad \text{Eq. 3}$$

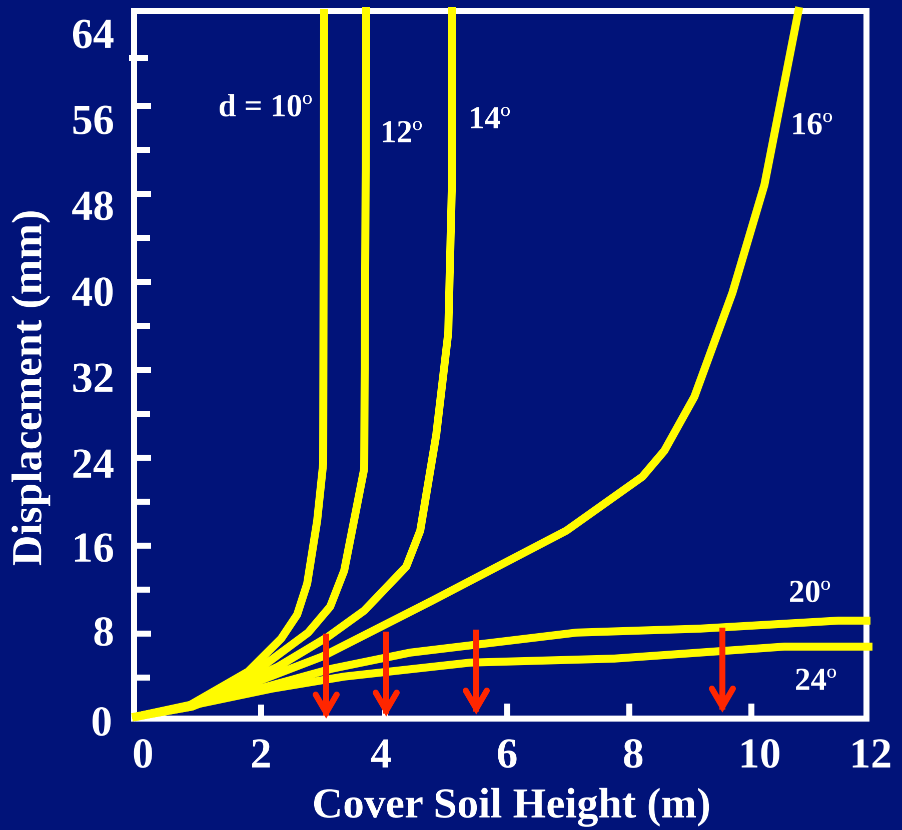
$$= \frac{(7.69)(\tan 14^\circ)(L) + (15{,}900)(0.0015)}{2.54(L)}$$

$$FS = \frac{1.92L + 23.85}{2.54L}$$

Results:

Slope Length	FS	Slope Length	FS
10 m	1.69	40 m	0.99
20	1.23	50	0.94
30	1.07	60	0.91

Cover Soil Stability by FEM vs. Limit Equilibrium



Relationship between Cover Soil Height and Maximum Displacement (shown as curves) and Correlation to Limit Equilibrium (shown as arrows)
(Note that the slope angle is at 18.4°)

(ref. Wilson-Fahmy & Koerner, GS '93 Vancouver B.C.)

Additional Considerations

(a) Equipment Loads

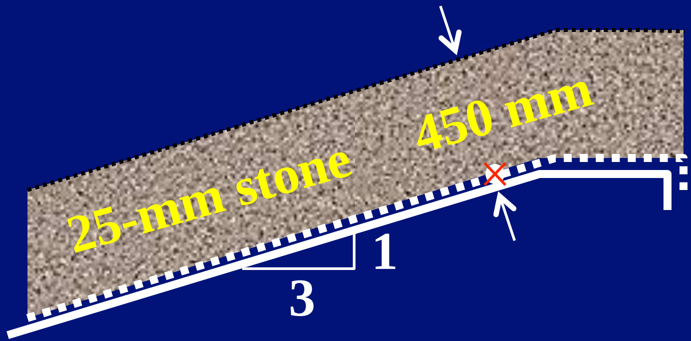
- always work up slopes!
- if not, add live (dynamic load)

(b) Seepage Forces

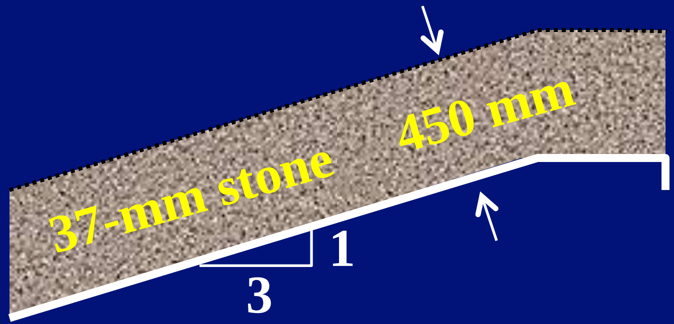
- use worse-case storm
- perform hourly tracking
- results in high drainage requirement
- or, use low k cover soil which then results in high surface runoff (possible erosion concerns)
- numerous slides (see following)

Seepage Induced Slides
(leachate collection systems)

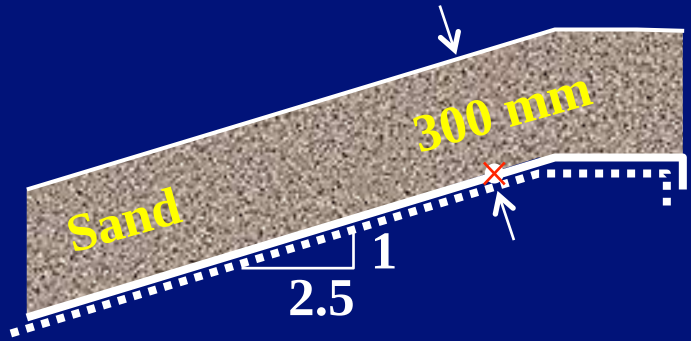
Case #1 - GT failure



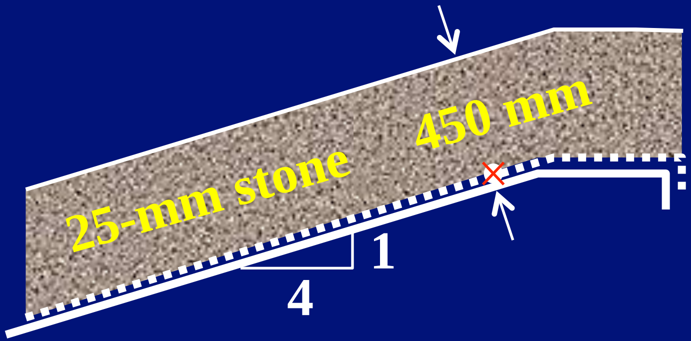
Case #2 - Stone slide



Case #3 - GM failure

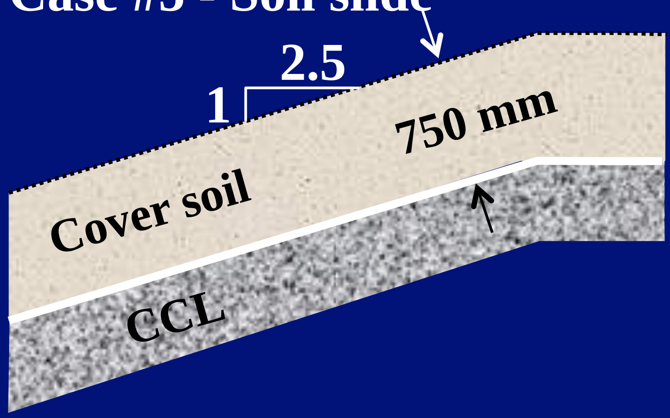


Case #4 - GT failure

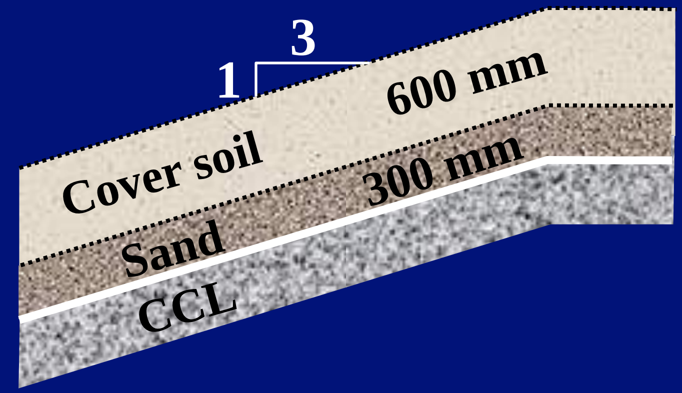


Seepage Induced Slides
(final cover systems)

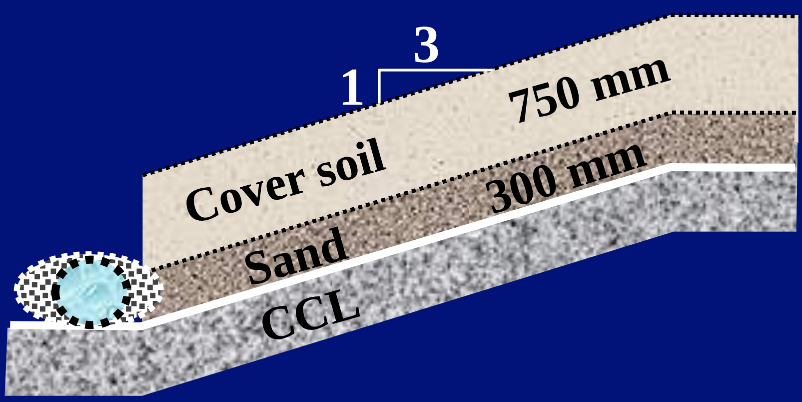
Case #5 - Soil slide



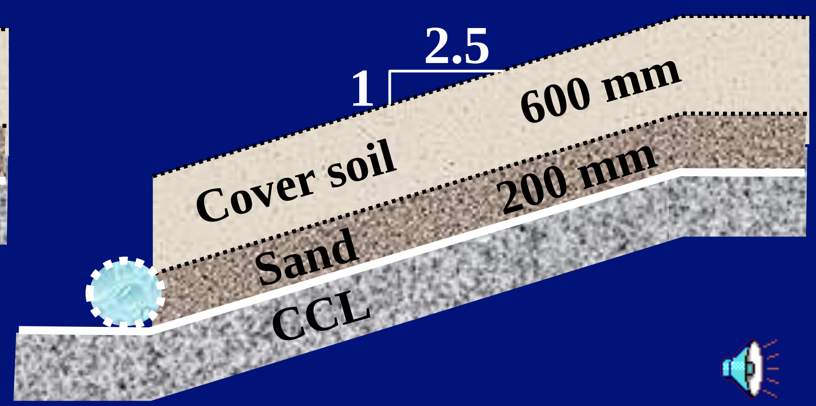
Case #6 - Soil/sand slide



Case #7 - Soil/sand slide



Case #8 - Soil/sand slide



Slope Instability Case Histories Involving Seepage Forces

No.	Upper Interface	Lower Interface	Slope Inclination (Hor.:Vert.)	Cover Soil Thickness, (mm)	Approx. Slope Length, (m)	Approx. Time after construction, (yr)	Cause of Seepage Force	Back Calculated Precipitation
(a) Slides of leachate collection layers before waste placement								
1	NW-NP-GT	HDPE-GM	3:1	450	45	1-2	fines in stone	14 mm/hr
2	Stone	HDPE-GM	3:1	450	30	3-4	fines in stone	44 mm/hr
3	VFPE-GM	NW-NP-GT	2.5:1	450	20	0.2-0.5	low initial permeability	1.0 mm/hr
4	NW-NP-GT	PVC-GM	4:1	450	90 (3 benches of 30 m each)	1-2	ice wedge at toe of slope	35 mm/hr
(b) Slide of final cover/drainage layers after waste placement								
5	Silty sand	CCL	2.5:1	750	40	2-3	no drainage layer	0.42 mm/hr
5	Sand	CCL	3:1	600+300	50	5-6	low initial sand permeability	1.20 mm/hr
7	Sand	CCL	3:1	750+300	45	5-6	fines clogging gravel around pipe	1.34 mm/hr
8	Sand	CCL	2.5:1	600+200	90 (2 benches of 45 m each)	4-5	fines clogging GT around pipe	0.38 mm/hr

Additional Considerations (cont’d)

(c) Seismic Forces

- required in Subtitle "D” (but not in Subtitle “C” ???)
- major implications since FS-values are usually low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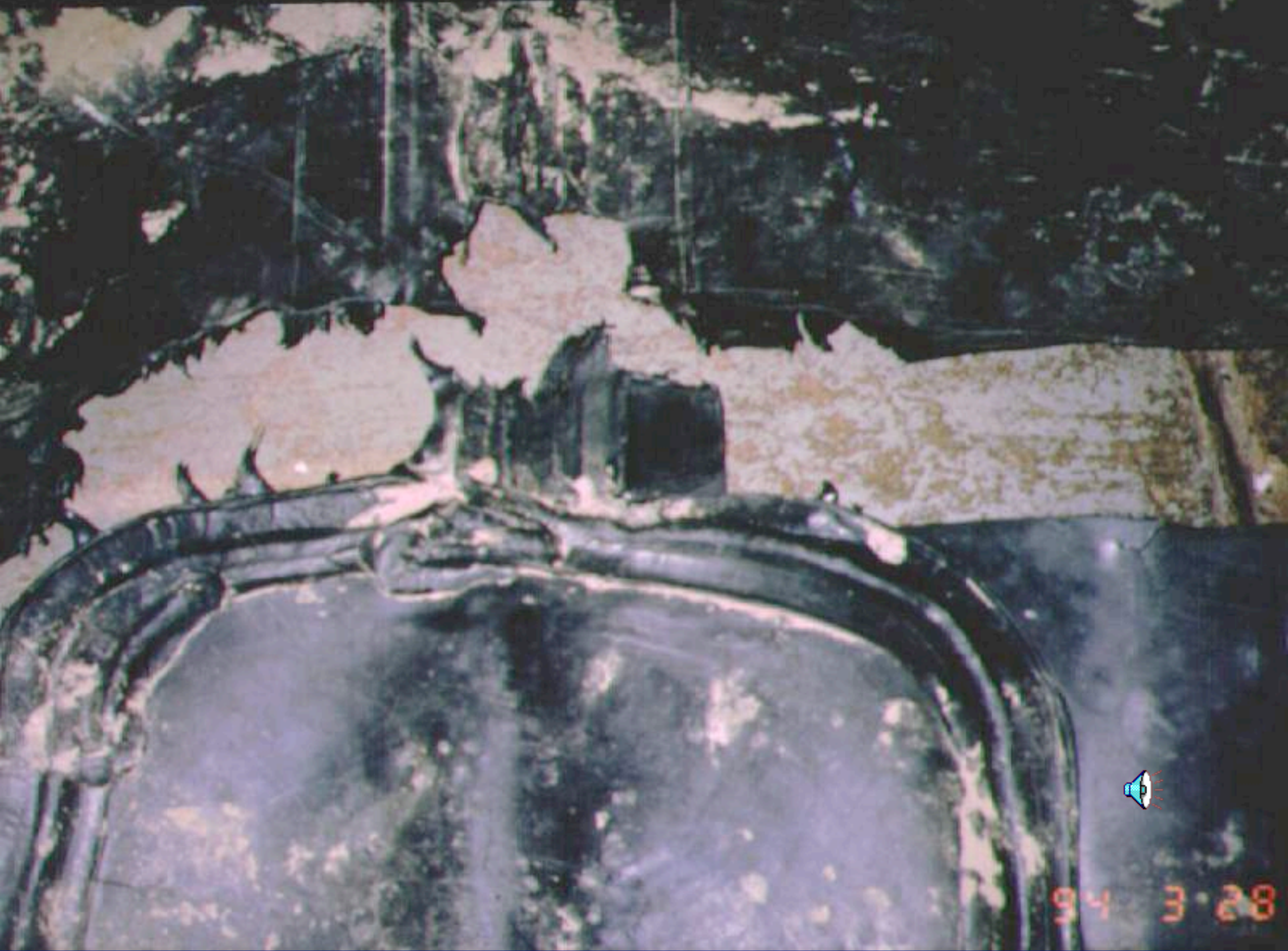
16"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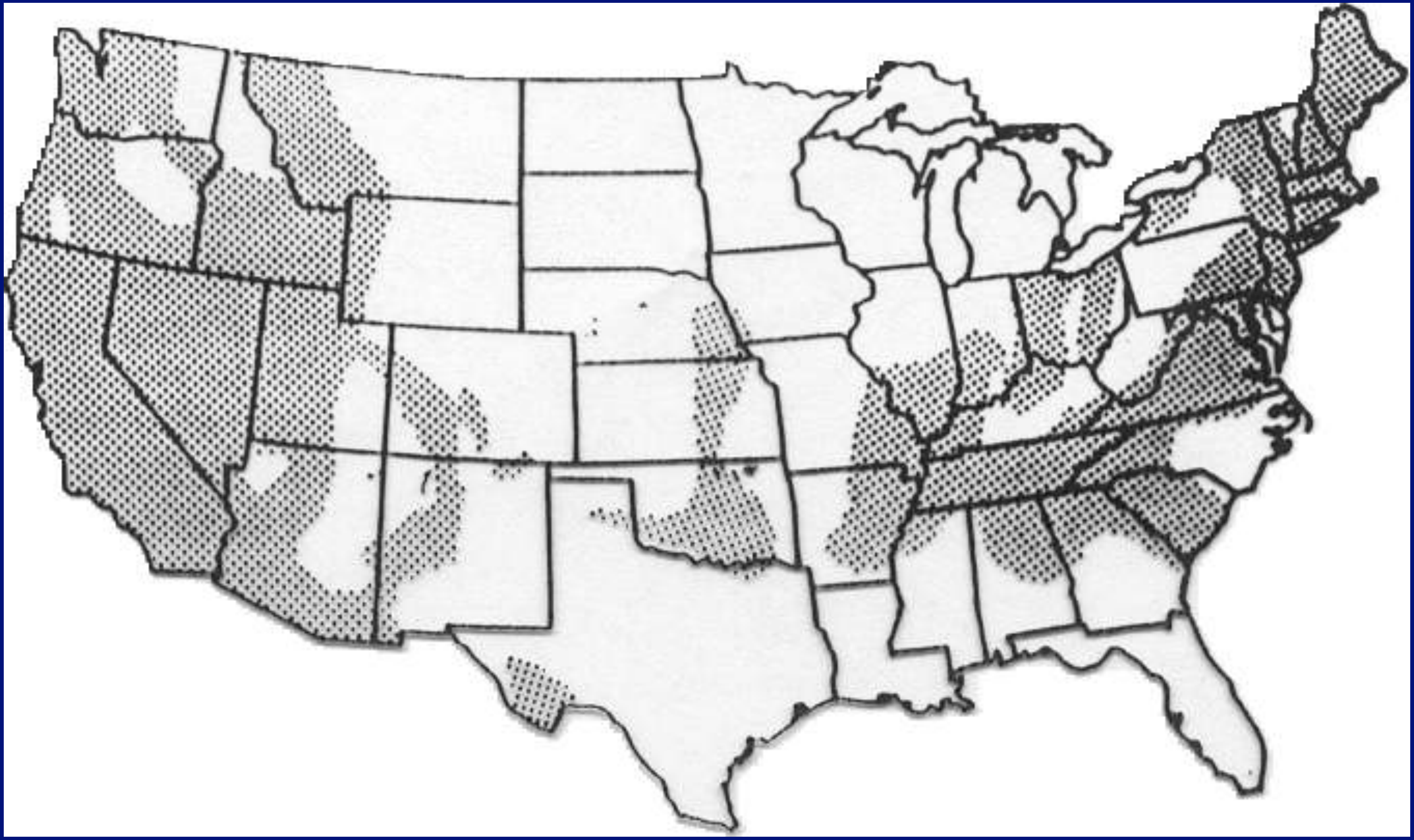
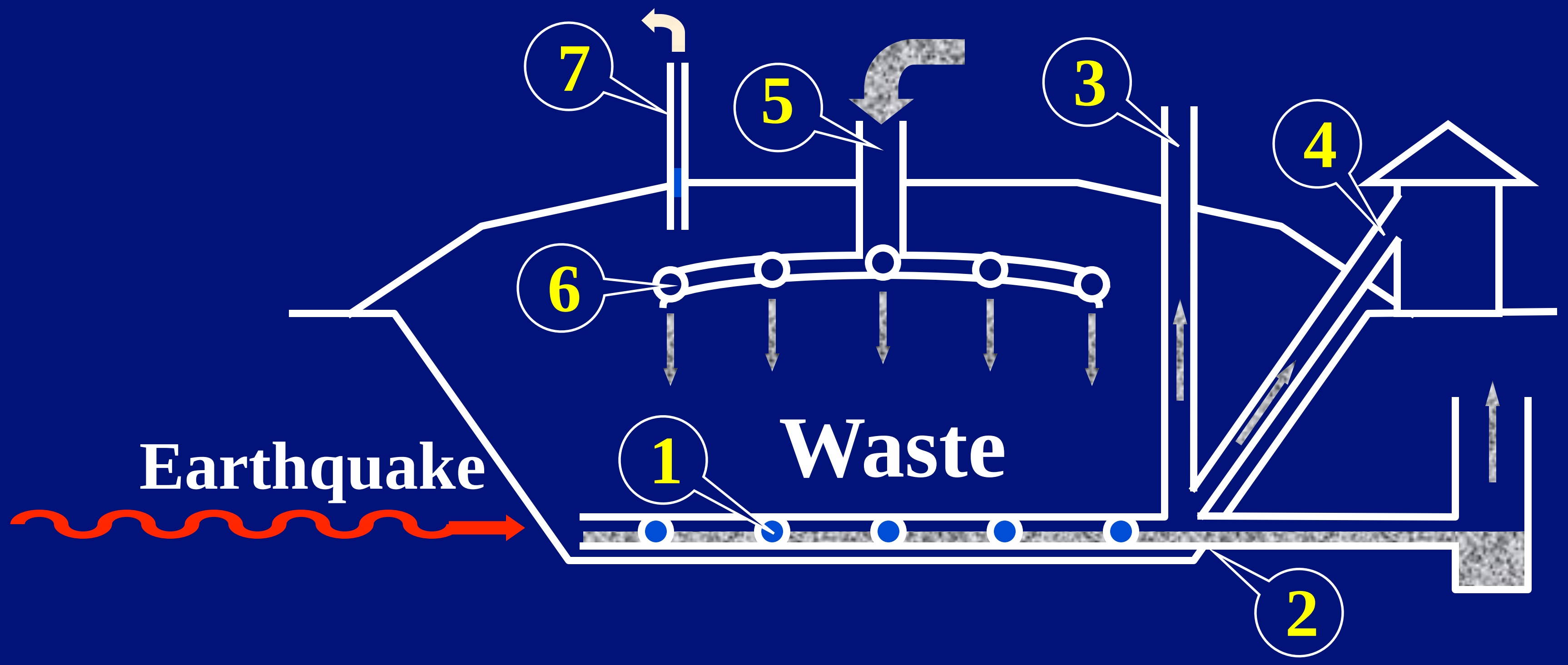
Areas where Seismic Design is Required



Seismic Concerns Regarding "Plumbing"



1. Leachate collection system
2. Pipe penetrations
3. Leachate withdrawal manholes
4. Leachate withdrawal slope risers
5. Leachate injection pipes
6. Leachate recirculation systems
7. Gas extraction systems

Summary of numeric examples for different cover soil slope stability scenarios

after Koerner and Soong, 6ICG, 1998, pp. 1-26

Example No.	Situation or condition	Control FS-value	Scenarios decreasing FS-values	Scenarios increasing FS-values
1	standard example	1.25		
2a	equipment up-slope		1.24	
2b	equipment down-slope		1.03	
3	seepage forces		0.93	
4	seismic forces		0.94	
5	toe (buttress) berm			1.35-1.40
6	tapered cover soil			1.57
7	veneer reinforcement (intentional)			1.57
8	veneer reinforcement (nonintentional)			varies

Textured Geomembranes

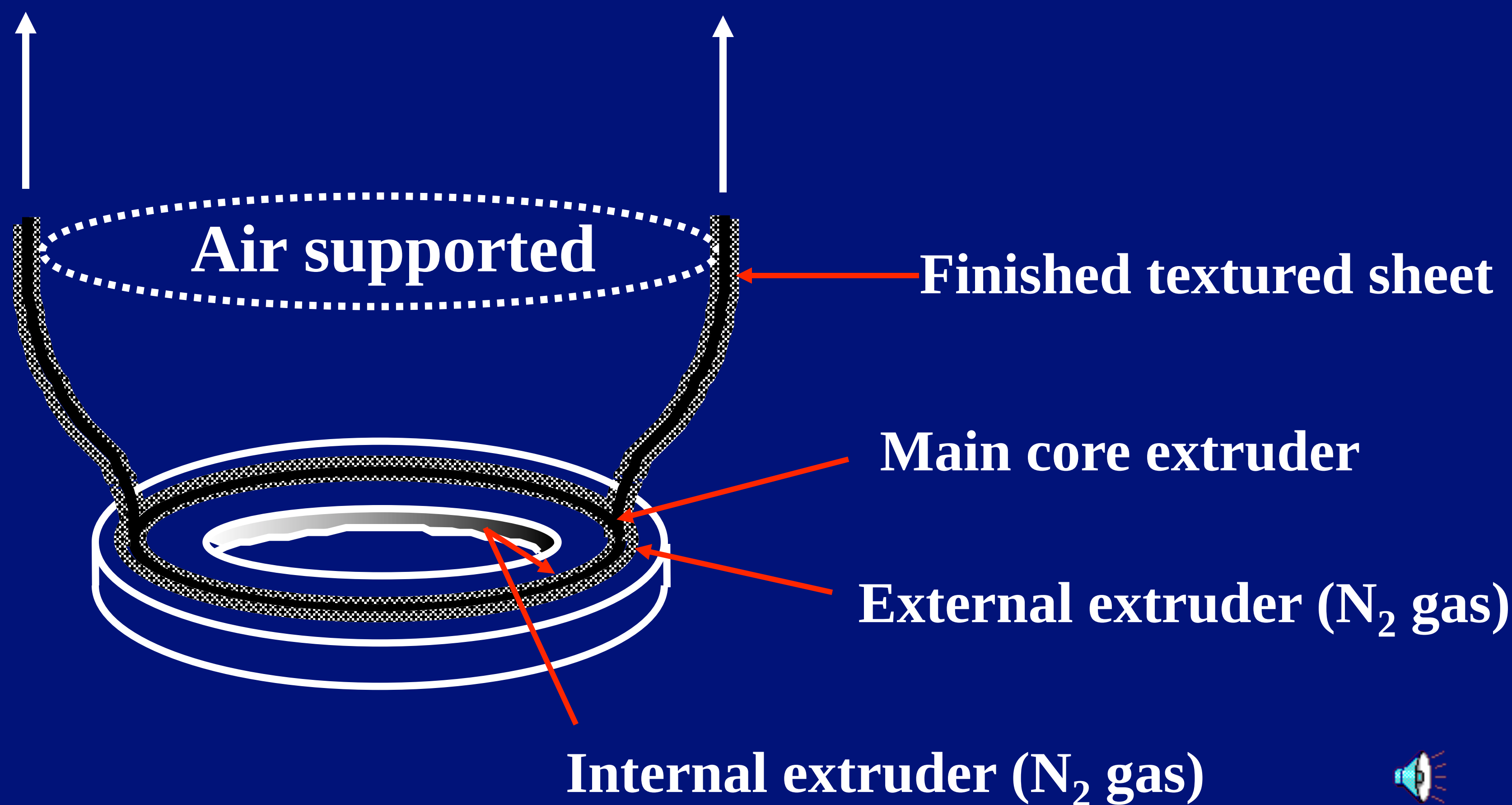
(a) Coextrusion with nitrogen gas

(b) Impingement of hot polyethylene particles

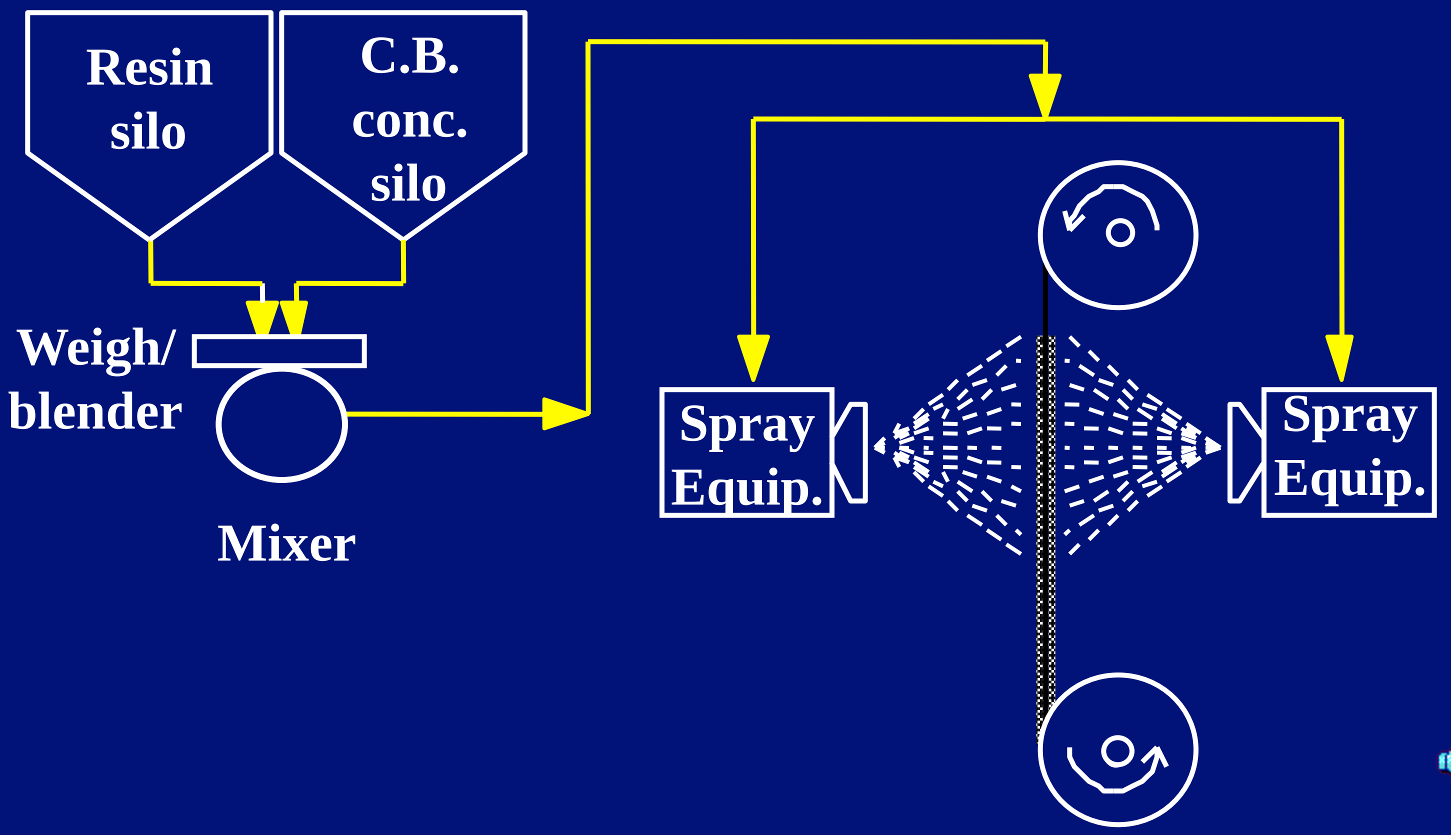
(c) Lamination with polyethylene foam

(d) Structured, or patterned, surface

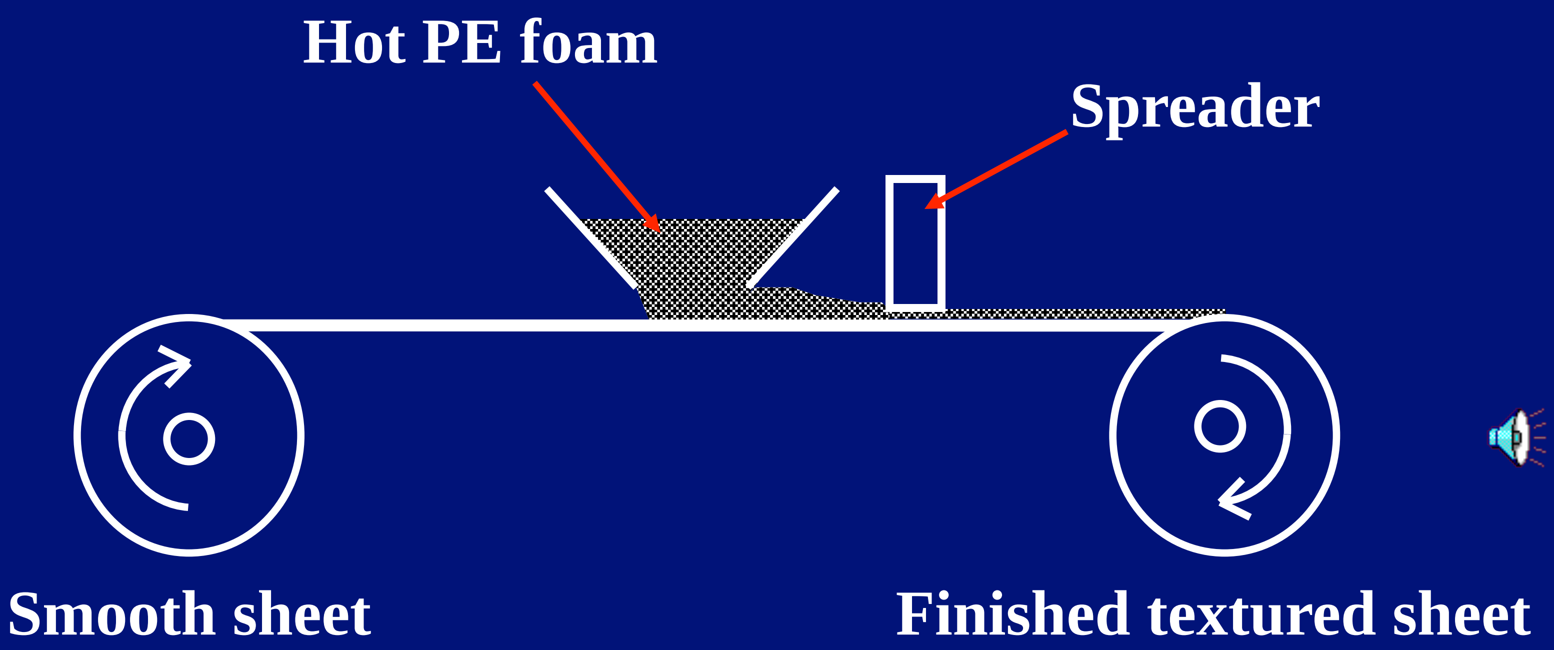
(a) Coextrusion with nitrogen gas



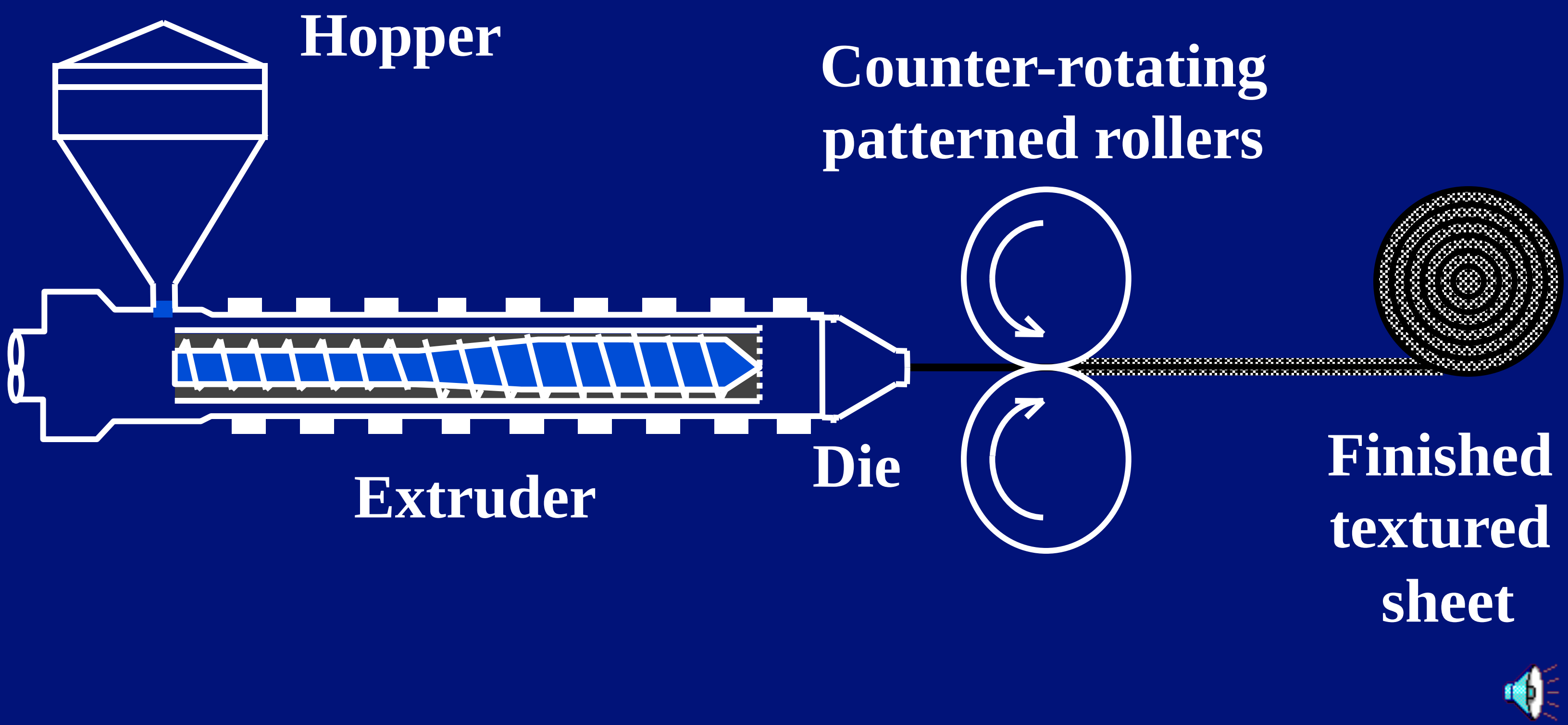
(b) Impingement of hot polyethylene particles



(c) Lamination with polyethylene foam



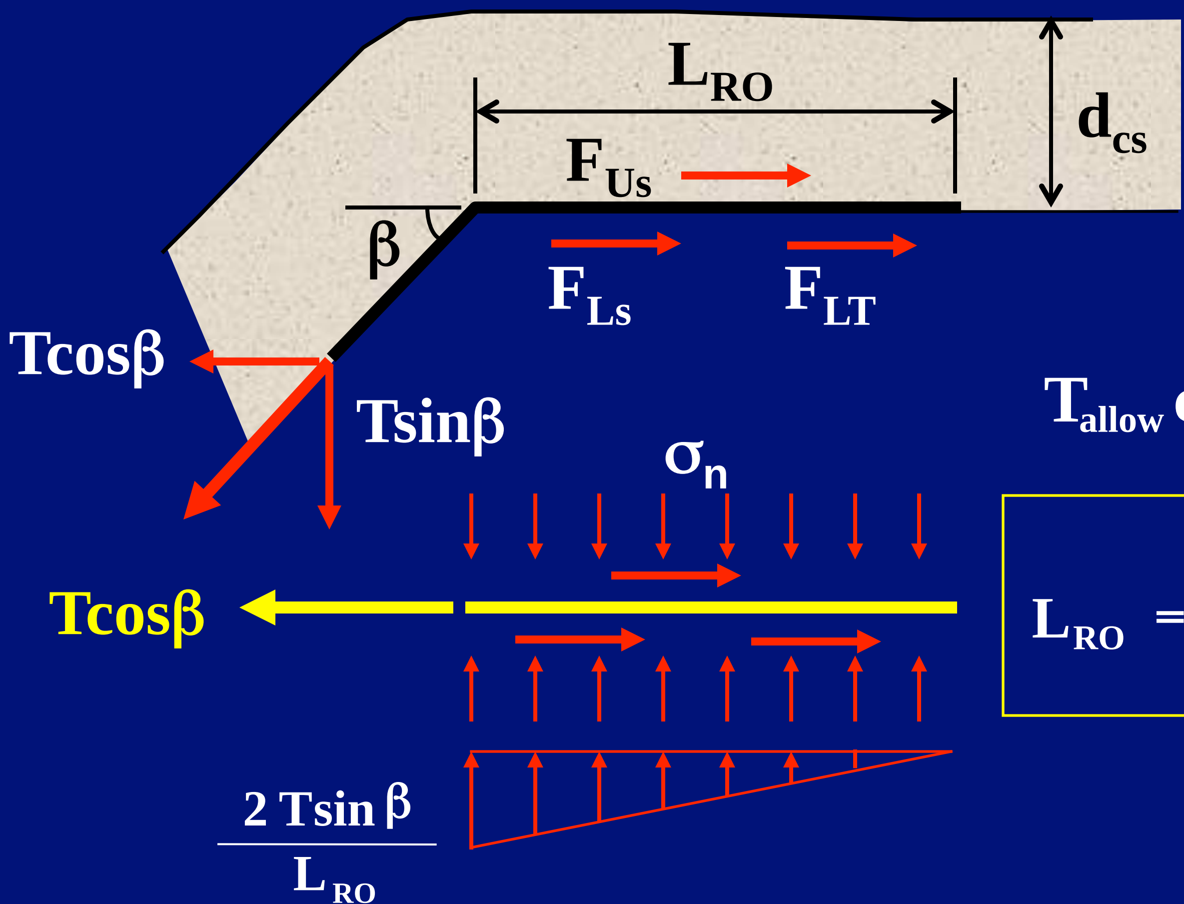
(d) Structured, or patterned, surface



Some Concerns on Textured Sheet

- Optimal amount of texturing?
- Uniformity of texturing?
- Sheet thickness measurement?
- Property modification via texturing or structuring?
- Permanence of texturing?
- Can textured sheet be generically specified or will each type of texturing require product specific testing?

3.1(c) Geomembrane Anchorage
(runout only)



$$T_{allow}\cos\beta = F_{U\sigma} + F_{L\sigma} + F_{LT}$$

$$L_{RO} = \frac{T_{allow}\left(\cos\beta - \sin\beta\tan\delta_L\right)}{\sigma_n\left(\tan\delta_U + \tan\delta_L\right)}$$

Example:

What is the FS of a 3.0 m long runout of 1.0 mm thick LLDPE with σ_{allow} = 7000 kPa. Use 300 mm thick cover soil at 16.5 kN/m^3 and 30° friction angle on a 3(H)-to-1(V) slope

Solution:

$$L_{RO} = \frac{(700)(0.001)\left[\cos 18.4 - (\sin 18.4)(\tan 30)\right]}{(16.5)(0.30)\left[\tan 0 + \tan 30\right]}$$

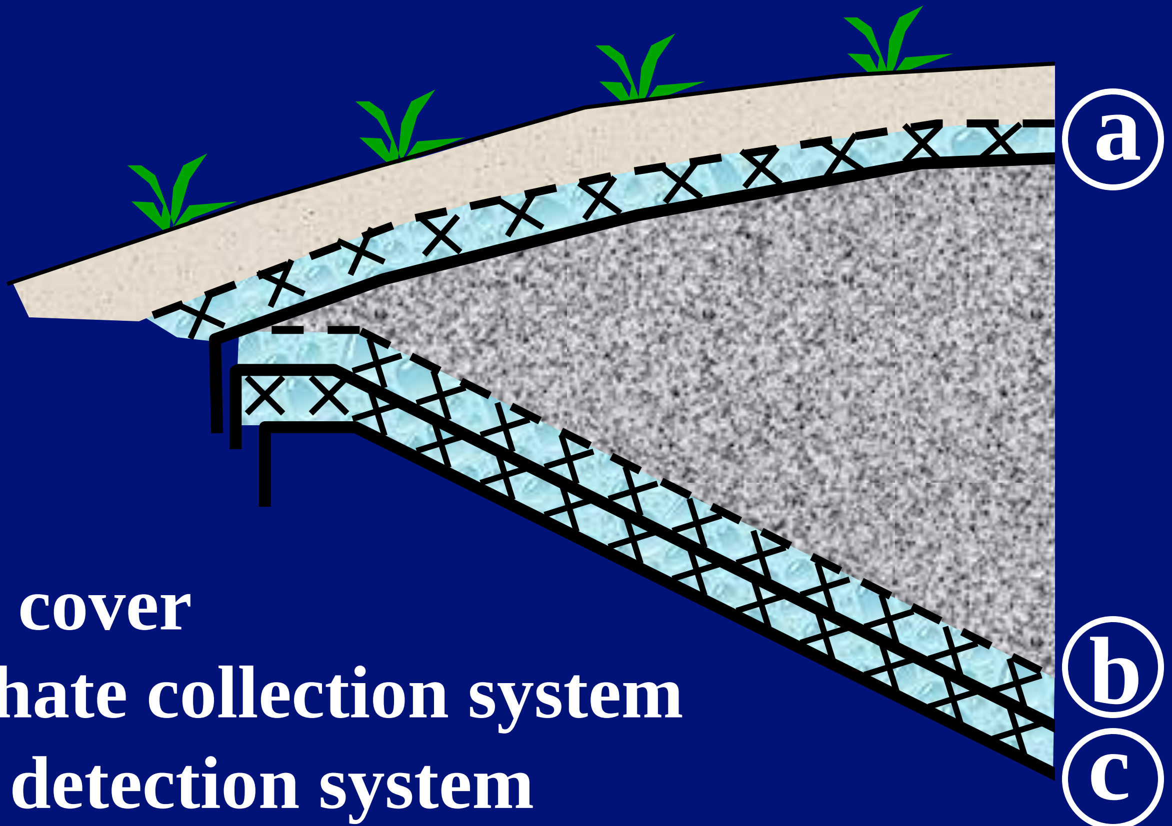
$$= \frac{5.37}{2.86} = 1.9\text{m}$$

and

$$FS = \frac{L_{RO}\,(\text{actual})}{L_{RO}\,(\text{reqd})} = \frac{3.0}{1.9} = 1.6$$

Note: It is much more efficient to bury the GM "tail" in a vertical anchor trench. Comparable problem gives L_{RO} = 1.0 m and d_{AT} = 0.5 m, see Koerner (1998)

3.2 GN Drains and GT/GN/GT Composite Drainage Layers



(a) Final cover
(b) Leachate collection system
(c) Leak detection system

3.2(a) Drainage Layer in Final Cover

$$FS = \frac{q_{allow}}{q_{reqd}}$$

where

q_{allow} = ASTM D4716 test (modified by reduction factors)

q_{reqd} = site-specific water percolation through cover soil, see Koerner and Daniel, Final Covers, ASCE Press, 1997

3.2 (b) Leachate Collection Layer

$$FS = \frac{q_{allow}}{q_{reqd}}$$

where

q_{allow} = ASTM D4716 test (modified by reduction factors)

q_{reqd} = leachate generation using EPA's **HELP** model

EPA's HELP Model

Theory: Hydraulic continuity equation

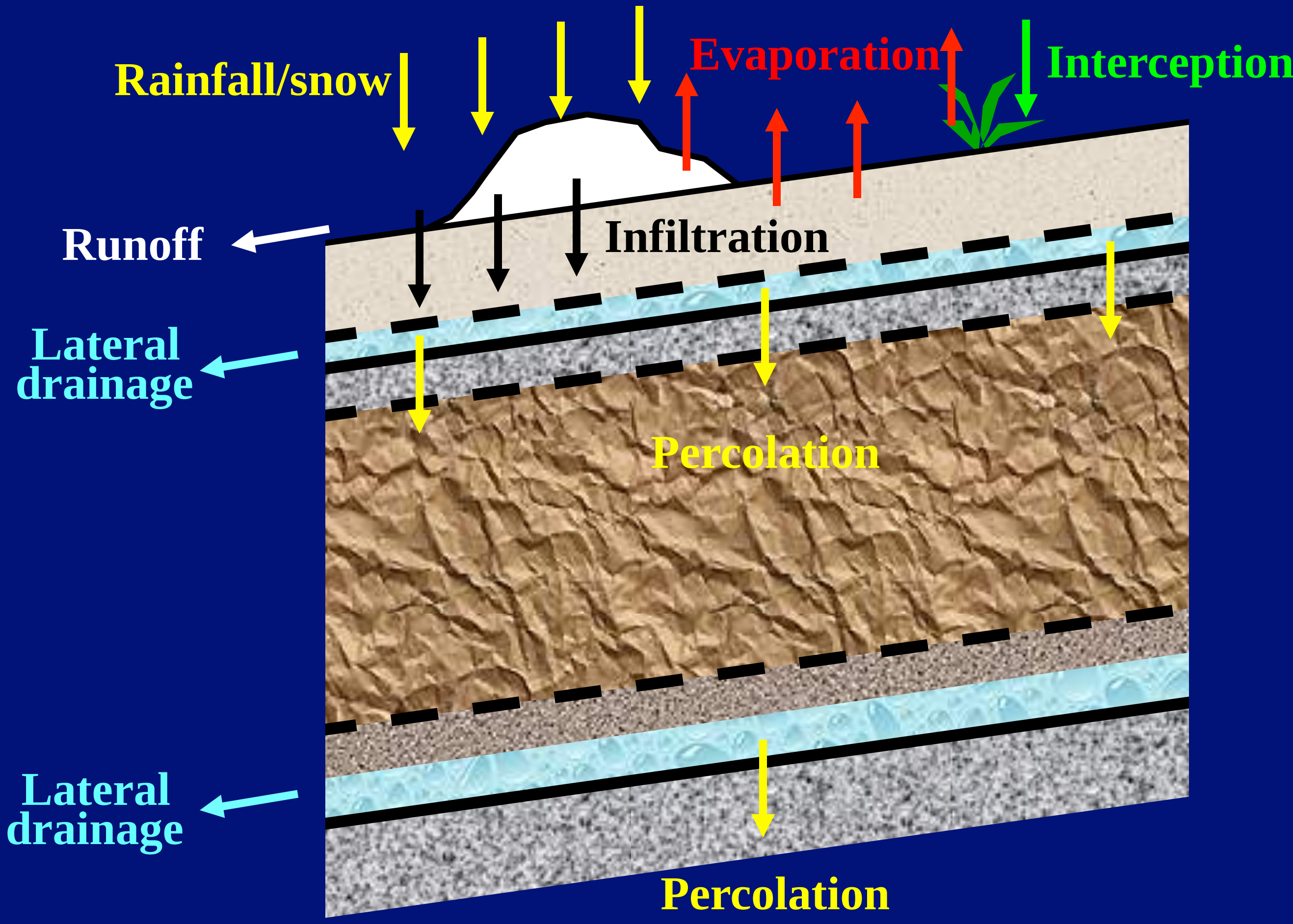
Concept: Amount and distribution of leachate is a function of the site hydrology, waste characteristics and landfill geometry

Assumption: (a) validity of Darcy's Law
(b) the landfill is active with no runoff

Use: Throughout the U.S. by designers and regulators (and now used worldwide)

HELP Model simulation process

(Tracks moisture migration as a function of time)



3.2(c) Geonet Leak Detection Design

$$FS = \frac{q_{allow}}{q_{reqd}}$$

where

q_{allow} = ASTM D4716 test (modified by reduction factors)

q_{reqd} = assumed leakage rate through primary liner which is difficult to estimate, options are:

- estimate number and size of holes
- base on field data (later)
- use multiple of de-minimus ($\simeq$ 10 l/ha-day)

Note: 10 l/ha-day $\simeq$ 1 gal/acre-day

Example:

What is FS for a GN leak detection with $q_{ult} = 1.66 \times 10^{-4}$ m^2/s at 100 times de minimus leakage (10 lphd). Landfill slope is 6% and 300 m long.

Solution:

$$q_{allow} = q_{ult}\left[\frac{1}{RF_{IN} \times RF_{CR} \times RF_{CC} \times RF_{BC}}\right]$$

$$= 1.66 \times 10^{-4}\left[\frac{1}{1.75 \times 1.7 \times 1.75 \times 1.75}\right]$$

$$= 0.182 \times 10^{-4}\ m^2/s$$

$$q_{reqd} = \frac{(100)(10)(0.001)}{(10{,}000)(24 \times 60 \times 60)}(300)$$

$$= 3.5 \times 10^{-7}\ m^2/s$$

$$FS = \frac{q_{allow}}{q_{reqd}} = \frac{0.182 \times 10^{-4}}{3.5 \times 10^{-7}} = 52,\ \text{OK}$$

Next File