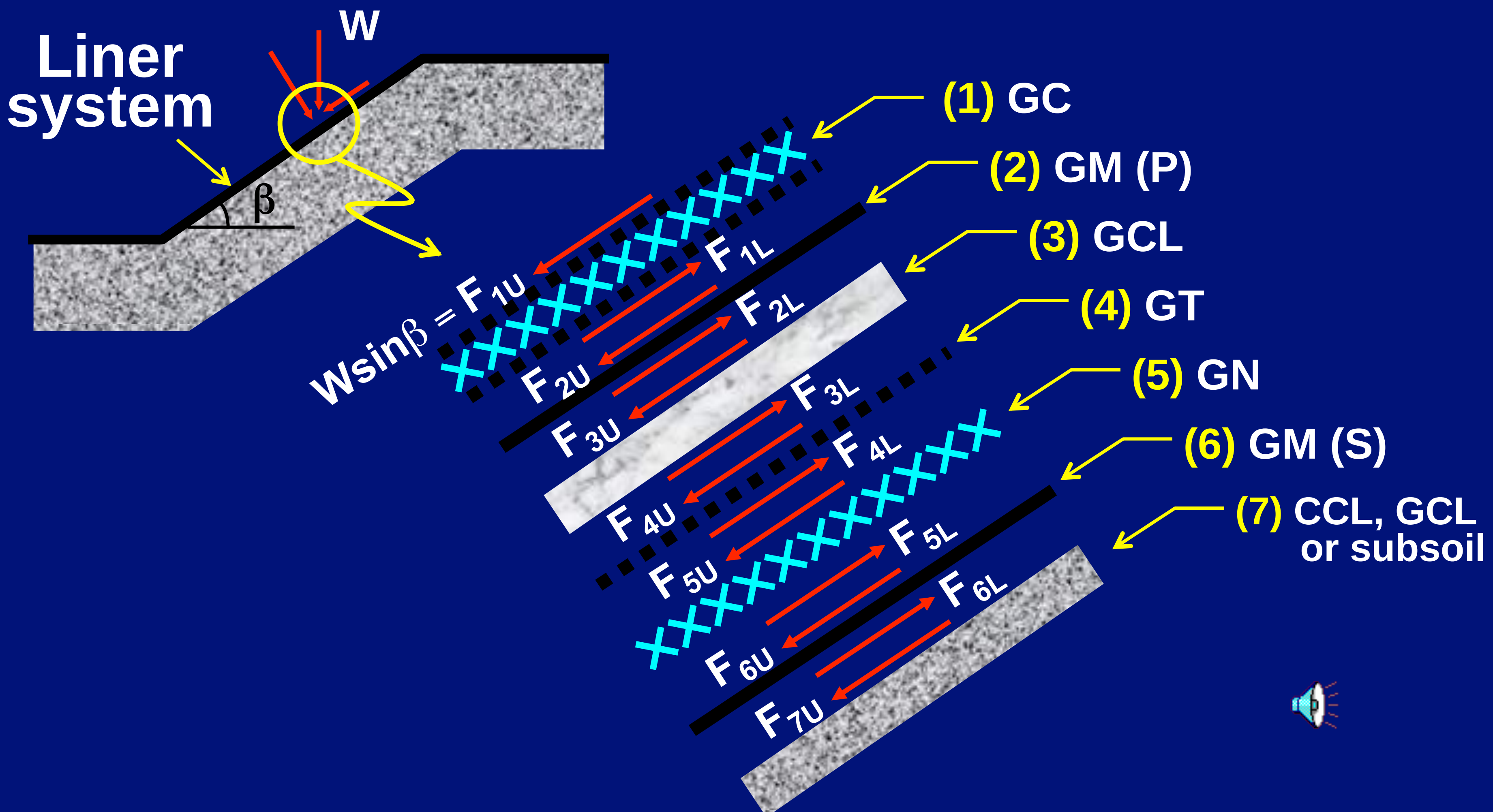
4.5 Multilined Side Slope Stability

- Requires shear response of each interface
- Requires wide width strength of each component
- Current design is based on limit equilibrium
- Strain compatibility should be addressed
- FEM models are being developed
- Failures have occurred (e.g., Kettleman Hills)


'88 3 2

Multilined Side Slope Considerations Necessary for Stability Analysis



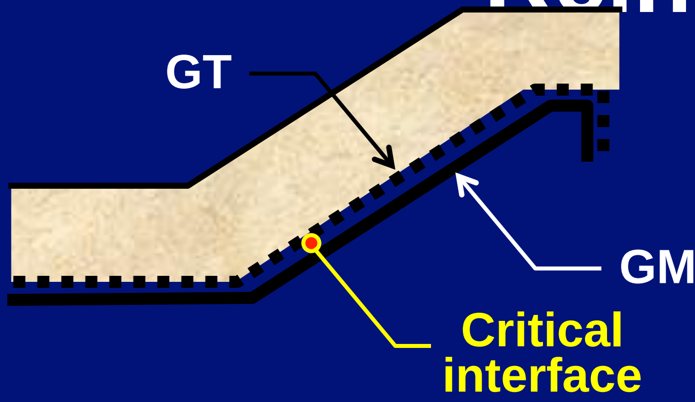
Testing Required:

- shear strengths of every interface (both peak and residual)
- wide width tensile strength of every geosynthetic

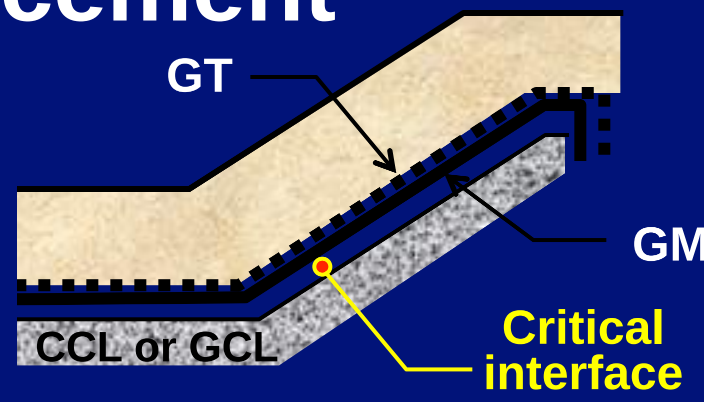
Calculation Results:

- if $\tau_U = \tau_L$; component is in pure shear
- if $\tau_U < \tau_L$; pure shear up to τ_U (balance not mobilized)
- if $\tau_U > \tau_L$; tension in component(s) equal to the difference $T = (\tau_U - \tau_L)\ t$

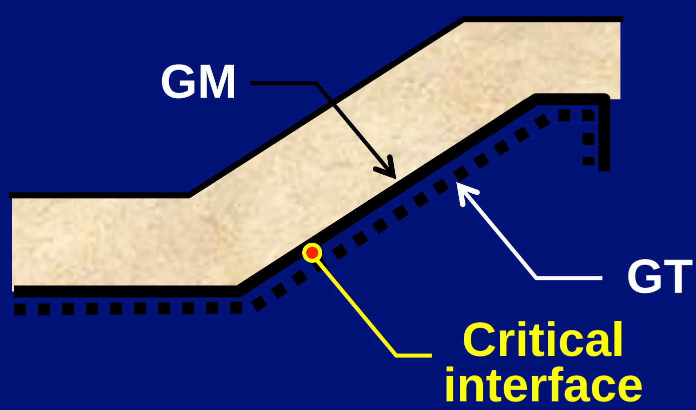
Nonintentional Veneer Reinforcement



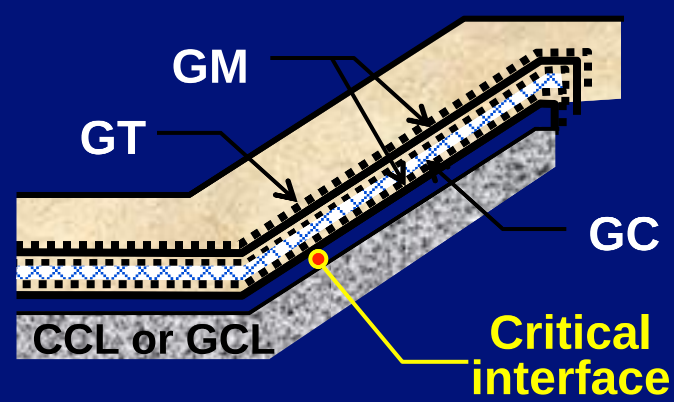
(a) GT sliding on GM



(c) GT and GM sliding on CCL or GCl



(b) GM sliding on GT

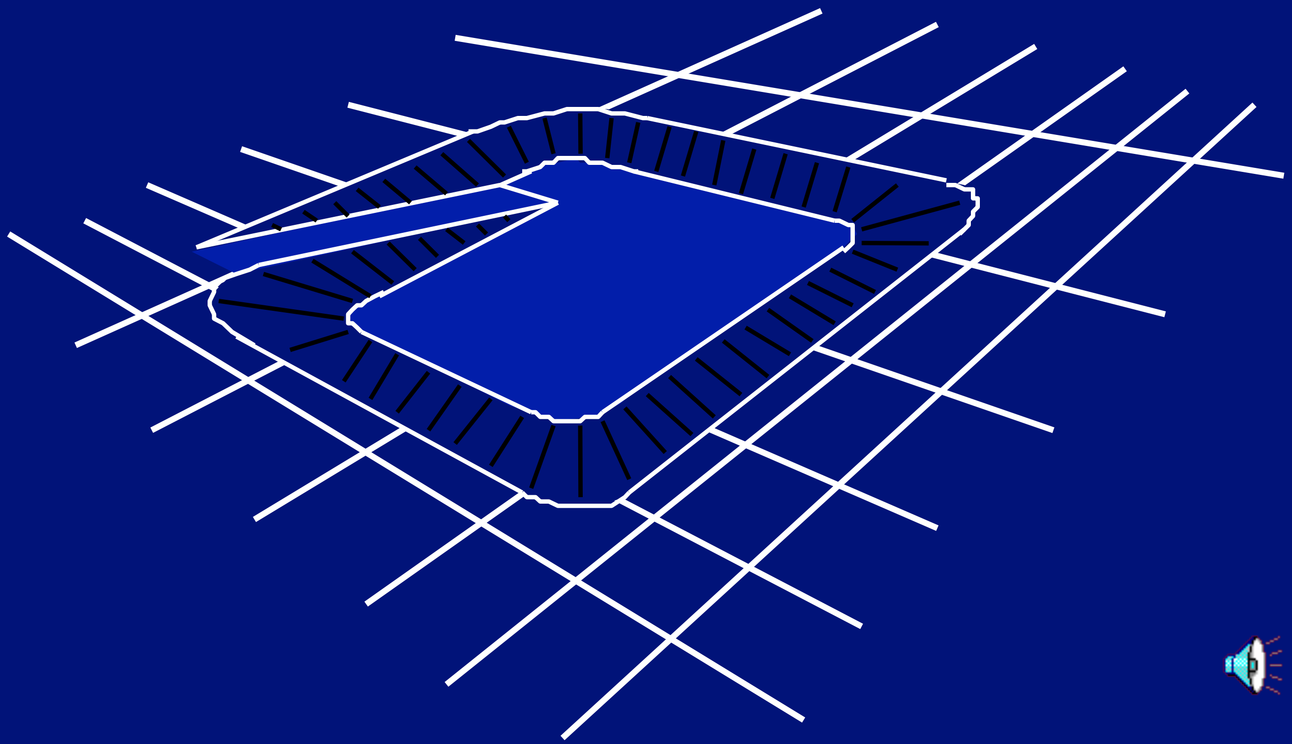


(d) Double liner system sliding on CCL or GCL

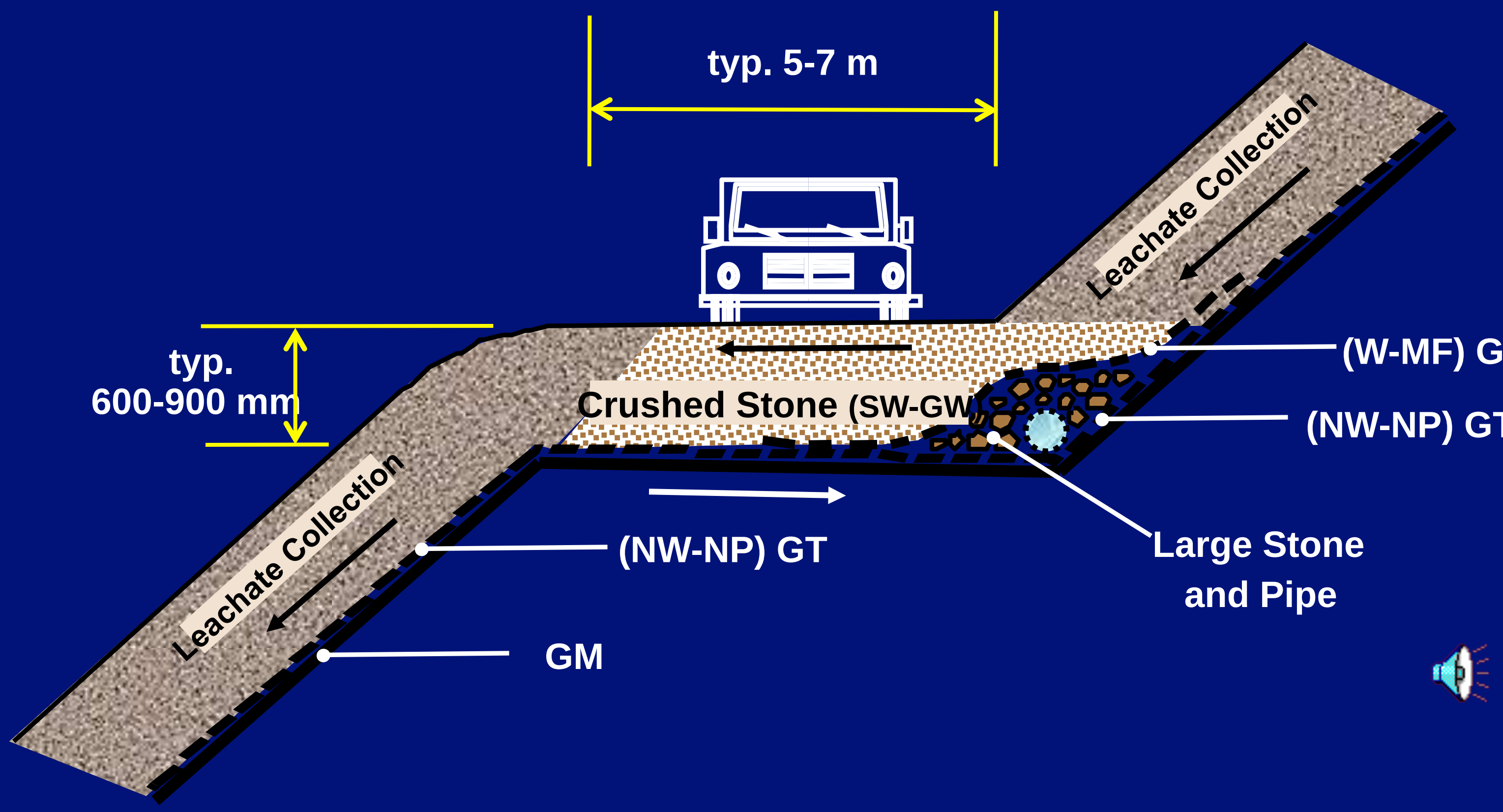
4.6 Access Ramps

- difficult design detail
- requires full continuity of liner and drainage system before soil for ramp is placed and compacted
- conservative design takes up considerable air-space
- problems have occurred:
  - tensile stressing of GM
  - extrusion of GCL bentonite
  - inadequate drainage

Typical geometry of a below-grade landfill access ramp



Typical cross section of a below-grade landfill access ramp



4.7 Stability of the Solid Waste Mass Itself

General concerns

- high landfills
- steep slopes
- canyon configurations
- poor foundation soils
- poor liquids management
- uncontrolled operations

Waste failures (Koerner and Soong, 1999)

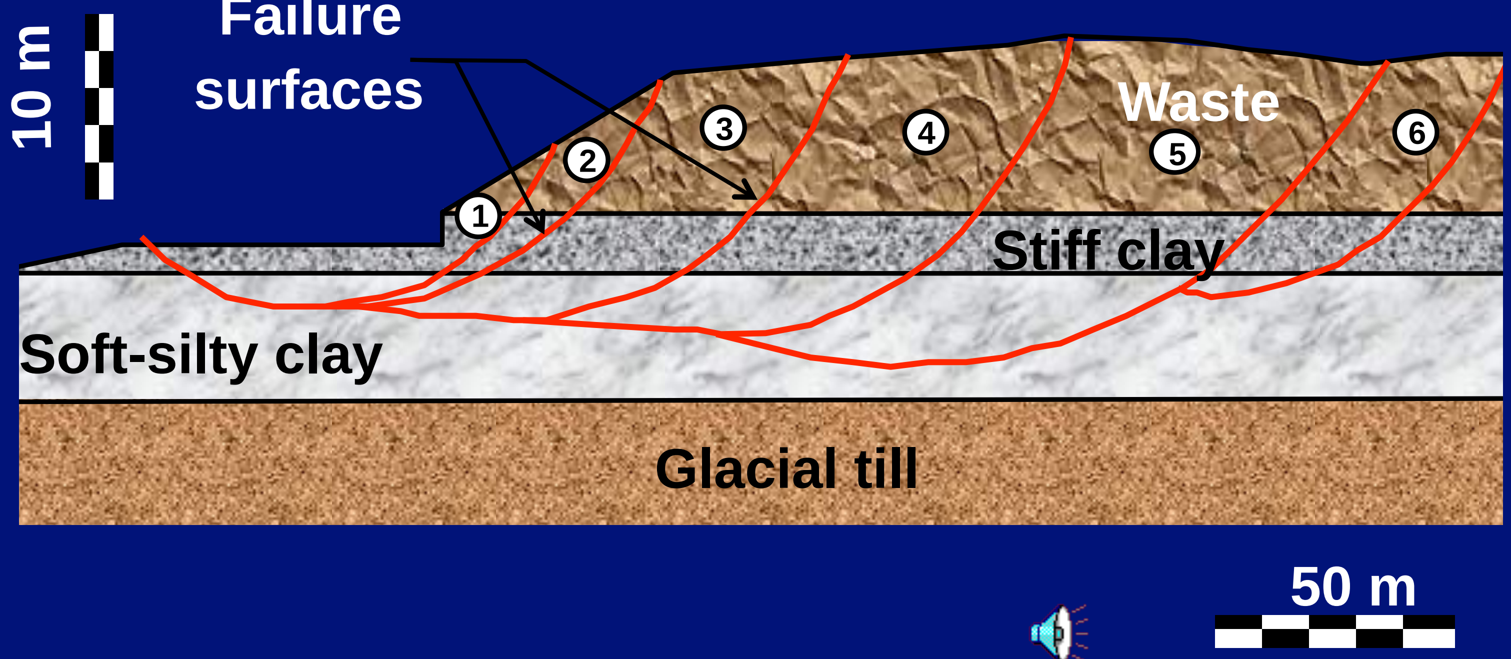
Identification	Year	Location	Type	Quantity of Waste Involved (m^3)
Unlined Sites				
U-1	1984	N. America	single rotational	110,000
U-2	1989	N. America	multiple rotationa	500,000
U-3	1993	Europe	translational	470,000*
U-4	1997	N. America	translational	1,100,000
U-5	1997	N. America	single rotational	100,000
Lined Sites				
L-1	1988	N. America	translational	490,000
L-2	1994	Europe	translational	60,000
L-3	1997	N. America	translational	100,000
L-4	1997	Africa	translational	300,000
L-5	1997	S. America	translational	1,200,000

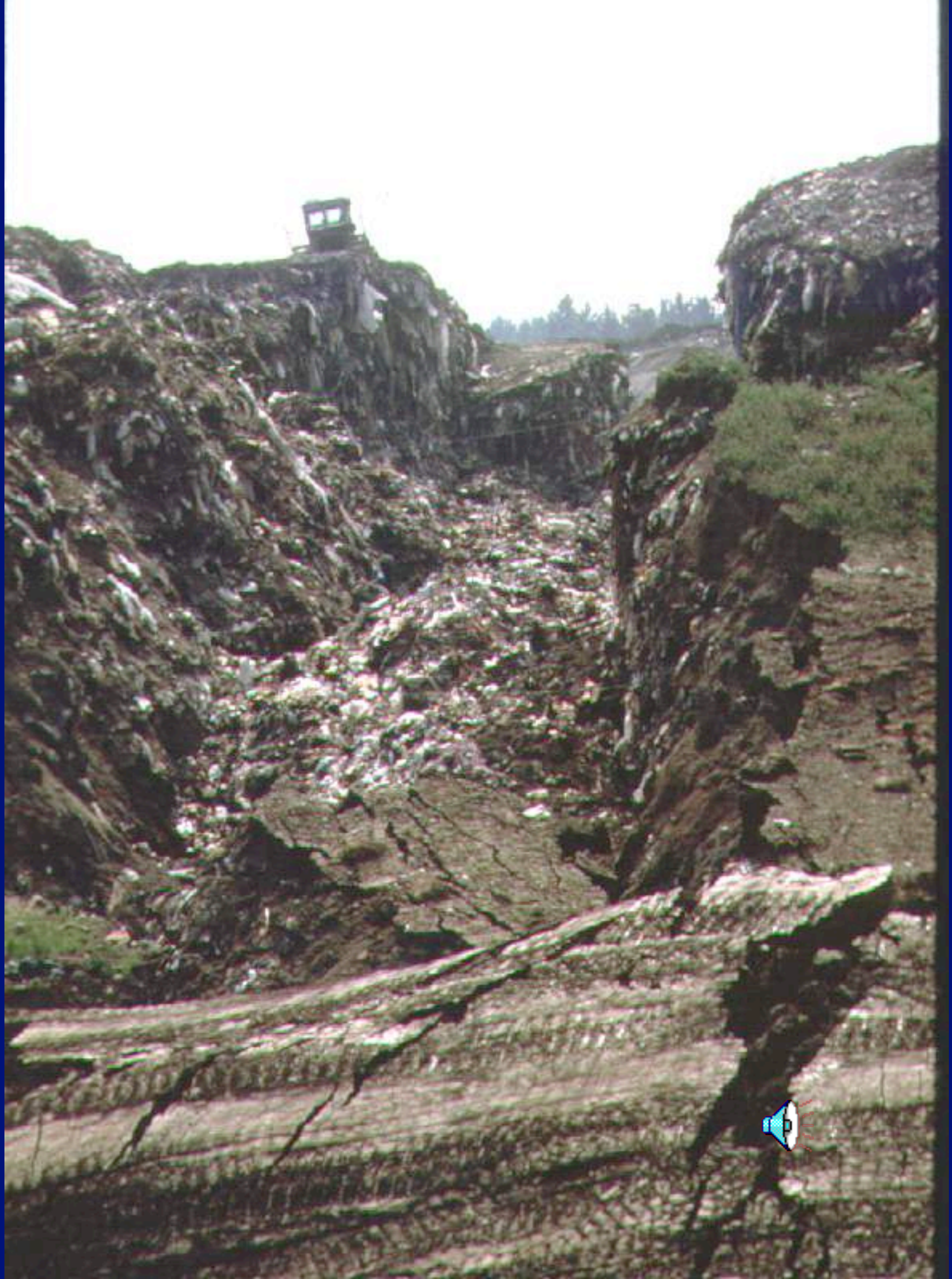
***included 27 deaths!**

U-1 (1984)

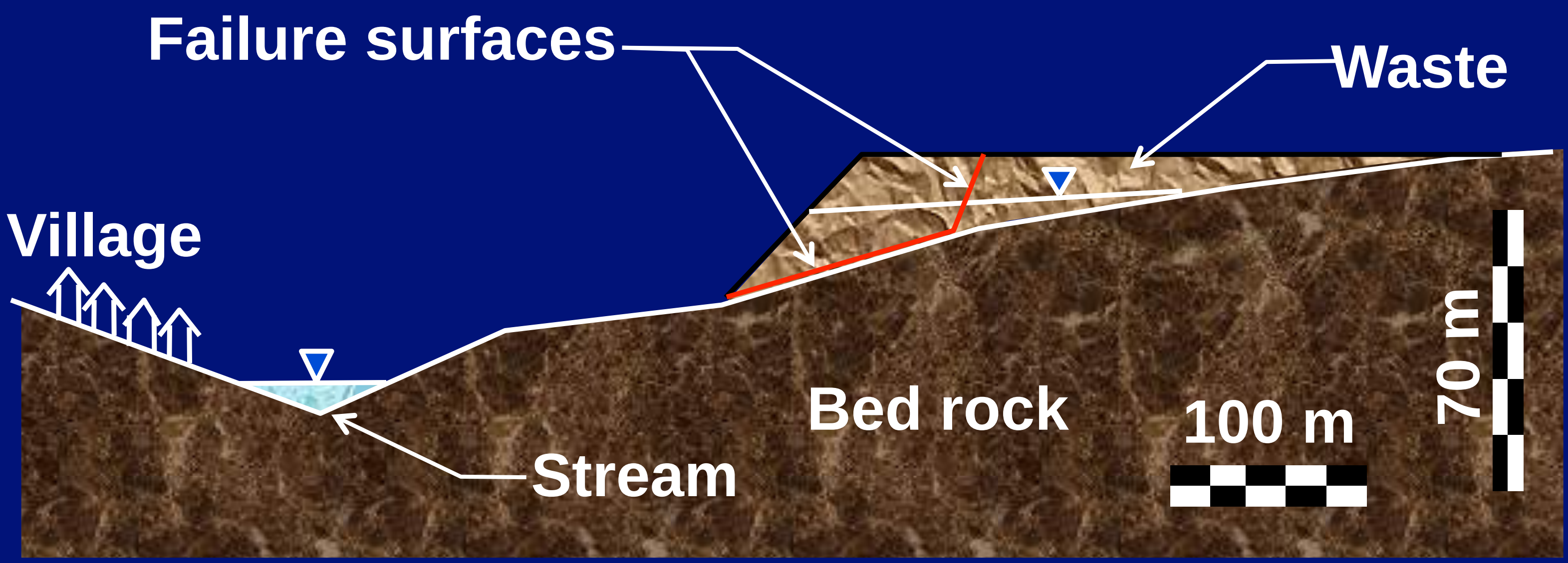

Failure
surface
Waste
Toe
Berm
Tidal marsh deposit
Stiff subgrade
20 m

U-2 (1989)

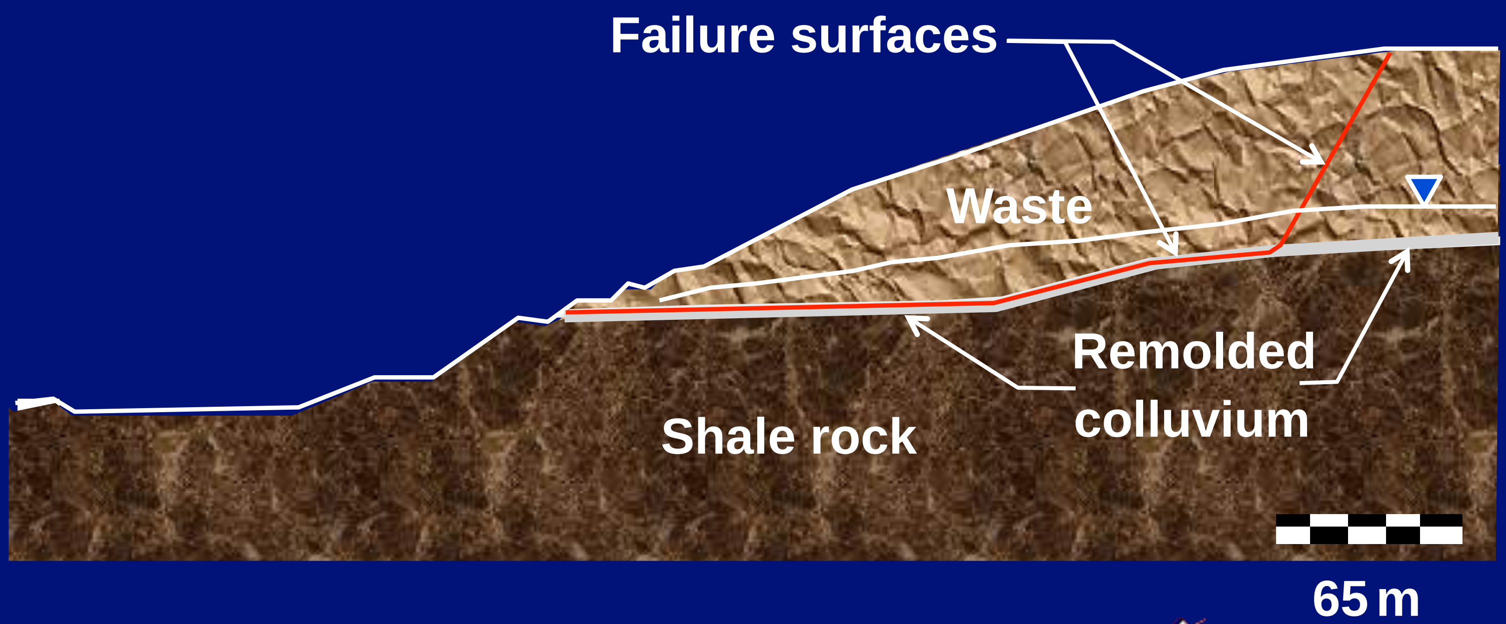

10 m
Failure
surfaces
Waste
1
2
3
4
5
6
Stiff clay
Soft-silty clay
Glacial till
50 m

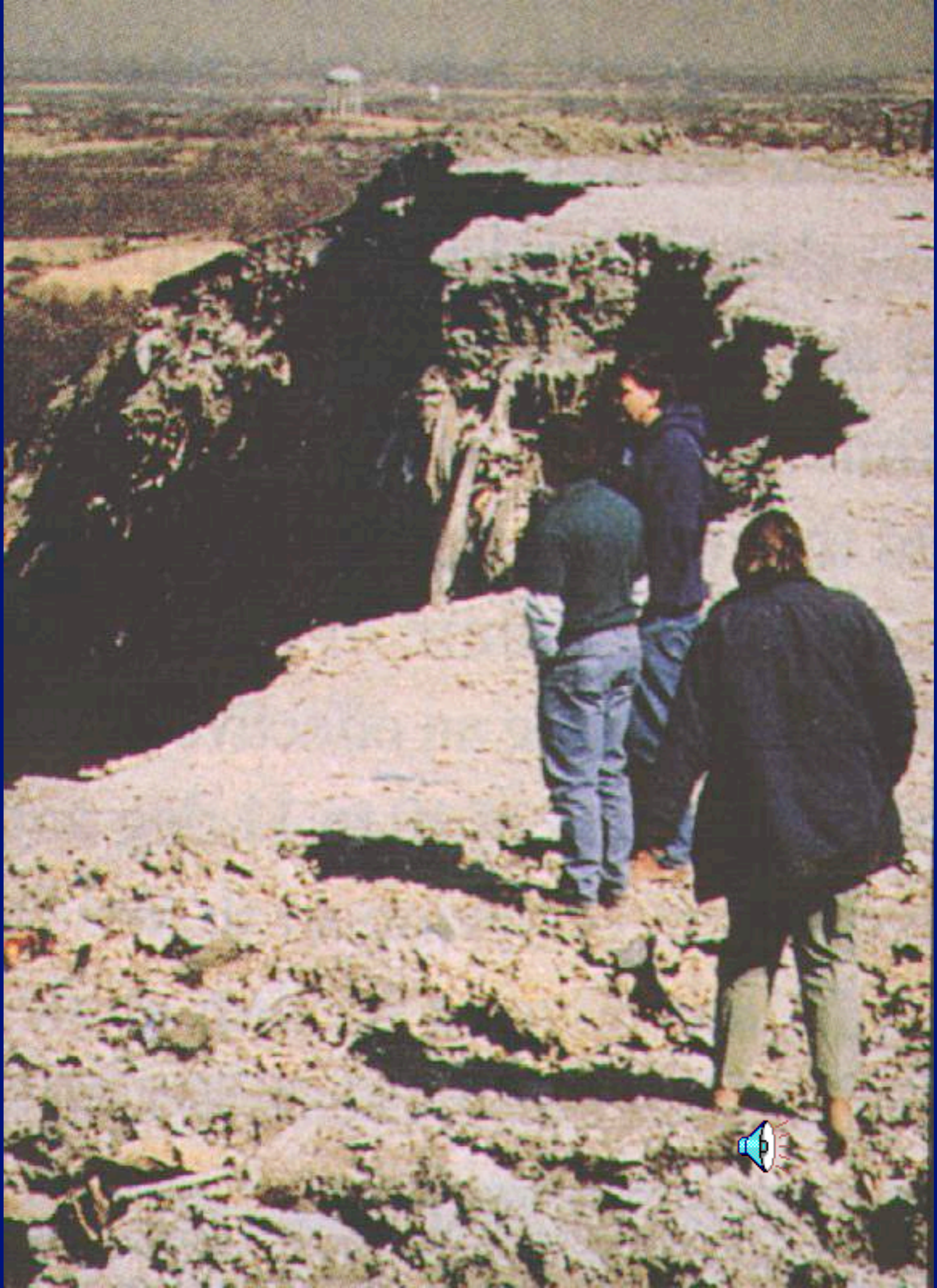


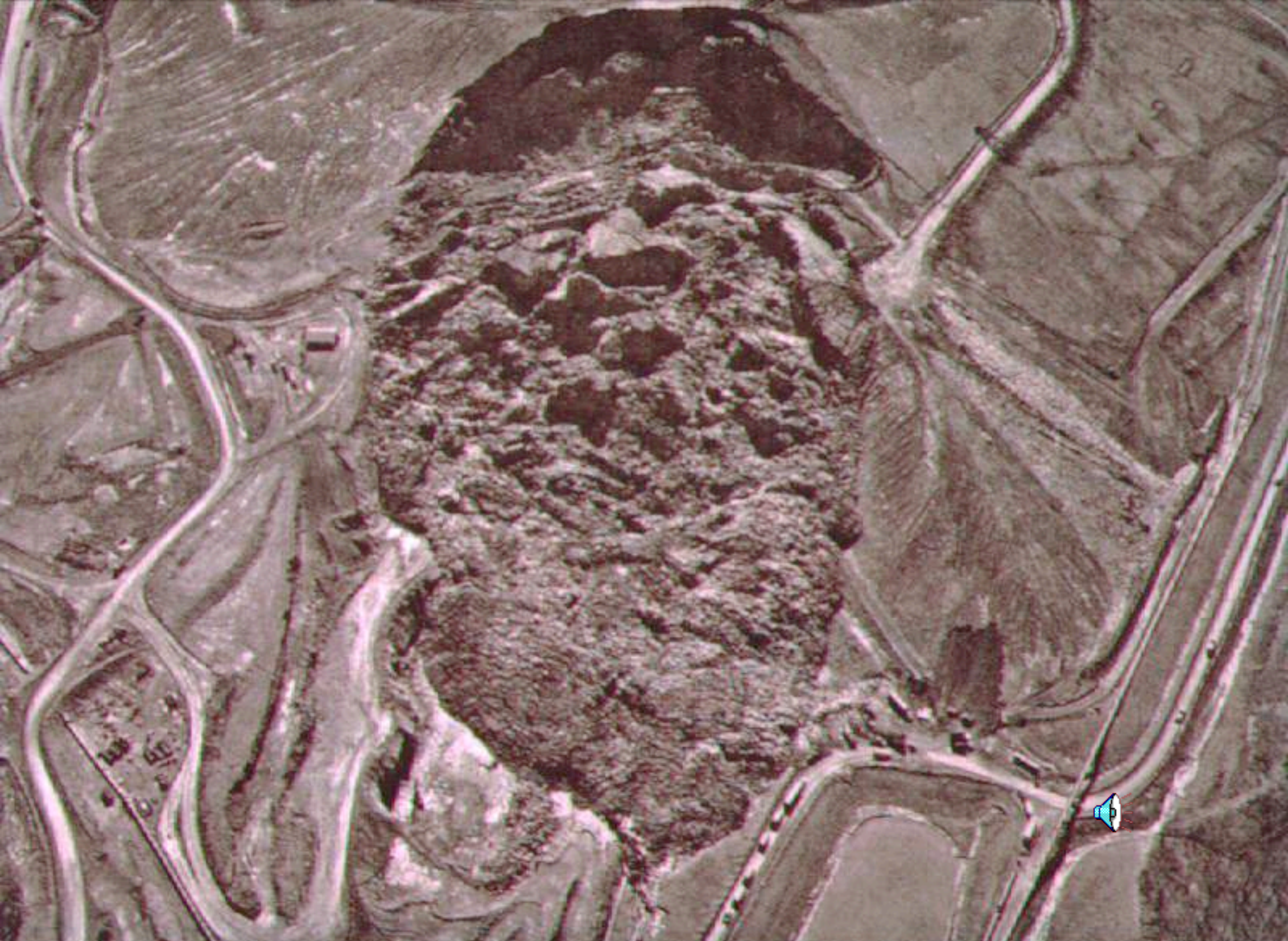
U-3 (1993)



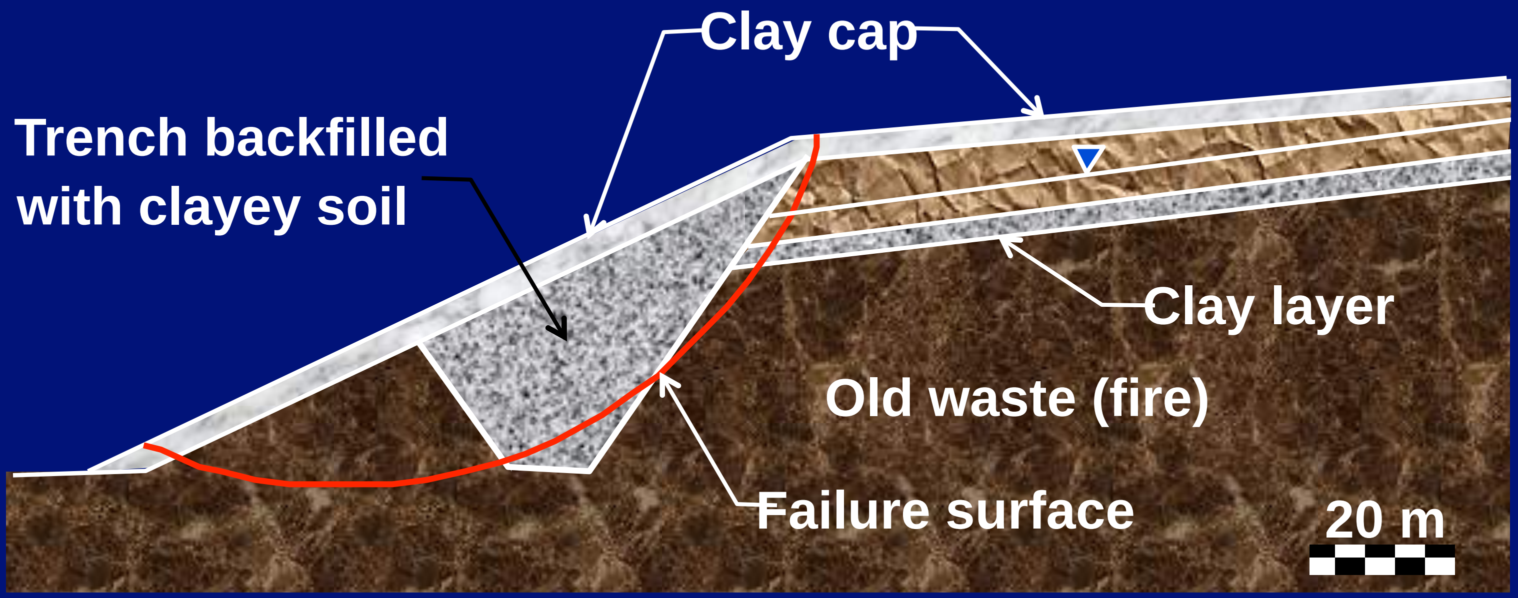
U-4 (1996)





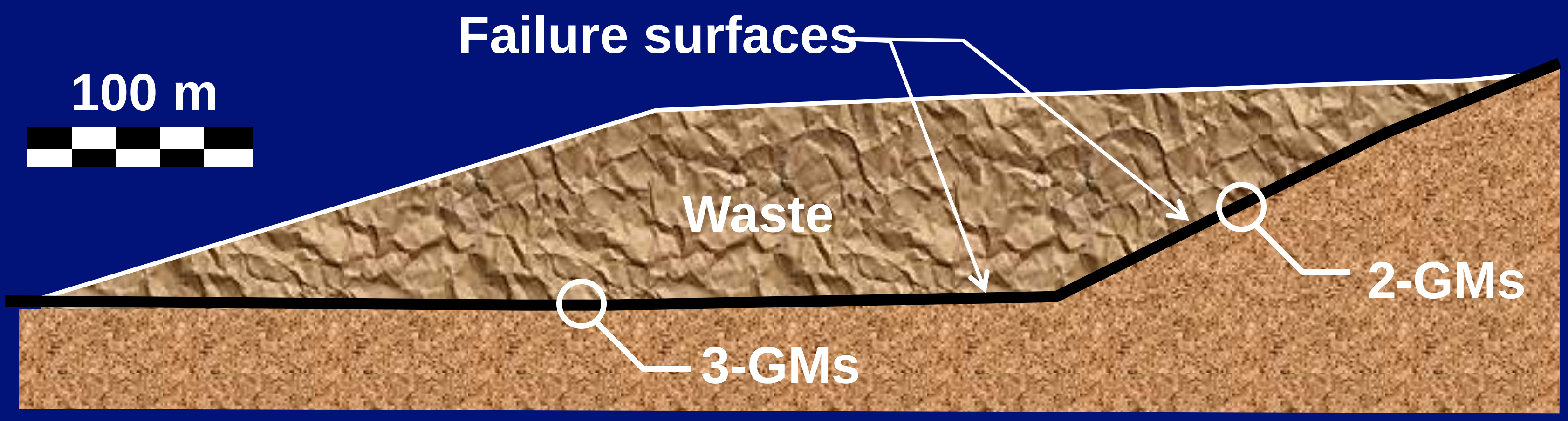


U-5 (1997)

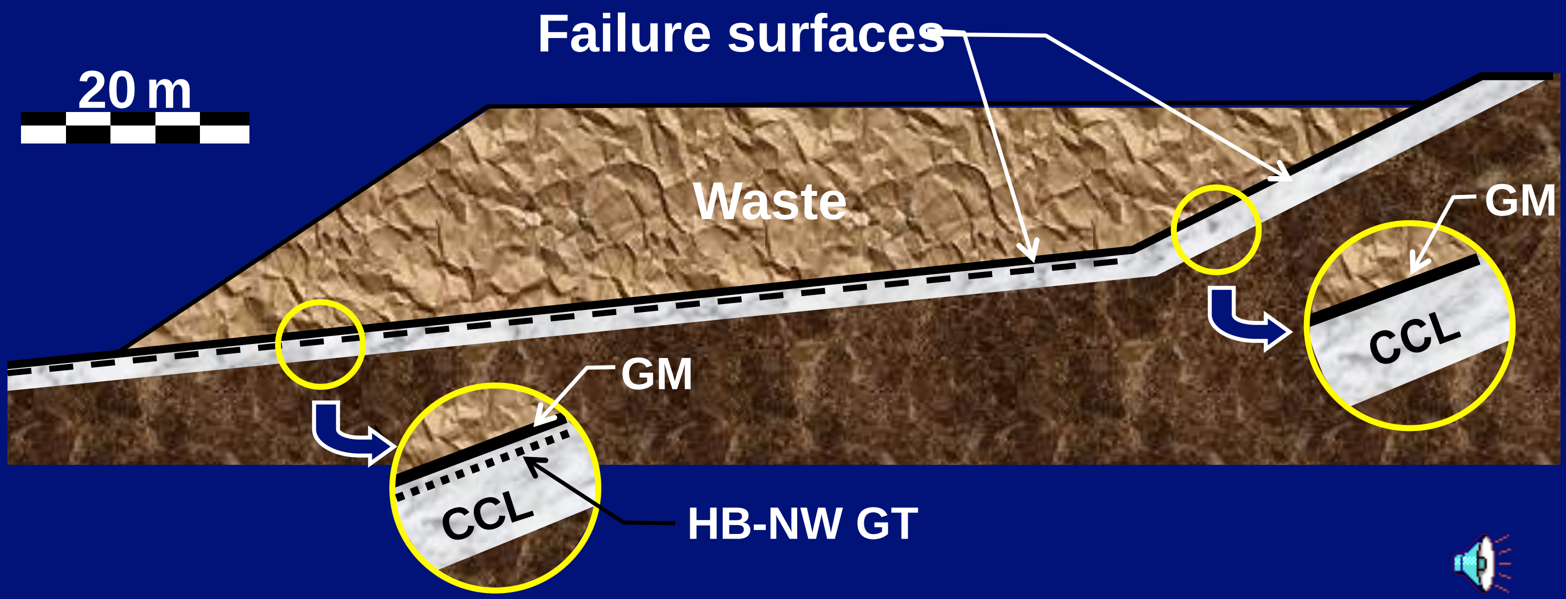


Clay cap
Trench backfilled
with clayey soil
Clay layer
Old waste (fire)
Failure surface
20 m

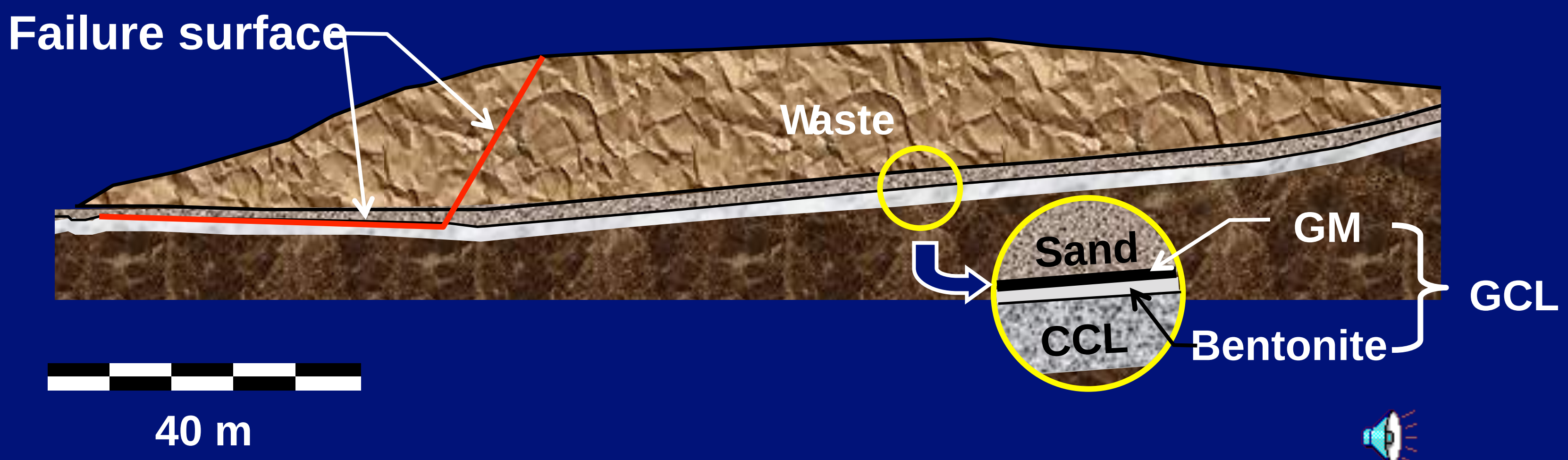
L-1 (1988)



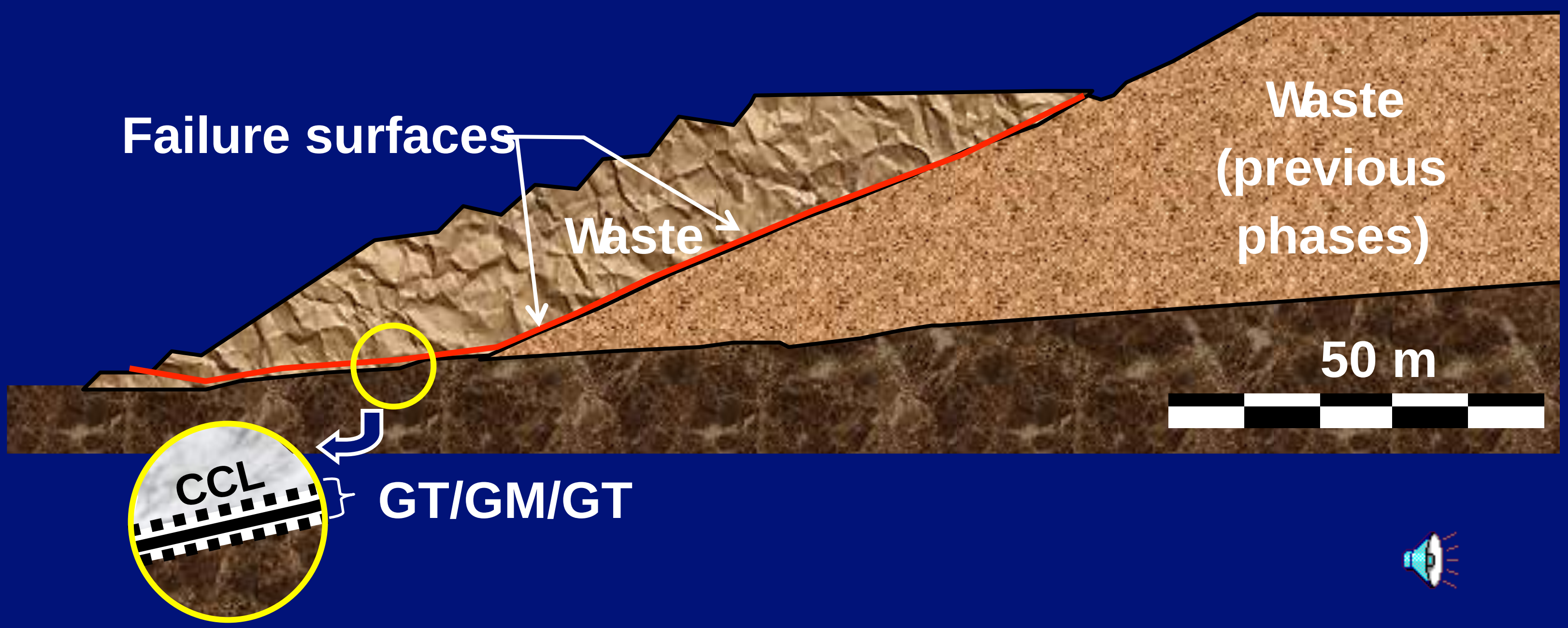
L-2 (1994)



L-3 (1997)

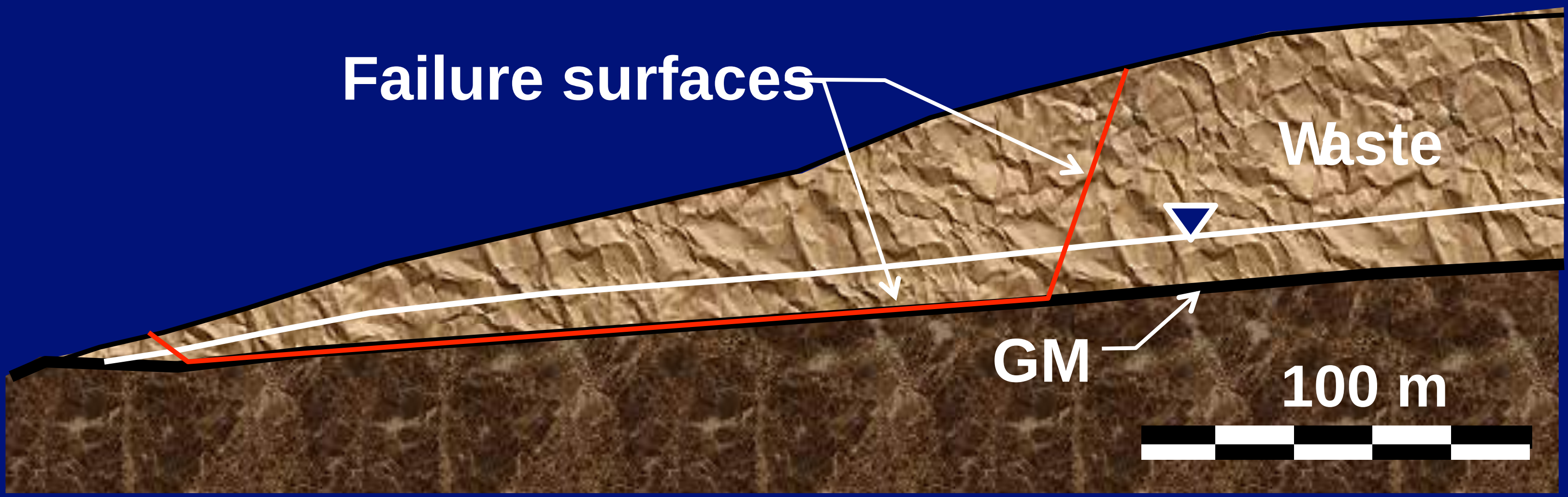


L-4 (1997)



Failure surfaces
Waste
Waste
(previous
phases)
50 m
CCL
GT/GM/GT

L-5 (1997)



Summary of Triggering Mechanisms Involved in the Case Histories of this Study

Case History	Reason for low initial FS-value	Triggering mechanism
U-3	Leachate buildup within waste mass	Excessive buildup of leachate level due to ponding
U-4		Excessive buildup of leachate level due to ice format
L-4		Excessive buildup of leachate level due to liquid waste
L-5		Excessive buildup of leachate level due to leachate i
L-1	Wet clay beneath GM (i.e.,GM/CCL)	Excessive wetness of the GM/CCL interface
L-2		Excessive wetness of the GM/CCL interface
L-3		Excessive wetness of the bentonite in an unreinforced GCL
U-1	Wet foundation or soft backfill soil	Rapid rise in leachate level within the waste mass
U-2		Foundation soil excavation exposing soft clay
U-5		Excessive buildup of perched leachate level on clay l

Note: excessive liquids above, below or within the failure surfaces were the triggering mechanisms and the ultimate causes of failure in all ten case histories presented and analyzed in this study.

Summary of Wedge Factors for the Case Histories Analyzed in This Study

Unlined Landfills

Case History	Triggering Mechanism		$FS_{3\text{-}D}$	$FS_{2\text{-}D}$	Wedge Factor
U-1	Rapid rise in leachate level	w/o[1]	1.00	0.87	1.15
		w[2]	0.94	0.86	1.09
U-2	Foundation soil excavation exposing soft cla	w/o	1.00	0.73	1.37
		w	0.95	0.72	1.32
U-3	Excessive leachate level buildup	w/o	1.00	0.85	1.18
		w	0.88	0.75	1.17
U-4	Additional leachate head buildup near the to	w/o	1.00	0.83	1.20
		w	0.96	0.81	1.19
U-5	Buildup of perched leachate head	w/o	1.00	0.72	1.39
		w	0.97	0.69	1.41

1. w/o = without the triggering mechanism
2. w = with the triggering mechanism

Summary of Wedge Factors for the Case Histories Analyzed in This Study *(cont'd)*

Lined Landfills

Case History	Triggering Mechanism		$FS_{3\text{-}D}$	$FS_{2\text{-}D}$	Wedge Factor
L-1	Excessively wetness of GM/CCL interface	w/o[1]	1.00	0.91	1.10
		w[2]	0.95	0.81	1.17
L-2	Excessively wetness of GM/CCL interface	w/o	1.00	0.75	1.33
		w	0.93	0.65	1.43
L-3	Increasing wetness of the bentonite component of G	w/o	1.00	0.78	1.28
		w	0.88	0.70	1.26
L-4	Excessive pore pressure buildup along the critical interface	w/o	1.00	0.83	1.20
		w	0.88	0.67	1.31
L-5	Leachate head buildup due to excessive leachate inj	w/o	1.00	0.88	1.14
		w	0.70	0.61	1.15

1. **w/o = without the triggering mechanism**
2. **w = with the triggering mechanism**

4.8 Cover System Considerations

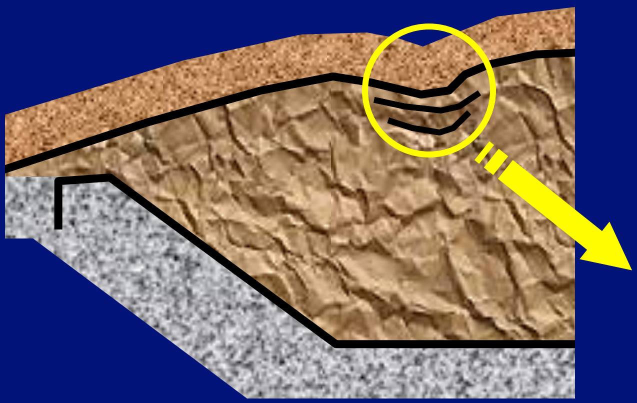
- surface layer (usually vegetated topsoil, but can be hard armor in arid areas)
- protection layer (usually thick layer of locally available borrow soil: t = 300 to 900 mm)
- drainage layer (critical to stability and must have adequate filter)
- barrier layer (dual purpose of keeping water out, gas in… GM, GCL and/or CCL)
- gas collection/foundation layer (gas transmission is generally necessary when GM is involved)

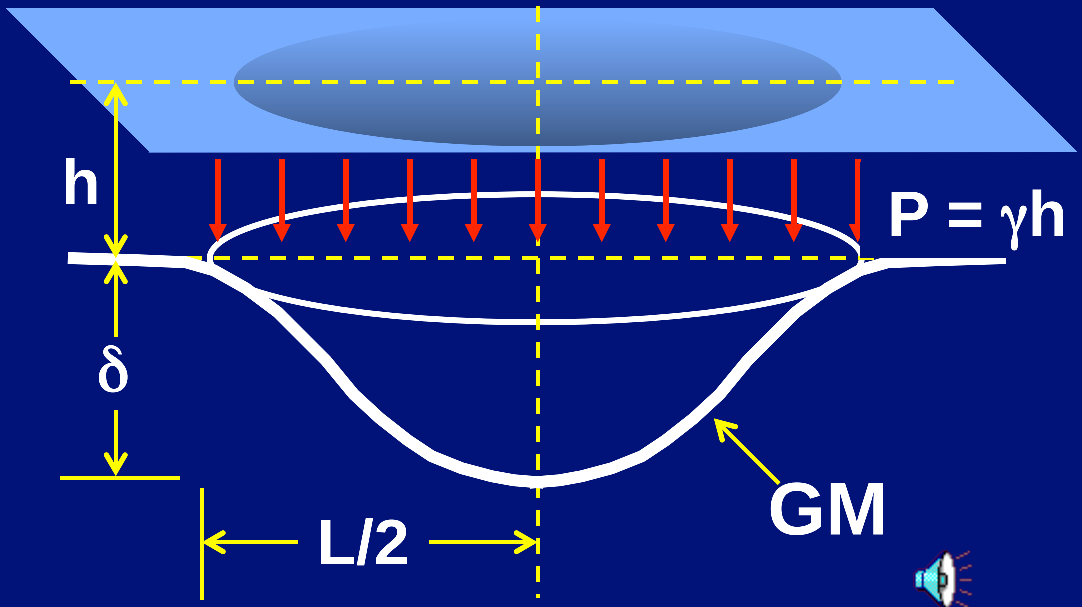
Major Components in a Cover System

Profile

Layer	Primary Functions	Usual Materials	General Considerations
Surface Layer	Promote vegetative growth; promote evapotranspiration; prevent erosion	Topsoil (humid site); cobbles (arid site); geosynthetic erosion control systems	Surface layer for control of water and/or wind erosion is always required
Protection Layer	Shore water; protect underlying layers from intrusion by plants, animals and humans; protect barrier layer from desiccation and freeze/thaw; maintain stability	Mixed soils; cobbles for biobarrier; possible capillary break in arid climates	Sizable thickness of protective layer is always required; surface layer and protection layer may be combined into a single ì cover soilî layer
Drainage Layer	Drain away infiltrating water to minimize barrier layer contact and to dissipate seepage forces	Sands; gravels; geotextiles; geonets; geocomposites; filters should be present	Drainage layer can be critical; necessary where excessive water passes through protection layer or seepage forces are present
Barrier Layer	Minimize infiltration of water into waste and escape of gas out of waste	Compacted clay liner; geomembranes; geosynthetic clay liners	Barrier layer is usually required; may not be needed at extremely arid sites
Gas Collection Layer	Transmit gas to collection points for removal and/or cogeneration	Sands; geotextiles; geonets; geocomposites	Required if waste produces gas

Tensile Stresses in GM Mobilized by Localized Subsidence of Cover Soil





Differential Settlement Issue

Geomembrane tensile stress:

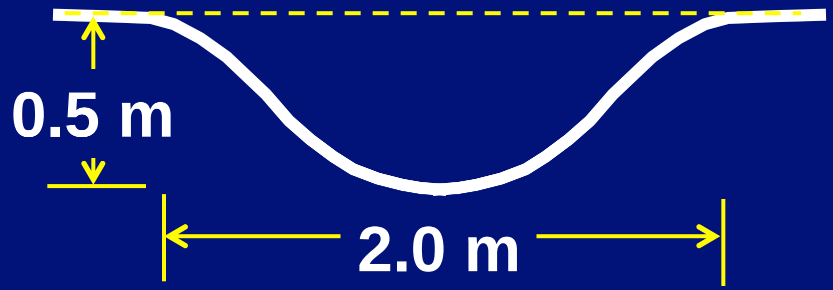
$$\sigma = \frac{\left(L^2 + 4\delta^2\right)^2 P}{16\delta L^2 t}$$

Geomembrane tensile strain:

$$\varepsilon\,(\%) = \left(\frac{\tan^{-1}\left(\frac{4L\delta}{L^2 - 4\delta^2}\right)\left(\frac{L^2 + 4\delta^2}{4\delta}\right) - L}{L} \right) \times 100 \quad \text{for } \delta < \frac{L}{2}$$

$$\varepsilon\,(\%) = \left(\frac{\left[\frac{L^2 + 4\delta^2}{4\delta}\right]\left[\pi - \sin^{-1}\left(\frac{4L\delta}{L^2 + 4\delta^2}\right)\right] - L}{L} \right) \times 100 \quad \text{for } \delta \geq \frac{L}{2}$$

Example:



Since 0.5 < 1.0, use

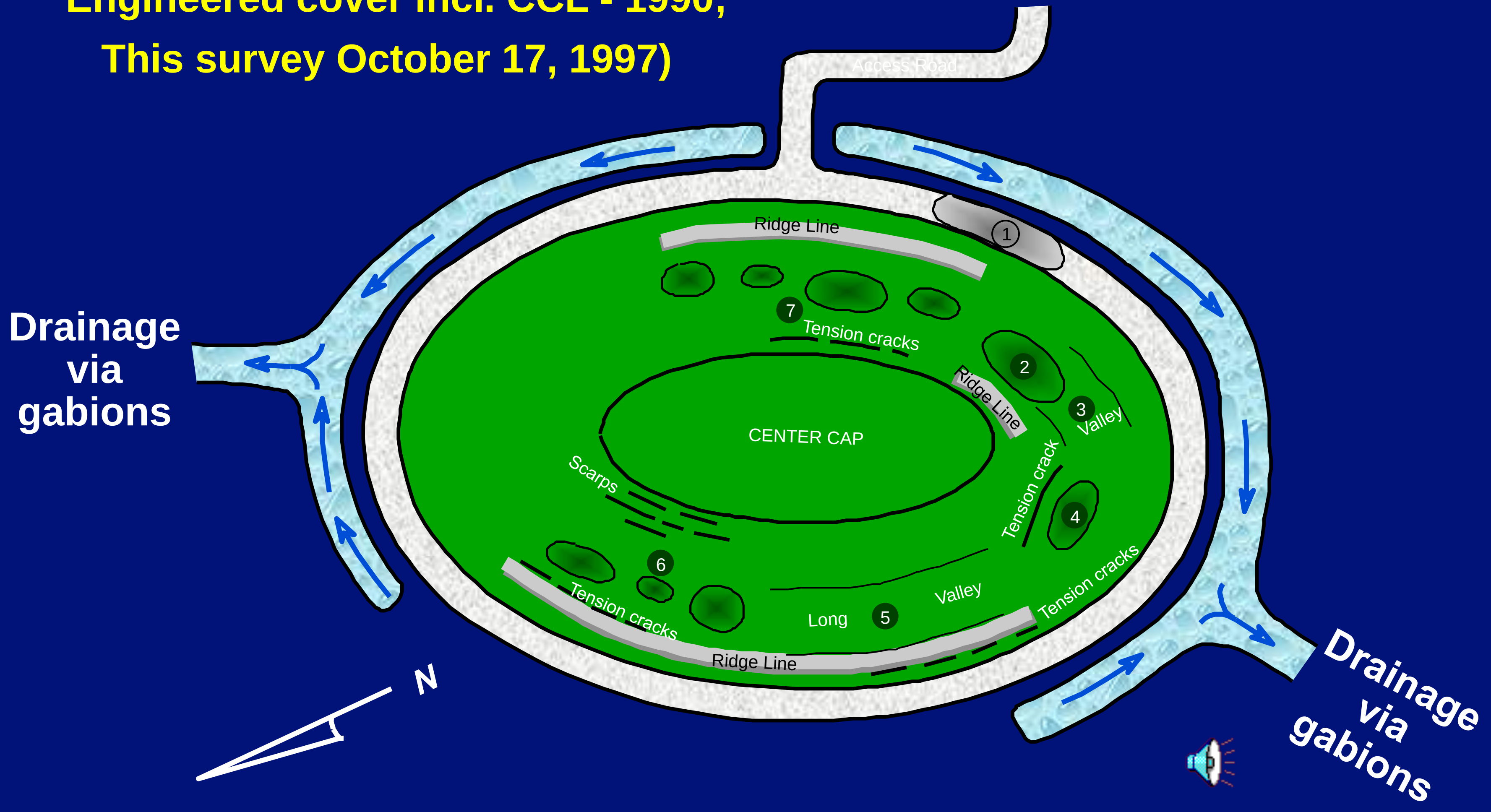
$$\varepsilon\,(\%) = \left[\frac{\tan^{-1}\left(\dfrac{4L\delta}{L^2-4\delta^2}\right)\left(\dfrac{L^2+4\delta^2}{4\delta}\right)-L}{L}\right]\times 100$$

with L = 2.0 m and δ = 0.5 m, ε = 15.9%

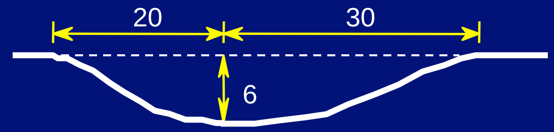
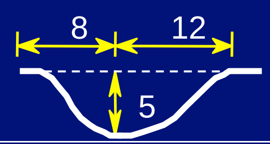
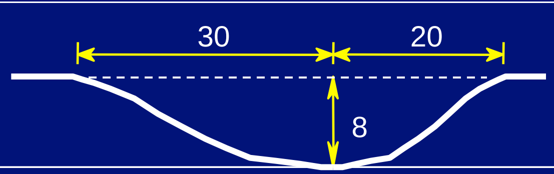
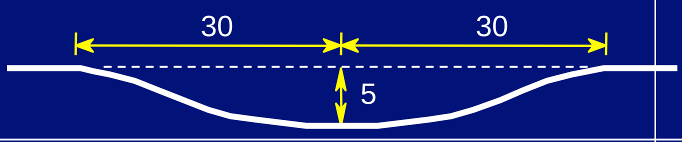
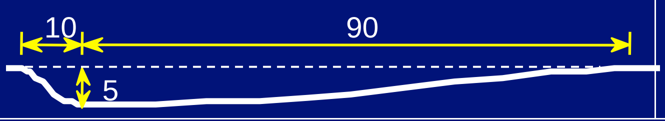
40 hectare MSW landfill (1969-1978)

Engineered cover incl. CCL - 1990;

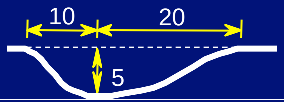
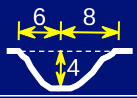
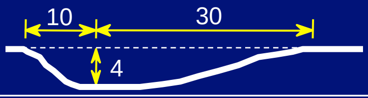
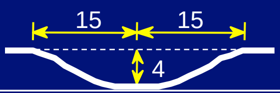
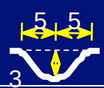
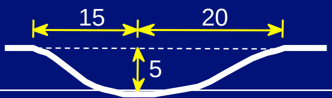
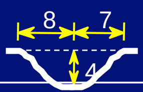
This survey October 17, 1997)



Various Differential Subsidence Patterns

Location	Description	Approx. Dimensions (ft)	Max. Strain (%)
1	Road subsidence		5.9
2	Major crater		24.3
3	100-ft long valley		10.4
4	Large crater		1.8
5	350-ft long valley		15.9

Various Differential Subsidence Patterns *(cont'd)*

Location	Description	Approx. Dimensions (ft)	Max. strain (%)
6	Three craters		15.9
			27.4
			10.4
7	Four craters		4.7
			22.5
			7.3
			15.9

How do CCL's Behave Undergoing Differential Settlement?

Data on Tensile Strain at Failure for Compacted Clay, LaGatta (1992)

Type or Source of Soil	w[1] (%)	P.I.[2] (%)	ε_t[3] (%)
Clayey Soil	19.9	7	0.80
Illite	31.4	34	0.84
Kaolinite	37.6	38	0.16
Anon. Dam	16.3	8	0.14
Rector Creek Dam	19.8	16	0.10
Woodcrest Dam	10.2	n/p	0.18
Wheel Oil Dam	11.2	n/p	0.07
Willard Embankment	16.4	11	0.20

1. Water Content
2. Plasticity Index
3. Tensile Strain at Failure

Ave = 0.31%!

How do GCL's Behave Undergoing Differential Settlement?

To a Breakthrough in Permeability (via LaGatta & Boardman)

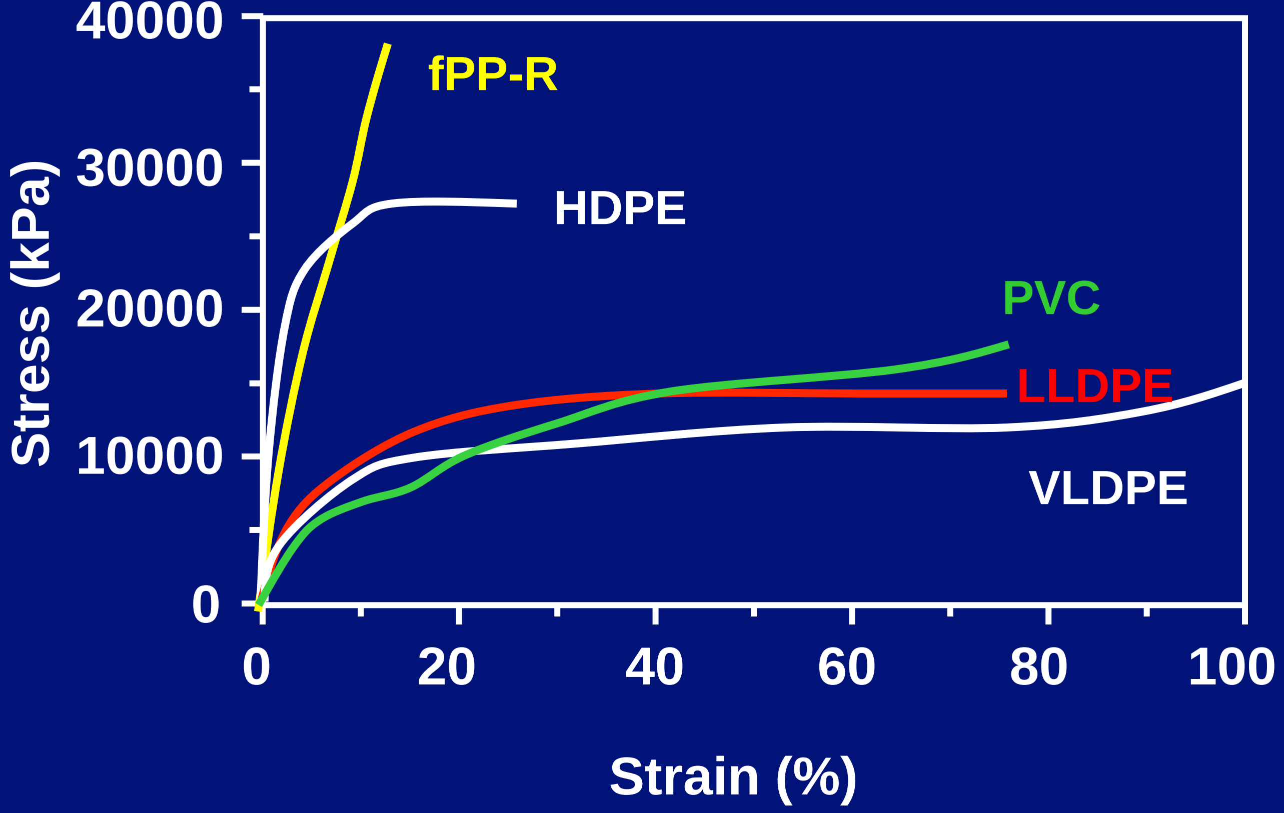
$$\varepsilon_t (\%) = 10 \text{ to } 15\ \%$$

To Break in 3-D Tension Test (via Koerner, et al.)

$$\varepsilon_f (\%) = 15 \text{ to } 26\ \%$$

How do GM's Behave Undergoing Differential Settlement?

(via GRI GM4 Test Method: Koerner, et al., ASTM STP 1081)



Resulting ε_f

fPP-R = 12%
HDPE = 25%
PVC = 75%
LLDPE = 75%
VLDPE = 100%

Summary of Influence of Individual Factors on Various Barrier Layers in Final Covers (after Daniel & Koerner)

Liner Component	Climate			Settlement			Cover Erosion/ Puncture Vulnerability		
	Arid	Cyclic	Humid	Major	Mod.	Nominal	Major	Mod.	Low
CCL	1	1	3	1	1	3	1	2	3
GM	5	4	4	4	5	5	1	1	3
GCL	3	3	4	2	3	4	1	1	3
GM/CCL	2	3	4	2	3	4	3	4	4
GM/GCL	5	4	5	3	4	5	2	3	4
GM/CCL/GM	4	4	5	3	4	5	4	5	5
GM/GCL/GM	5	5	5	4	5	5	4	5	5

Allowable Percolation			Gas Collection		Slope Inclination		
Ess. None	V. Little	Mod.	Gas	No Gas	< 9°	9-18°	> 18°
1	2	3	1	1	5	4	3
1	3	5	5	5	5	5	3
1	2	3	1	5	4	3	3
3	4	4	3	5	5	3	2
3	4	5	4	5	5	3	2
5	5	5	4	5	5	2	1
5	5	5	4	5	5	3	2

1 = Not acceptable
2 = Marginal
3 = Possibly OK
4 = Acceptable
5 = Best Possible

Benefit/Cost Assessment of Various Liner Cross Sections (after Daniel & Koerner)

No. of Barrier Layers	Description	Overall Benefit*	Est. Cost $/m^2	Benefit/ Cost Ratio	Ranking in Group
One Layer	CCL	34	5.00	6.8	3
	GM	63	3.00	21.0	1
	GCL	46	4.00	11.5	2
Two Layers	GM/CCL	58	8.00	7.2	2
	GM/GCL	66	7.00	9.4	1
Three Layers	GM/CCL/GM	72	11.00	6.5	2
	GM/GCL/GM	77	10.00	7.7	1

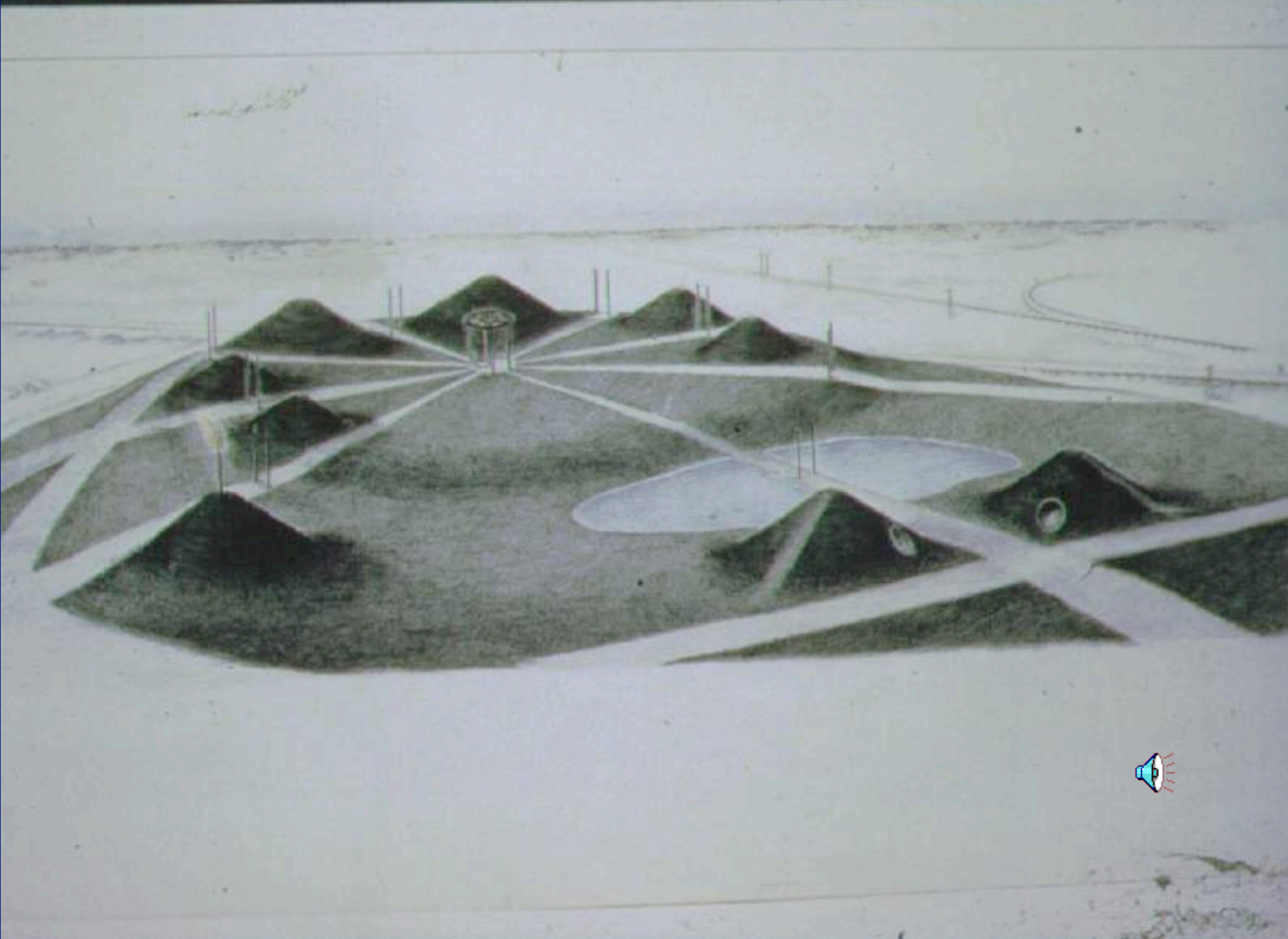
***Determined by summing horizontal rows in previous table**

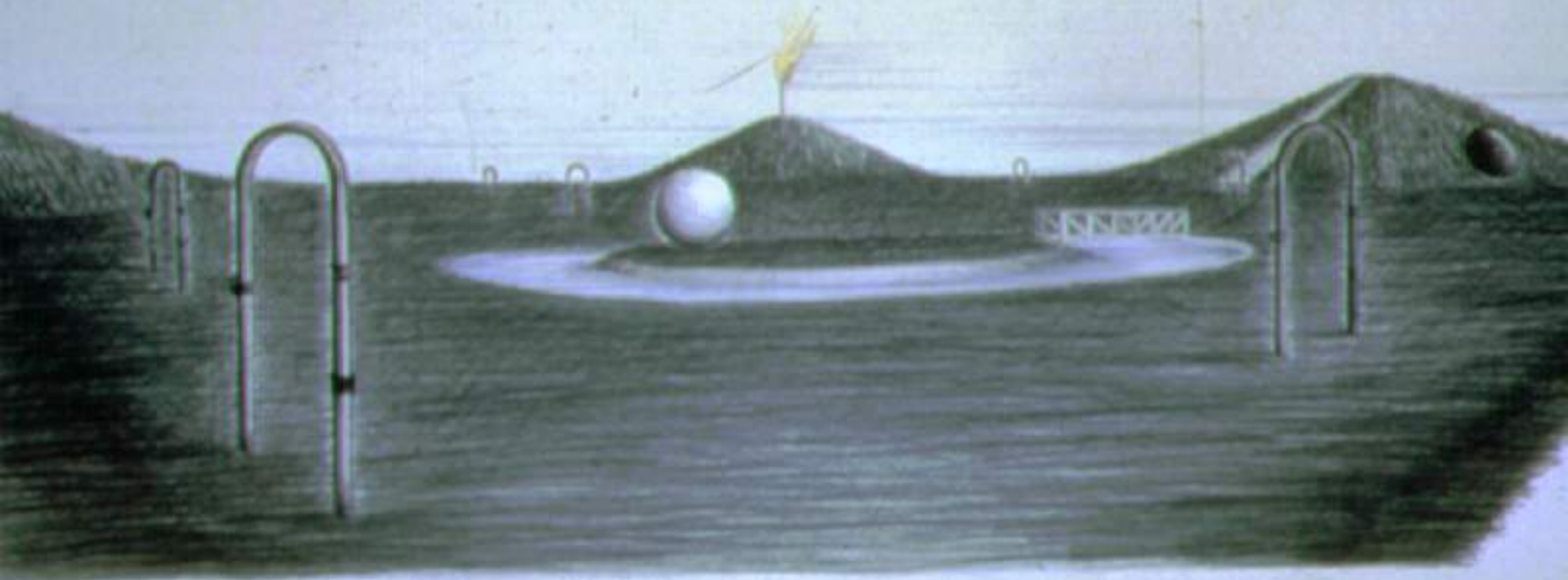
Conclusions

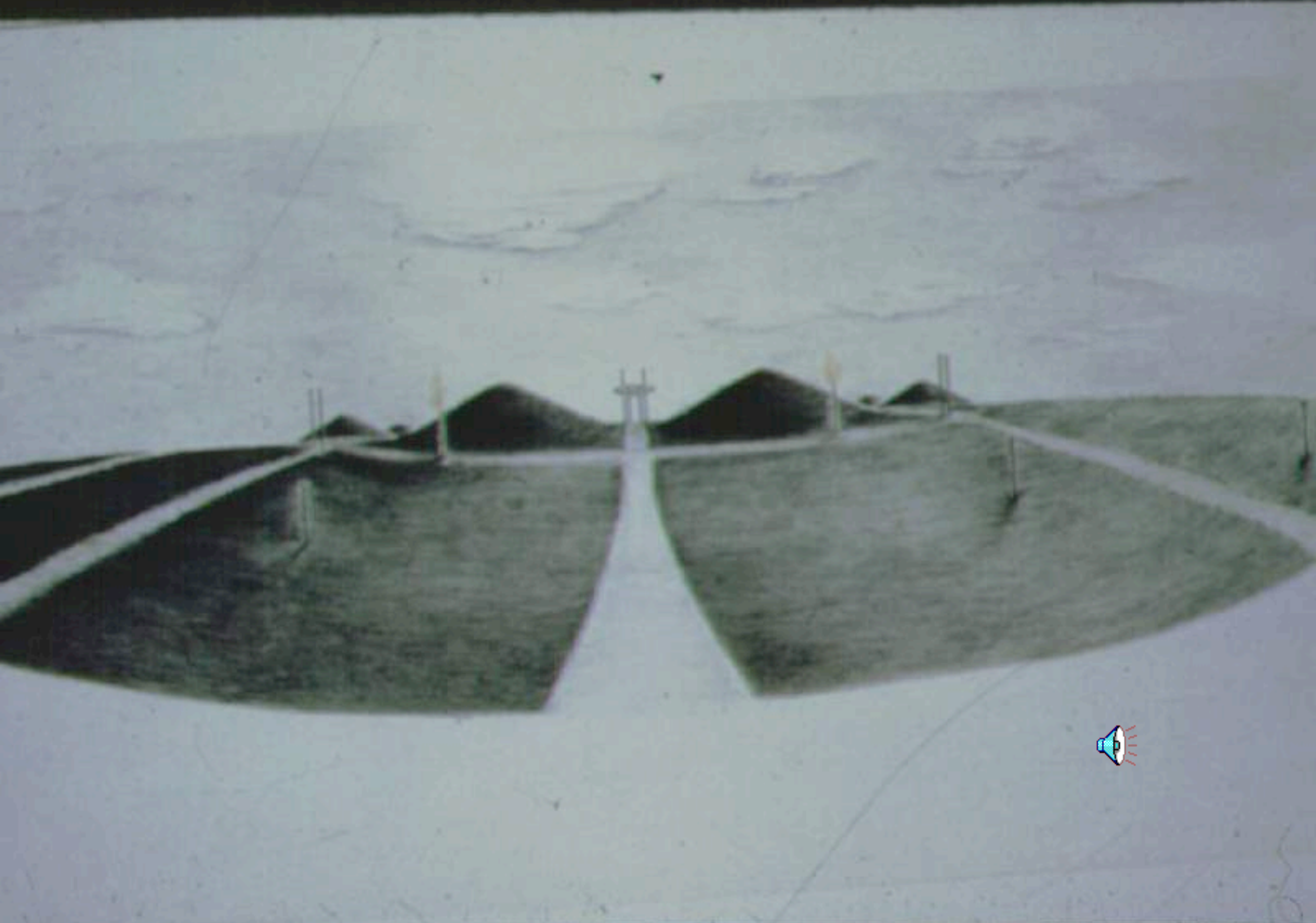
- CCL's should <u>**not**</u> be the general cover barrier of choice.
- GM's and GCL's are better both technically and based on benefit/ cost.
- The preferred cover barrier is a GM by itself or a GM/GCL composite.

Post Closure Uses of Landfills

- Golf courses
- Sports and athletic fields
- Jogging, hiking and biking trails
- Light industrial and staging areas
- Aesthetics and/or visual artworks







4.9 Erosion Control Geosynthetics

- soil erosion is a frequent occurrence in final covers
- can act through entire cover soil exposing the barrier
- erosion mechanisms are well understood
- GSs can provide temporary or permanent erosion control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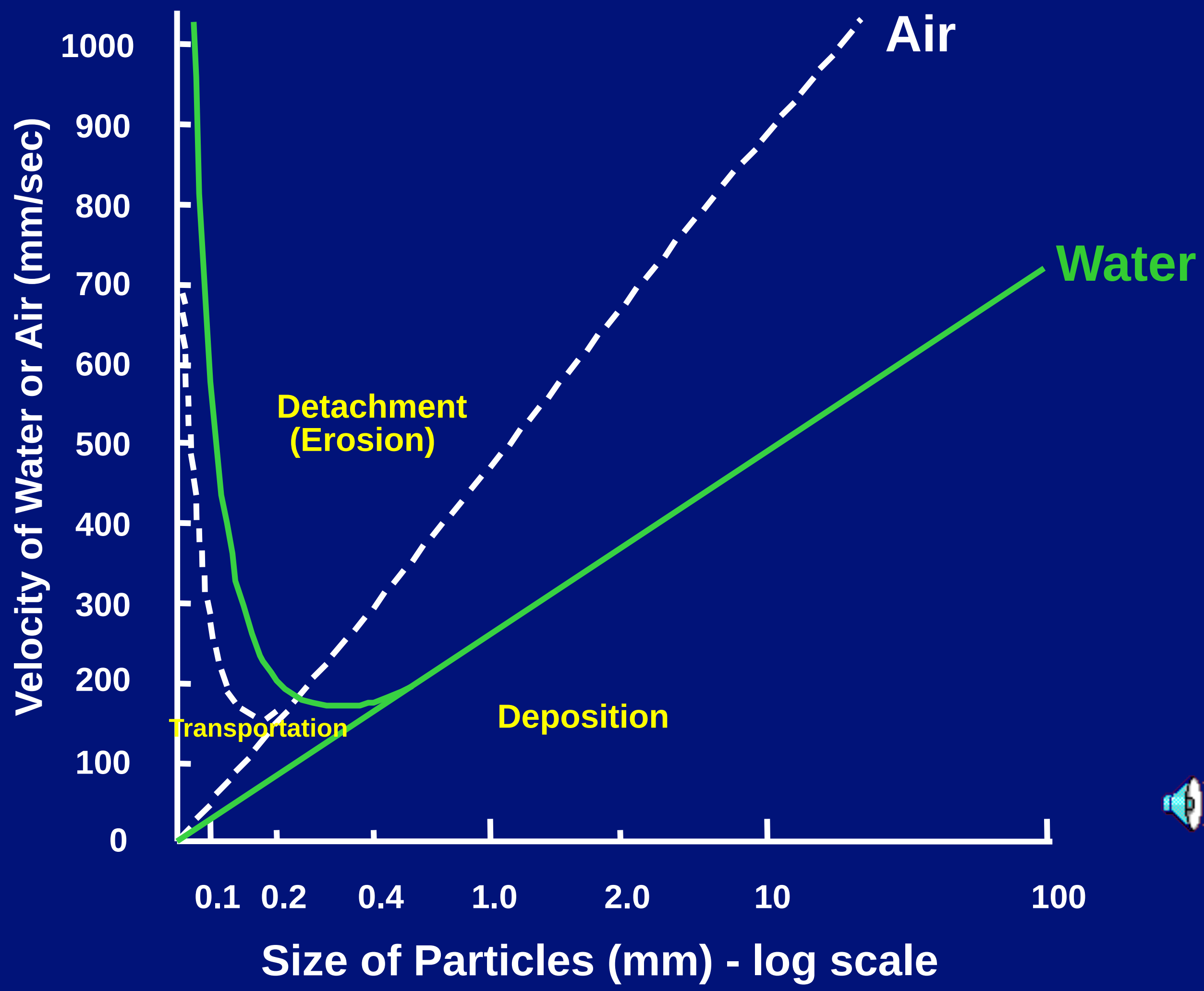
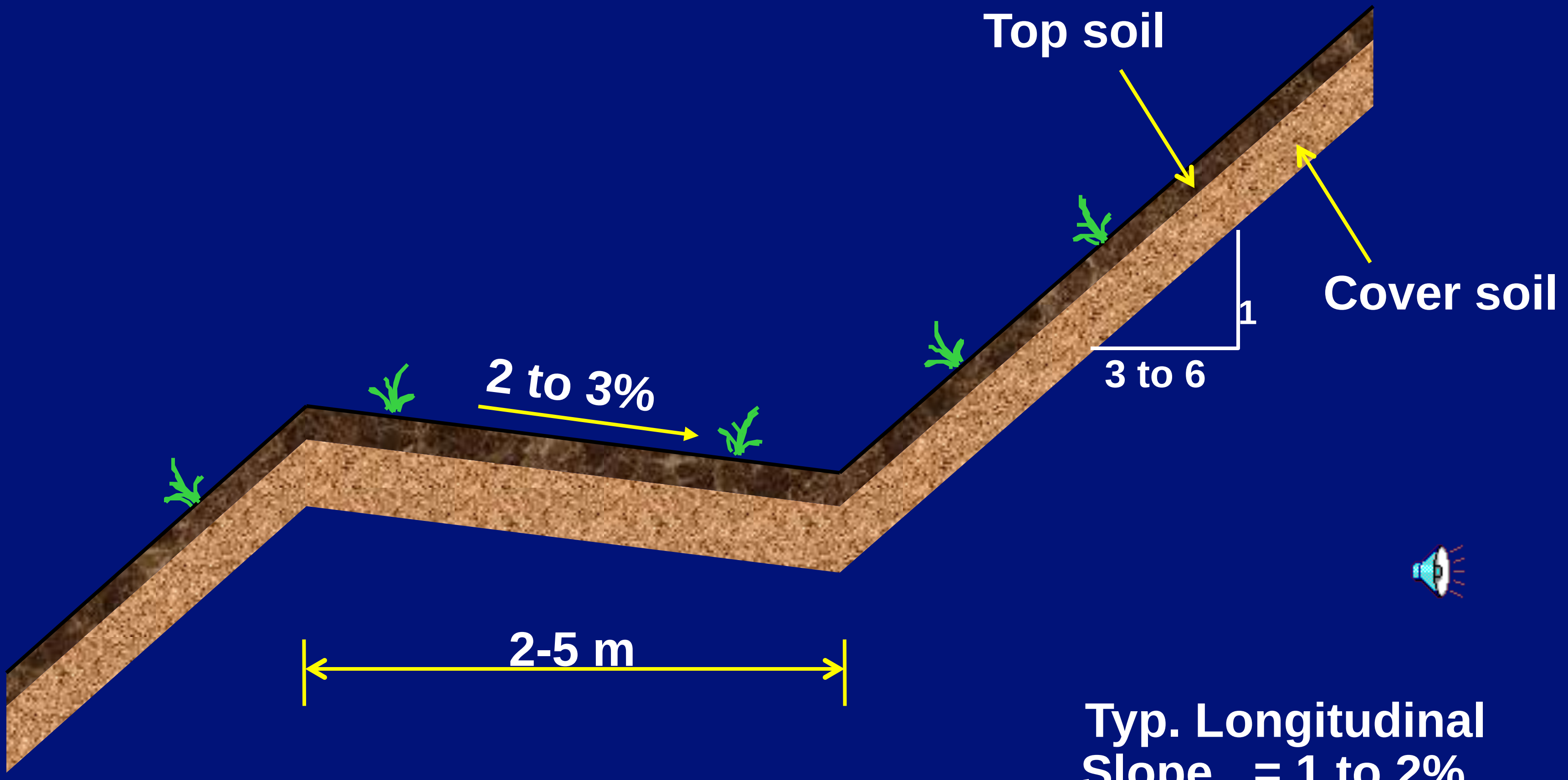
Erosion Mechanisms

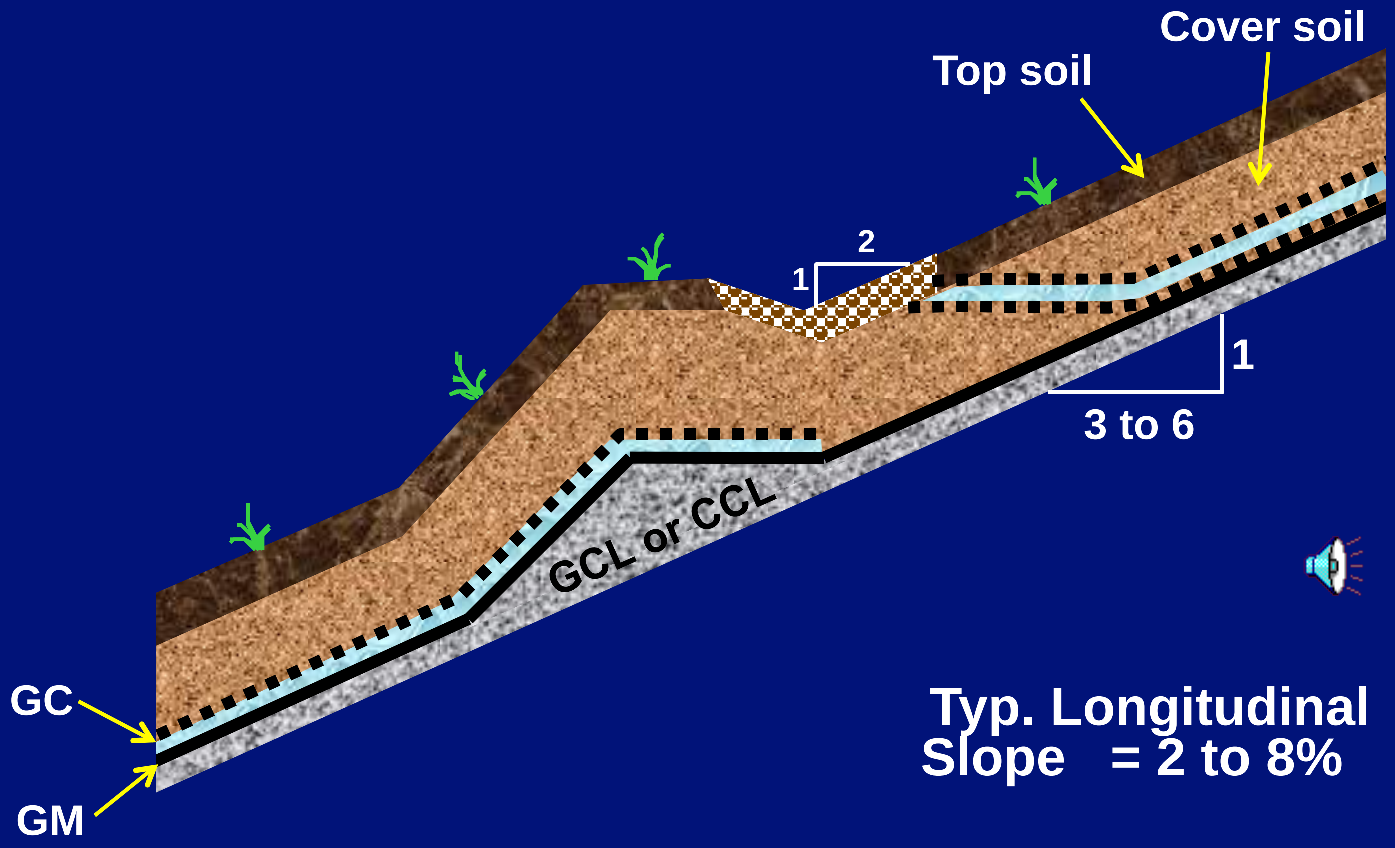


Typical Drainage Bench



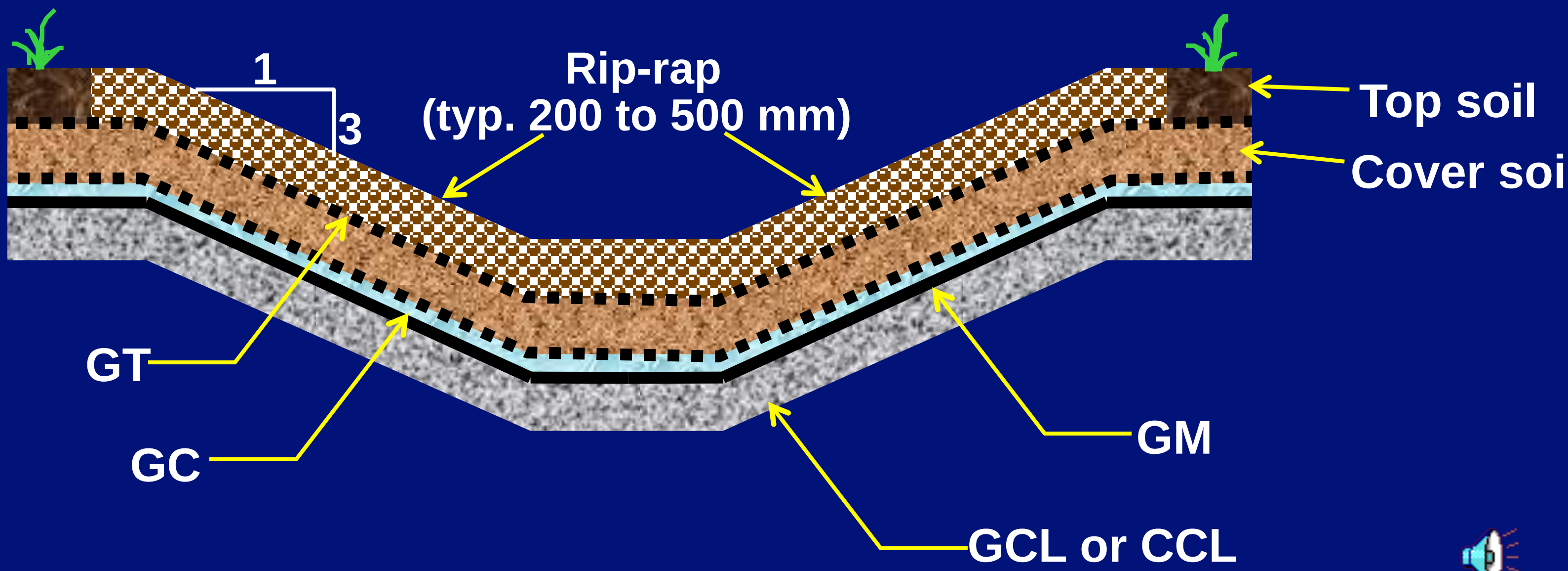
Typ. Longitudinal
Slope = 1 to 2%

Typical Terrace Channel



Typ. Longitudinal
Slope = 2 to 8%

Typical Letdown Channel



Typ. Longitudinal Slope = 8 to 33%

Various Erosion Control Materials (After M. S. Theisen, Jour. G & G)

TERMs	PERMs	
	Biotechnical-related	Hard armor-related
Straw, hay and hydraulic mulches	UV-stabilized fiber roving systems (FRSs)	Geocellular containmen systems (GCSs)
Tackifiers and soil stabilizers	Erosion control revegetation mats (ECRMs)	Fabric formed revetments (FFRs)
Hydraulic mulch geofibers	Turf reinforcement mat (TRMs)	Vegetated concrete blo systems
Erosion control meshes and nets (ECMNs)	Discrete length geofibesrs	Concrete block system Stone riprap
Erosion control blanket (ECBs)	Vegetated geocellular containment systems (GCSs)	Gabions
Fiber roving systems (FRSs)		

Erosion Control Test Methods

Category	Test	Method	Temporary	Long-Term
Physical	open area	CoE	S	S
	thickness	ASTM D1777	S	S
	resiliency	ASTM D1777	S	S
	weight	ASTM D5261	P	P
	flexibility	ASTM D1388	P	P
	soil holding capability	unknown	P	P
	soil conformance	unknown	P	P
Mechanical	tensile	ASTM D5035	P	P
	impact	ASTM D1424	S	S
	tear	ASTM D4533	S	S
	puncture	GRI GS -1	S	S
	peel	ASTM 413	P or S	P or S
	shear	ASTM D5321	P or S	P or S
Hydraulic	water absorption	ASTM D471	P	P
	swelling	ASTM D543	P	P
	soil detachment	GRI ECS1	P	P
	soil transportation	GRI ECS2	P	P
Endurance	UV resistance	ASTM D4355	P	P
	smolder resistance	FTMS-CCC-5-191B	S	S
	biodegradability	ASTM D3083	P	P
	leachate resistance	unknown	S	S

P = primary consideration
S = secondary consideration

Next File