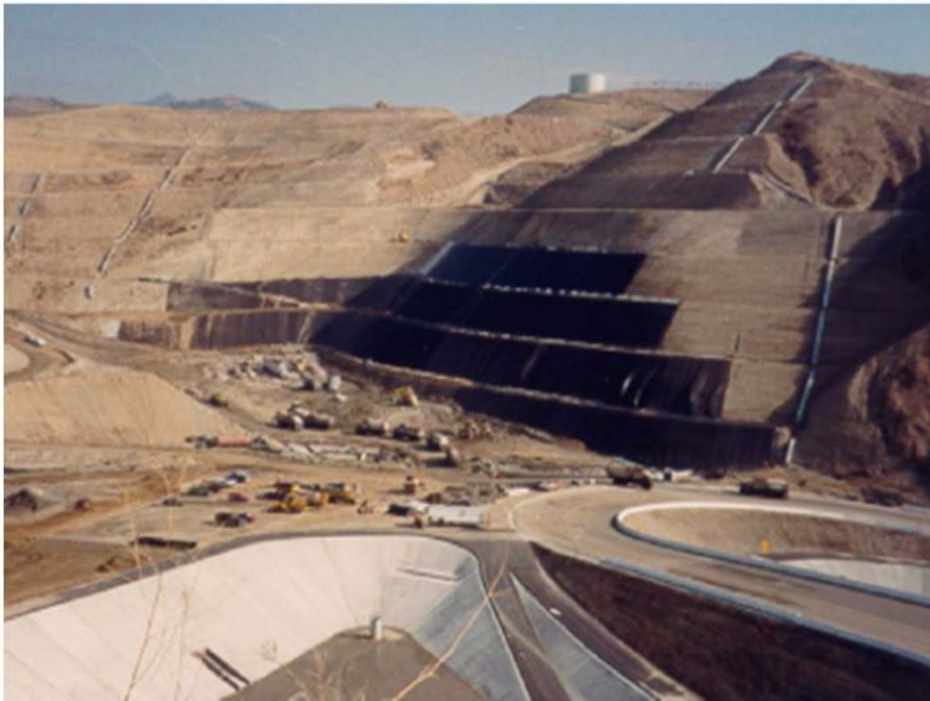


# Geosynthetic Engineering: Lessons from 30 Years of Landfills Performance

GEOSYNTEC | MMI | SIREM | GSM

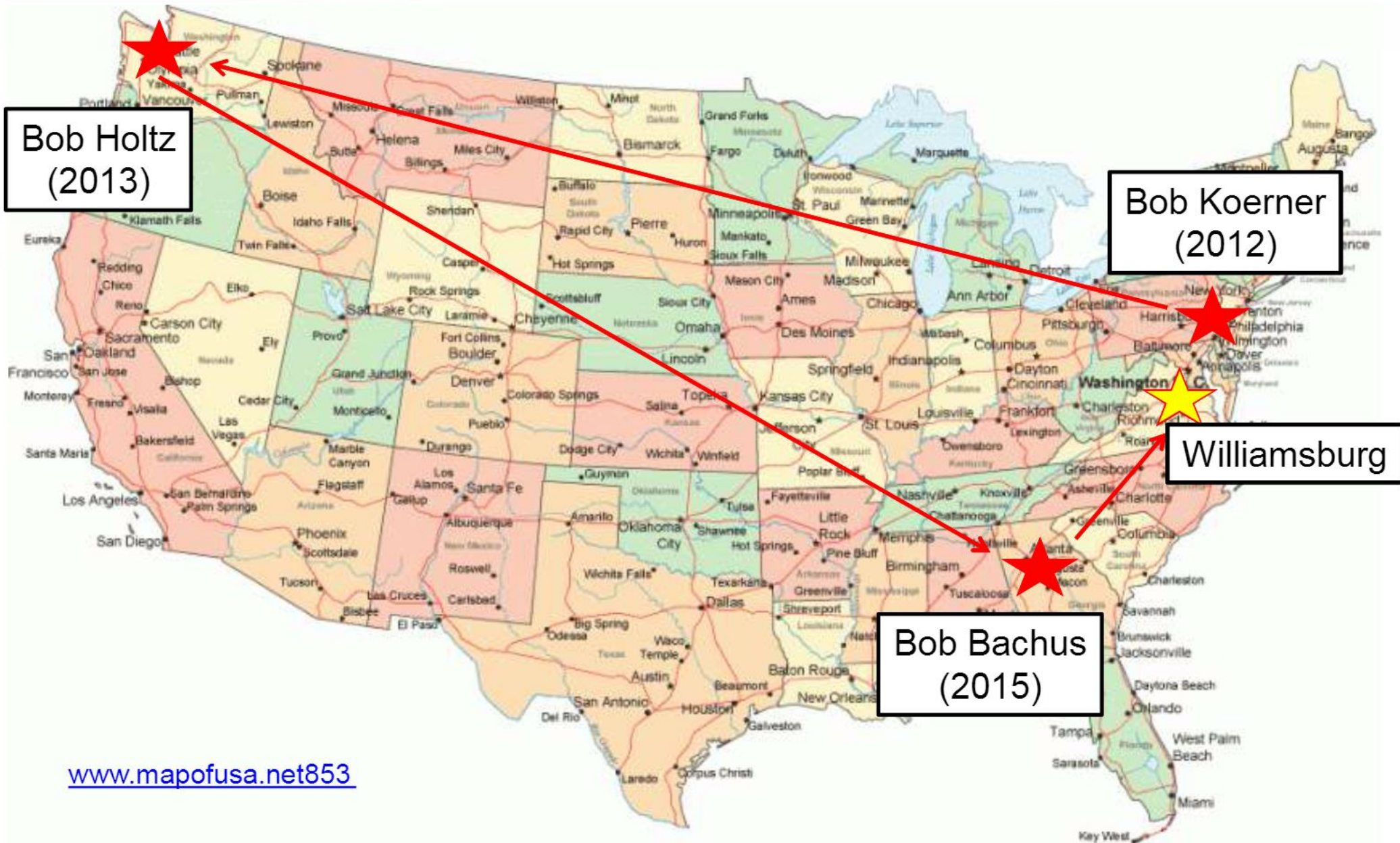
 **GEOVIRGINIA**  
2015  
Lessons Learned in Geotechnical Engineering  
Williamsburg, VA  
April 27 - April 29

Robert C. Bachus, Ph.D., P.E., D.GE  
Rudolph Bonaparte, Ph.D., P.E., D.GE  
Geosyntec Consultants  
Atlanta, GA



Williamsburg, VA.  
29 April 2015

# Geosynthetics Lessons – Bob<sup>3</sup>



[www.mapofusa.net853](http://www.mapofusa.net853)

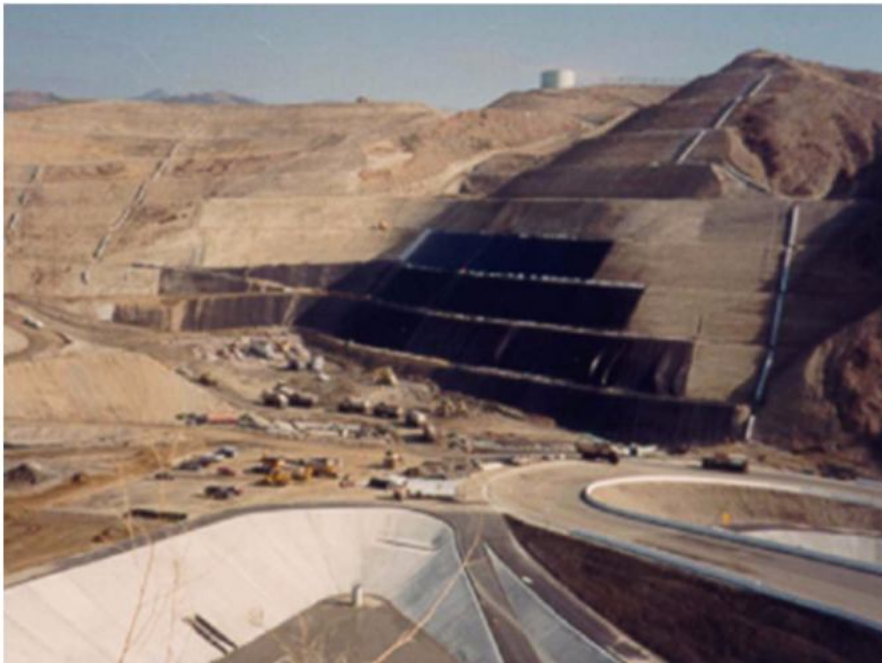


## History of Geosynthetics - GeoVirginia

- Bob #1: Dr. Robert M. Koerner, Drexel University
  - Geosynthetic Reinforced MSE Wall Failures and Their Remediation, GeoVirginia, 2012
- Bob #2: Dr. Robert D. Holtz, University of Washington
  - Geosynthetic Reinforced Soil: From the Laboratory to the Familiar, GeoVirginia, 2013
- Bob #3: Dr. Robert C. Bachus, Geosyntec Consultants
  - Geosynthetic Engineering: Lessons from 30 Years of Landfill Performance, GeoVirginia, 2015

# Geosynthetic Engineering: Lessons from 30 Years of Landfill Performance

- Landfills helped catapult the geosynthetics industry
- 30 years of experience has provided innumerable lessons
- Geosynthetics play an increasingly important role in civil and environmental engineering projects



“Those who cannot remember the past are condemned to repeat it.” (Santayana, 1905)



# Geosynthetic Engineering: Lessons from 30 Years of Landfill Performance

- Part I: Landfill History and Significance
- Part II: Geosynthetics 101
- Part III: Geosynthetics in Landfills
- Part IV: Lessons from Geosynthetics in Landfills

Geosynthetics may be the perfect solution to your problem...



[www.thebeausejourpulpit.wordpress.com](http://www.thebeausejourpulpit.wordpress.com)

**BUT**



<http://lisbethcalandrino.com>

## Part I: Birth of Modern Landfill Design

- Major goal of USEPA since founding in 1970 has been on environmentally safe and secure containment of waste in landfills, building on Solid Waste Disposal Act (1965)
- Resource Conservation and Recovery Act (RCRA) promulgated on 21 October 1976 defined primary laws governing disposal of solid and hazardous waste
- Subtitle D of RCRA addresses management of non-hazardous solid waste
- Federal requirements first published on 9 October 1991 defined federal requirements for public and private landfills receiving municipal solid waste were codified in Subpart 258, Title 40, Code of Federal Regulations (CFR) and are referenced as the “Subtitle D Regulations.”
- Effective date of Regulations: 9 October 1993 (22 years ago)



## Specific Requirements of Subtitle D

<http://www.epa.gov/solidwaste/nonhaz/municipal/landfill.htm>

- **Location restrictions**—ensure that landfills are built in suitable geological areas away from faults, wetlands, flood plains, or other restricted areas.
- **Composite liners requirements**—include a flexible membrane (geomembrane) overlaying two feet of compacted clay soil lining the bottom and sides of the landfill, protect groundwater and the underlying soil from leachate releases.
- **Leachate collection and removal systems**—sit on top of the composite liner and removes leachate from the landfill for treatment and disposal.
- **Operating practices**—include compacting and covering waste frequently with several inches of soil help reduce odor; control litter, insects, and rodents; and protect public health.
- **Groundwater monitoring requirements**—requires testing groundwater wells to determine whether waste materials have escaped from the landfill.
- **Closure and postclosure care requirements**—include covering landfills and providing long-term care of closed landfills.
- **Corrective action provisions**—control and clean up landfill releases and achieves groundwater protection standards.
- **Financial assurance**—provides funding for environmental protection during and after landfill closure (i.e., closure and postclosure care).

## Specific Requirements of Subtitle D

<http://www.epa.gov/solidwaste/nonhaz/municipal/landfill.htm>

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- **Leachate Collection and Removal Systems**—sit on top of the composite liner and **removes leachate** from the landfill for treatment and disposal.
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- **Closure and Postclosure Care Requirements**—include covering landfills and providing long-term care of closed landfills.
- **Corrective Action Provisions**—control and clean up landfill releases and achieves groundwater protection standards.
- **Financial Assurance**—provides funding for environmental protection during and after landfill closure (i.e., closure and postclosure care).



# Enter the World of Geosynthetics

Geosynthetics = Modern Landfill Design

- Containment (“flexible membrane”)
- Drainage (“removes leachate”)



(after J.P. Giroud)

## Part II: Geosynthetics in Landfill Design

- Geosynthetics are manmade (plastic) products
  - We can control properties and variability (within limits)
  - We can choose between products (multiple sources)
- Geosynthetics can be “used” on a design project or they can be “designed” for use on the project
- Concept to Remember:

### Design by Function

referenced to Dr. Robert Koerner

Drexel University and Geosynthetics Institute (GSI)



# Geosynthetics 101 – What and When?

- A planar product manufactured from **polymeric** material used with soil, rock, earth, or other geotechnical engineering related material as an integral part of a human-made project, project, or system (ASTM D4439)
- Polymer – poly (many) + meros (parts)
- Feedstock is ethylene gas that is reacted with catalyst to form discrete particles
  - Polyethylene (Ziegler) and Polypropylene (Natta) shared Nobel Prize in 1963



# Were Geosynthetics Born in 1967?

- I just want to say one word to you...just one word. (*yes sir.*)
- Are you listening? (*yes, I am.*)
- PLASTICS! (*exactly how do you mean?*)
- There's a great future in plastics....think about it.
- Will you think about it? (*yes, I will.*)
- Enough said....that's a deal.

Dustin Hoffman and Walter Brooke  
(The Graduate)



roomforapony.net

George Koerner and Bob Koerner  
(The Geosynthetics Institute)



<http://www.geosynthetic-institute.org>



# Polymers in Geosynthetics

- Cross-linking of polymers is important
  - Thermoplastic (heat, melt, cool many times)
    - Polyethylene (PE)
    - Polypropylene (PP)
    - Polyvinyl chloride (PVC)
    - Polyester (PET)
    - Chlorosulfonated polyethylene (CSPE or Hypalon)
    - Polystyrene (PS or Styrofoam)
  - Thermoset (heat, soften/melt, cool once)
    - Butyl (rubber)
    - Ethylene propylene diene terpolymer (EPDM)
    - Ethylene vinyl acetate (EVA)

# Polymer Chemistry

- Glass Transition Temperature ( $T_g$ )
  - below this temperature, material is brittle
- Melting Temperature ( $T_m$ )
  - above this temperature, material flows

<u>Material</u>	<u><math>T_g</math> (°C)</u>	<u><math>T_m</math> (°C)</u>
PE	-125	+141
PP	-7	+187
PVC	+81 to +98	+273
EPDM	-54	n/a

- Chemical Fingerprinting
  - Thermogravimetric Analysis (TGA) – mass loss upon heating due to vaporization of components
  - Differential Scanning Calorimetry (DSC) – heat flow for  $T_g$  (endothermic), crystallization (exothermic), and  $T_m$  (endothermic).



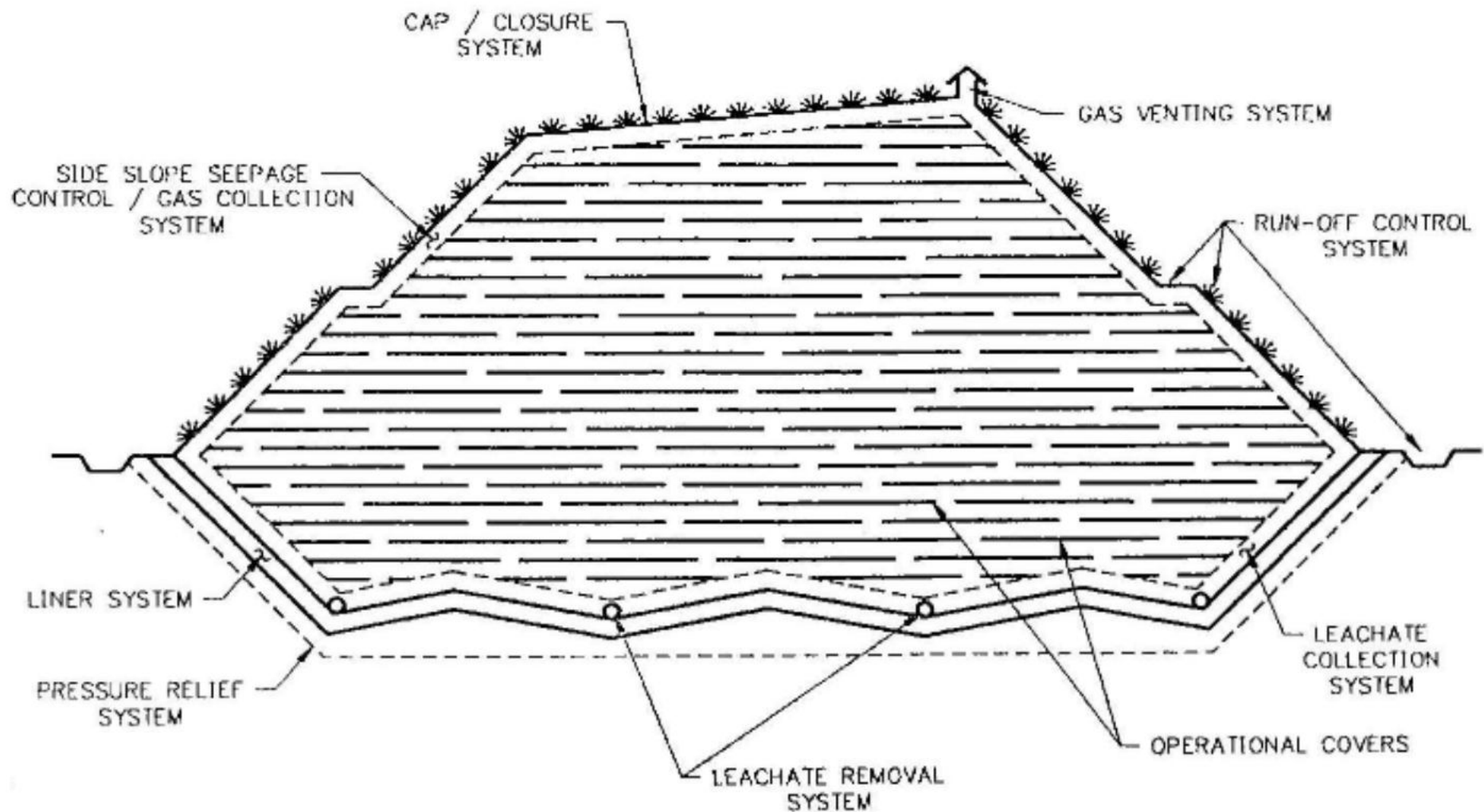
# Polymer Chemistry

- Materials used in Geosynthetics
  - Resin (specific polymer)
  - Additives (e.g., antioxidants, processing aids, lubricants)
  - Fillers (e.g., carbon black)
  - Plasticizers
- Specific Gravity and Thermal Expansion of Polymers

<u>Material</u>	<u><math>G_s</math></u>	<u>Thermal Expansion (<math>\epsilon^{-5}</math> per <math>^{\circ}\text{C}</math>)</u>
PE	0.96	13
PP	0.91	6
PET	1.22 or 1.38	4 to 5
Nylon	1.14	5 to 5.5
EPDM	1.10	4 to 5

(after Koerner, 2005)

# Part III: Landfills and Geosynthetics



(after Fluet, 2000)



## Geosynthetics: *Engineered* Plastics

### Design by Function

- Geomembrane ..... containment
- Geotextile ..... separation, filtration, permeability, cushion, reinforcement
- **Collectively referenced as “Geo...Stuff”**
- Geocomposite ..... filtration, drainage, transmissivity, erosion protection, wick drains
- Geogrid ..... reinforcement
- Geosynthetic Clay Liner (GCL) ..... containment
- Geotubes ..... drainage
- Geocells ..... confinement, surface protection, erosion resistance

# Geomembrane





# Smooth and Textured Geomembrane

Various manufacturing techniques to produce different thickness and surface



Smooth

[geosyntheticmagazine.com](http://geosyntheticmagazine.com)



Textured

(after J.P. Giroud)

# Geomembrane

- Function: Low permeability to liquid and gas
- Manufacturing controls (varies by manufacturer)
  - Extrusion
  - Blown film
  - Calendaring
- Properties of importance
  - Physical
  - Mechanical
  - Endurance (chemical, biological, thermal)
  - Seaming adjacent flat panels/sheets



# Geomembrane - Physical Properties

- Thickness - ASTM D5199
  - smooth sheet
- Density – ASTM D1505
  - PE and PP have  $G_s < 1.0$
- Melt Flow Index – ASTM D1238
- Water Vapor Transmission – ASTM E96
  - Indirect measure of  $k < 1 \times 10^{-11}$  cm/s
- Solvent Vapor Transmission – ASTM E96

# Geomembrane - Mechanical Properties

- ASTM Methods depend on polymer type (e.g., HDPE, VLDPE, PVC, PP)
- Tensile Strength
  - Index
  - Wide width
  - Multiaxial
- Tear Strength
- Impact Strength
- Puncture Strength

# Geomembrane - Endurance Properties

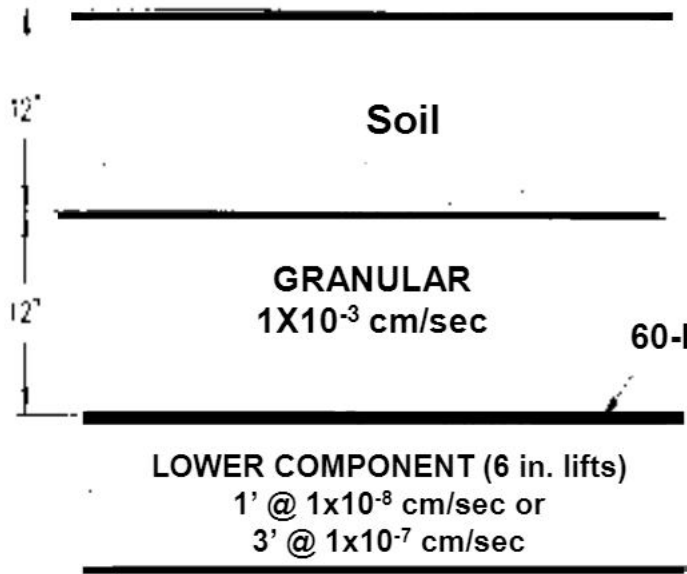
- Ultraviolet Resistance
  - Small wavelength light attacks chains
  - Carbon black addition
    - PE  $\approx$  2 to 3%; PVC  $\approx$  10 to 15%
- Radioactive Resistance
- Chemical Resistance
  - USEPA 9090
  - Landfill leachates are generally OK
  - Hazardous waste may require immersion/exposure testing
- Thermal Resistance
  - Thermal expansion/contraction
  - Cold brittleness
- Oxidation Resistance
  - Use of antioxidants
- Biological Resistance
  - No specific tests developed
  - Generally thought that direct burial is OK



# Geomembrane - Seaming of Panels

- Critical in landfills – leakage minimization
- Type of Seams
  - Extrusion weld – PE (grind parent!)
  - Double hot-wedge weld - PE
  - Solvent bonded – PVC
- Seam testing
  - Destructive (peel and shear)
    - Shear: 90% (PE) and 80% (PVC) of base material
    - Peel: 60% of base at <10% separation
  - Non-destructive (soap box and pressure)
    - No bubbles under 5 psi vacuum
    - 30 psi for 5 minutes w/o loss of 2 psi
- In situ techniques (ultrasonic, electric wire)
  - Gaining popularity and acceptance
  - Destroy good seam and replace with inferior one?

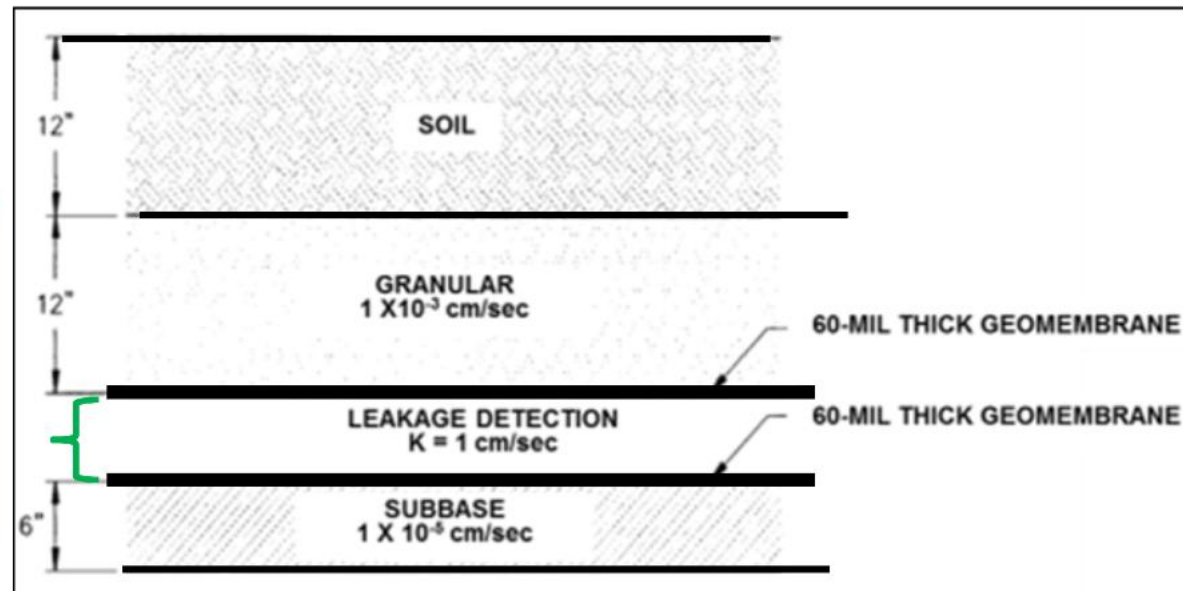
# Landfill Lining Systems



**Composite Liner**

**Composite Liner:** Two distinct and different low permeability units placed in intimate contact to form a single, low permeability liner system

**Double Liner:** Two distinct low permeability units separated by a high permeability unit to form a low permeability liner system exhibiting the ability to measure leakage



**Double Liner**

(after Fluet, 2000)

# Geomembrane and Liner Systems - Landfills



**Incremental Construction**

(after GSE, 2014)



**Very Large Exposed Area**

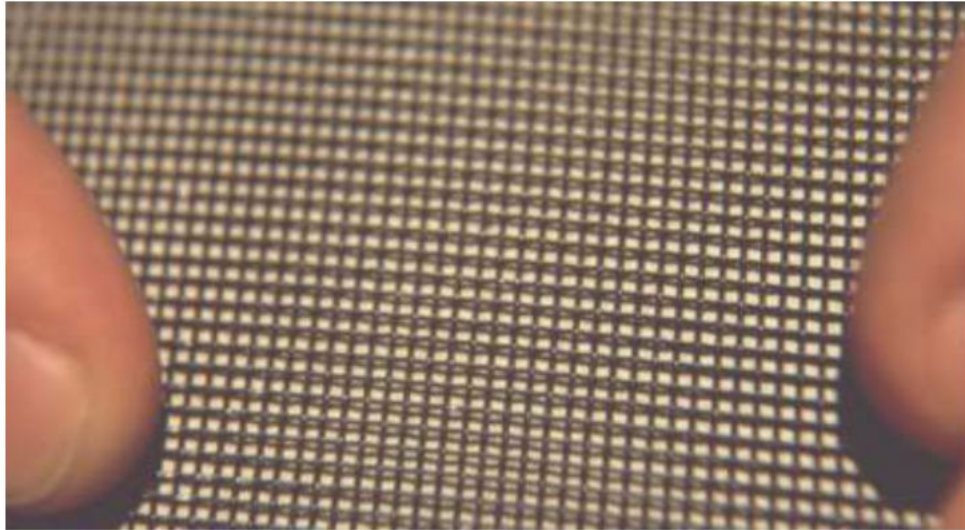




# Geotextile



# Types of Geotextile



(Woven monofilament - after J.P. Giroud)



High strength woven  
<http://www.geotextile-fabric.com>



Non-woven - <http://www.archiexpo.com/prod/tencate>



(Non-woven- after J.P. Giroud)



# Geotextile

- Function:
  - Reinforcement – woven
  - Filtration – non-woven (woven occasionally)
  - Separation - non-woven and woven
  - Drainage – non-woven
  - Cushion – non-woven
- Parent Materials – PET and PP (some PE)
- Fibers – monofilament, staple, slit film
- Construction
  - Woven – normal “weaving” process
  - Non-Woven – spun and heat bonded or needle-punched



# Geotextile

- Properties of Importance
  - Physical
  - Mechanical
  - Hydraulic
  - Endurance
  - Degradation
  - Seams
- Polymers used in geotextiles
  - PP 92%
  - PET 5%
  - PE 2%
  - Nylon 1%
- **Remember: Design by Function**
  - One size does NOT fit all

## Geotextile - Physical Properties

- Often referenced as “Index” properties
  - Thickness – ASTM D5199
  - Mass per Unit Area – ASTM D5261
    - oz/yd<sup>2</sup> or gm/m<sup>2</sup>
- Generally used as broad quality control or screening parameters for non-wovens

## Geotextile - Mechanical Properties

- Tensile strength and elongation
  - Grab – ASTM D4632 (4 inch w/ 1 inch grab)
  - Narrow strip – ASTM D751 (1 inch x 4 inch)
  - Wide width – ASTM D 4596 (8 inch x 4 inch)
- Multiaxial Burst – ASTM D3786 (5 inch  $\phi$ )
- Trapezoidal Tear – ASTM D4533 (0.6 inch cut)
- Puncture – ASTM D4833
- Creep – ASTM D5262



# Geotextile - Hydraulic Properties

- Apparent Opening Size (AOS or  $O_{95}$ )
  - Non-woven
  - ASTM D4751 (like a grain size distribution test)
  - Glass bead size where 5% pass through fabric
- Percent open area (POA)
  - Woven
- Permittivity – ASTM D4491 (cross-plane)
  - Like permeability test (2 inch head)
  - $\Psi = k_n / t$  ( $s^{-1}$ )
  - Related to flow rate (volume/time per area)
- Transmissivity – ASTM D4716 (in-plane)
  - $\phi = k_p * t$  ( $m^2/s$ )

- Endurance
  - Installation damage
  - Clogging
  - Abrasion
- Degradation
  - Ultraviolet – ASTM D4355
    - Sacrificial layer
    - Wrap in plastic
    - Minimize exposure
  - Others (temperature, oxidation, chemical, biological, polymer aging)

## Geotextile - Seaming Techniques

- Friction at overlap
- Heat Leister (generally, not recommended)
- Sewn - ASTM D4884
  - Prayer seam
  - J-seam
  - Butterfly seam

(Note: similar thread @ 2 to 4 per inch for 70% of parent strength is typical)





# Geonet



# Geocomposite - Drainage and Erosion



(after J.P. Giroud)



(after Intermas, 2014)



<http://www.archiexpo.com/prod/tencate>

**Drainage**

**Erosion Protection**



## Geonet and Drainage Geocomposite

- Function: Drainage of liquid and gas
- Manufacturing controls
  - Bi-planar
  - Tri-planar
  - Most commonly comprised of PE
- Properties of importance
  - Physical
- Hydraulic Thickness – ASTM D1777 and ASTM D5199
  - Usually tested under pressure
  - Intuitive correlation to drainage



## Geonet and Drainage Geocomposite

- Hydraulic Transmissivity – ASTM D4716
  - Similar to geotextile concept
    - Flow rate per unit width per unit gradient
  - Testing conditions control performance
    - Boundary conditions
    - Normal stress
    - Gradient
    - Orientation of strands
- For drainage geocomposites
  - Bonded geotextile is important
  - Bonded thermally (typical)

# Lining Systems for Leach Pads - Mines Geosynthetic Drainage Layer



(after GSE, 2014)

# Erosion Protection and Vegetation Non-landfill Applications



(after Tensar, 2014)



(after Tensar, 2014)



(after Interimas, 2014)



# Geocomposite – Geocell Non-landfill Applications



Empty Geocell

Steep Slope

Geocell Protection

Vegetation



(after Strata, 2014)

# Erosion and Vegetation Geocomposite

## Erosion Protection and Vegetation



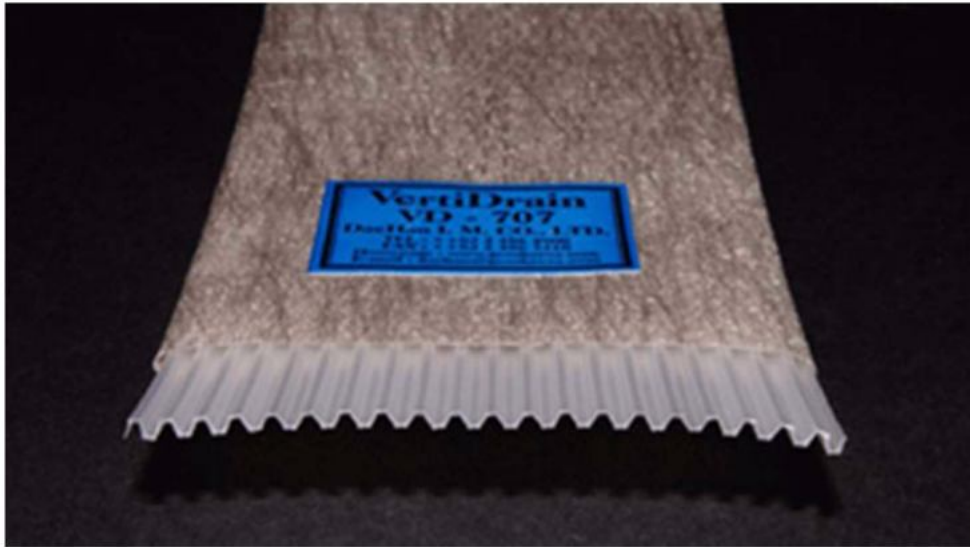
Are these  
“Geosynthetics”

**Coir Mat and Logs/Wattles**

(after Terrafix, 2014)



# Drainage Geocomposite Prefabricated Vertical Drains (Wick Drains)



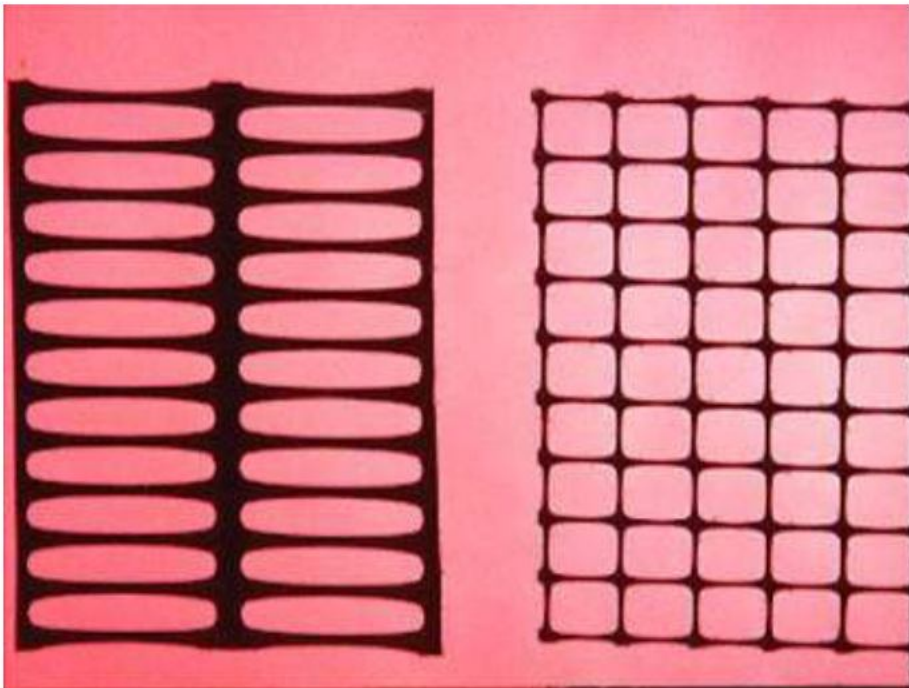
erkegroup.com



(after deMelo, 2012)



# Geogrid



**Uniaxial**  
**(Polyethylene or Polypropylene)**

**Biaxial**

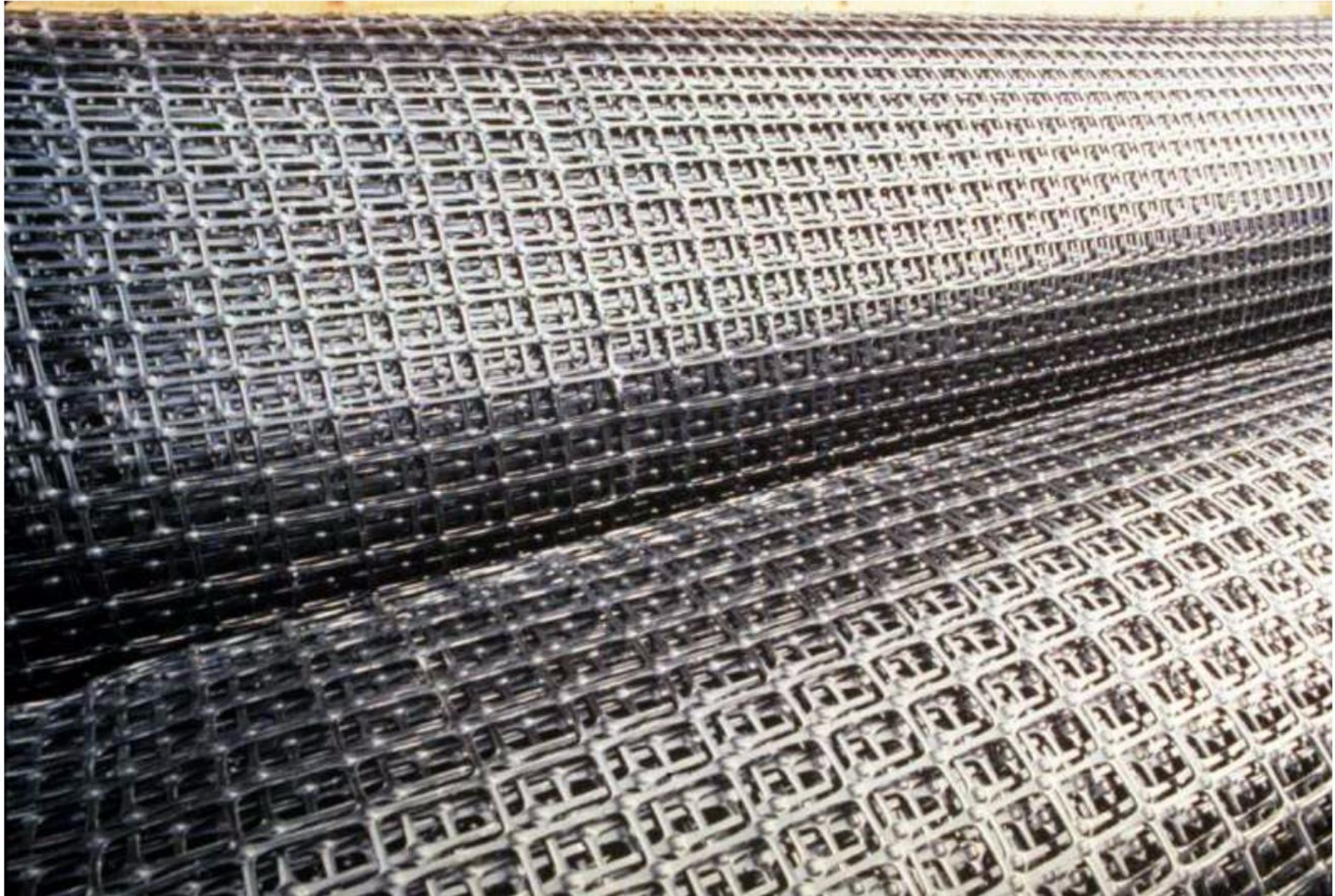


**Woven Coated Uniaxial or Biaxial**  
**(Polyester)**

(after J.P. Giroud)



# Geogrid



(after J.P. Giroud)

# Geogrid

- Function: Reinforcement
- Manufacturing controls
  - Uniaxial or biaxial (“drawn” to form apertures)
  - Woven or “knitted” with apertures
- Polymers
  - PE, PET, PP
  - Fiberglass
- Properties of importance
  - Physical
  - Mechanical
  - Endurance
  - Degradation



# Geogrid - Physical Properties

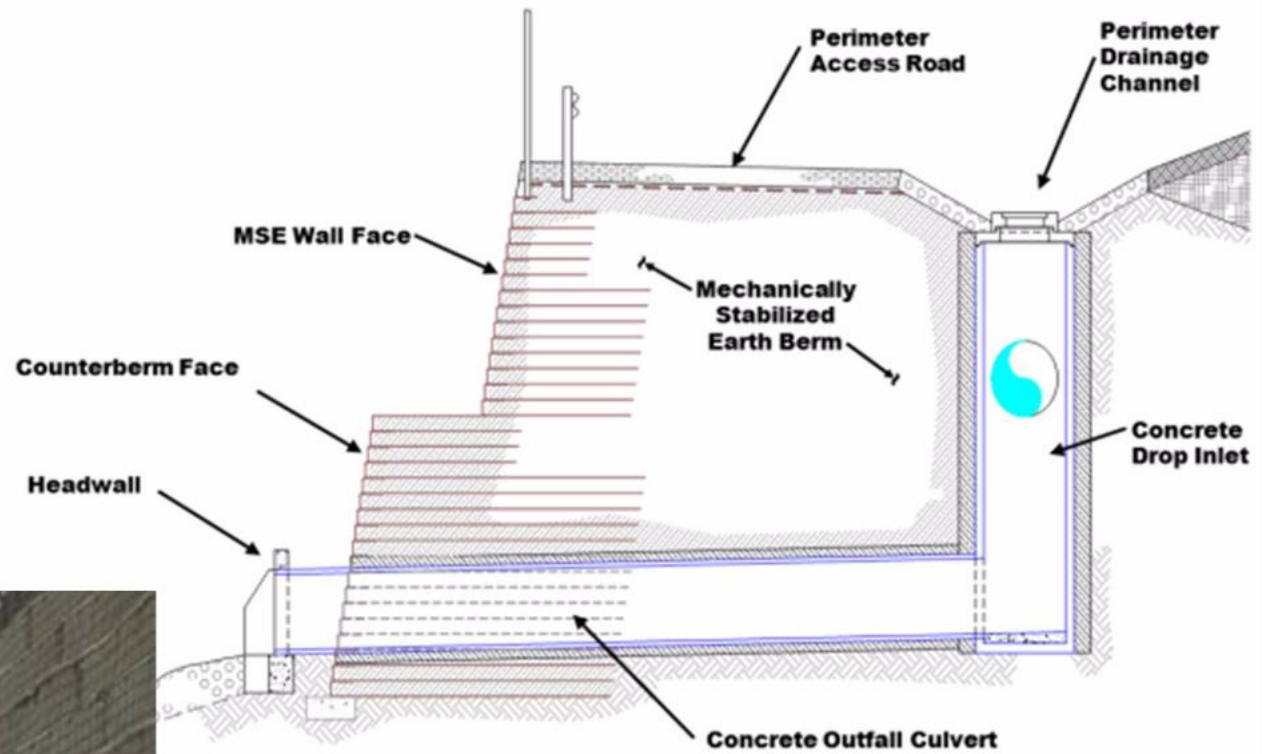
- Mass per unit area – ASTM D5261
  - oz/yd<sup>2</sup> or g/m<sup>2</sup>
- Aperture size

(Note: These properties are largely for quality control in manufacturing)

# Geogrid - Mechanical Properties

- Tensile strength (direction dependent)
  - ASTM D6637 – geogrid
  - ASTM D4595 – geotextile
  - ASTM D5321 – interface
- Creep – ASTM D5262
- Endurance and Durability
  - Similar to geotextiles and geomembranes
  - Construction survivability
    - Site-specific soils
    - Project compaction equipment
    - Project placement and compaction procedures

# Geogrid Reinforced Berm/Wall



(after deMelo, 2012)



# Geogrid Old Use and New Uses of Geogrids



Old  
Subgrade Reinforcement  
Reinforcement Over Old Landfills



New  
Long Wall Mining



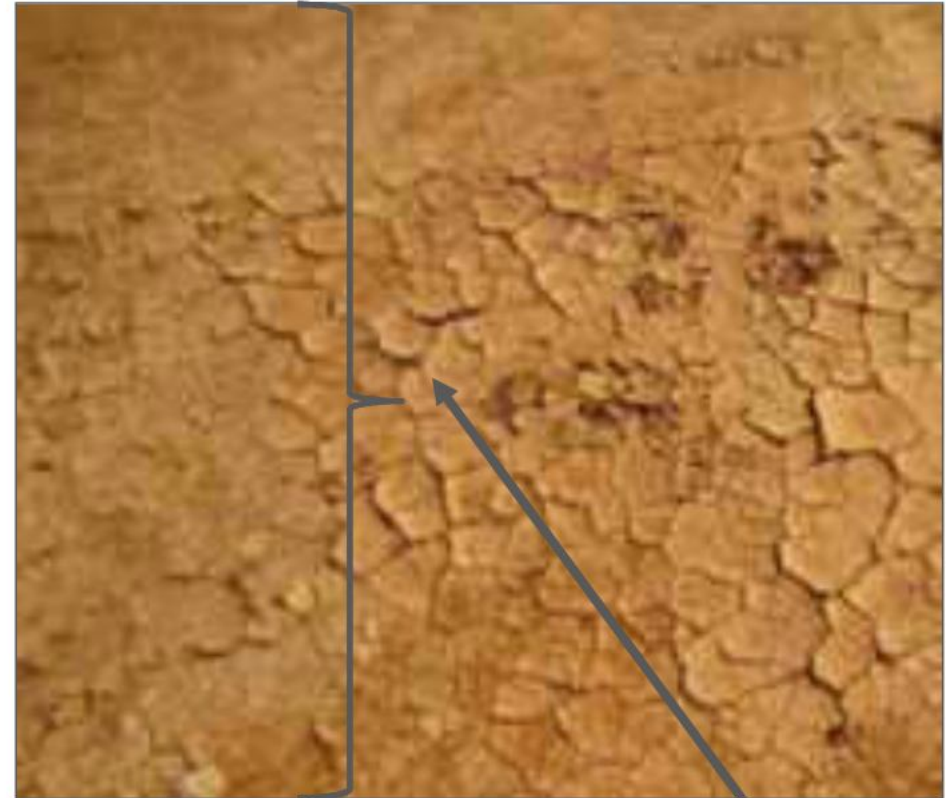
(after Tensar, 2014)

# Geosynthetic Clay Liner (GCL)





# Geosynthetic Clay Liner - Equivalency



Plus, is 0.375 inches of this really "equivalent" to 24 inches of this?

(after CETCO, 2009)



# Geosynthetic Clay Liner (GCL)

- Function: Low permeability
- Materials:
  - Geotextile and bentonite clay – majority
  - Bentonite and geomembrane – one manufacturer
- Properties
  - Physical
  - Hydraulic

## Geosynthetic Clay Liner (GCL) Physical Properties

- Bentonite mass per area – ASTM D5993
  - $\text{g/m}^2$  or  $\text{lb/ft}^2$
- Swell index – ASTM D5890
  - ml/2g sample in 100 ml water
- Fluid loss – ASTM D5891
  - ml/30 sec under 100 psi for fixed volume slurry

(Note: These properties primarily used for manufacturers quality control)

# Geosynthetic Clay Liner (GCL) Hydraulic and Strength Properties

- ASTM D5084 – Soil hydraulic conductivity
- ASTM D5887 – Specific to GCLs
- Test Conditions
  - Normal stress
  - Specific liquid (chemical) constituents after hydration
  - Wet-dry cycles (not freeze-thaw)
  - Cation exchange
- ASTM D6243 – Interface shear strength
- Test Conditions
  - Normal stress
  - Moisture content and hydration
  - Specific liquids (chemicals) after hydration




## Part IV: Lessons from Landfills (apologies to David Letterman)


1. Geosynthetic containment systems work when designed
2. CQA is mandatory for success
3. Interfaces are real and have to be included in design
4. Composite action brings synergies of soil and geosynthetic
5. Intimate contact is essential for performance
6. Thermal properties must be considered in operations
7. GCLs are complex materials
8. Filter systems must be designed
9. Exposure and protection are essential considerations
10. Soil reinforcement and MSE berms present challenges
11. Water continues to be our enemy
12. Manufacturers are innovative and supportive folks

# 1. Containment Systems Work


- Properly designed and constructed landfill liner and cover systems perform well




EPA  
U.S. Environmental Protection Agency



GEOSYNTEC  
CONSULTANTS




ILLINOIS  
UNIVERSITY

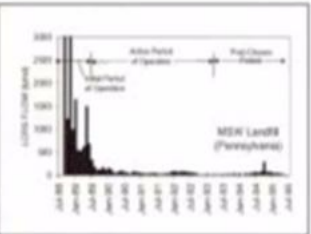


Drexel  
UNIVERSITY

EPA/600/R-02/099  
December 2002

## Assessment and Recommendations for Improving the Performance of Waste Containment Systems





by

Rudolph Braganza, Ph.D., P.E. Geosyntec Consultants Atlanta, GA 30342	David E. Daniel, Ph.D., P.E. University of Illinois Urbana, IL 61801	Robert M. Koerner, Ph.D., P.E. Drexel University Philadelphia, PA 19104
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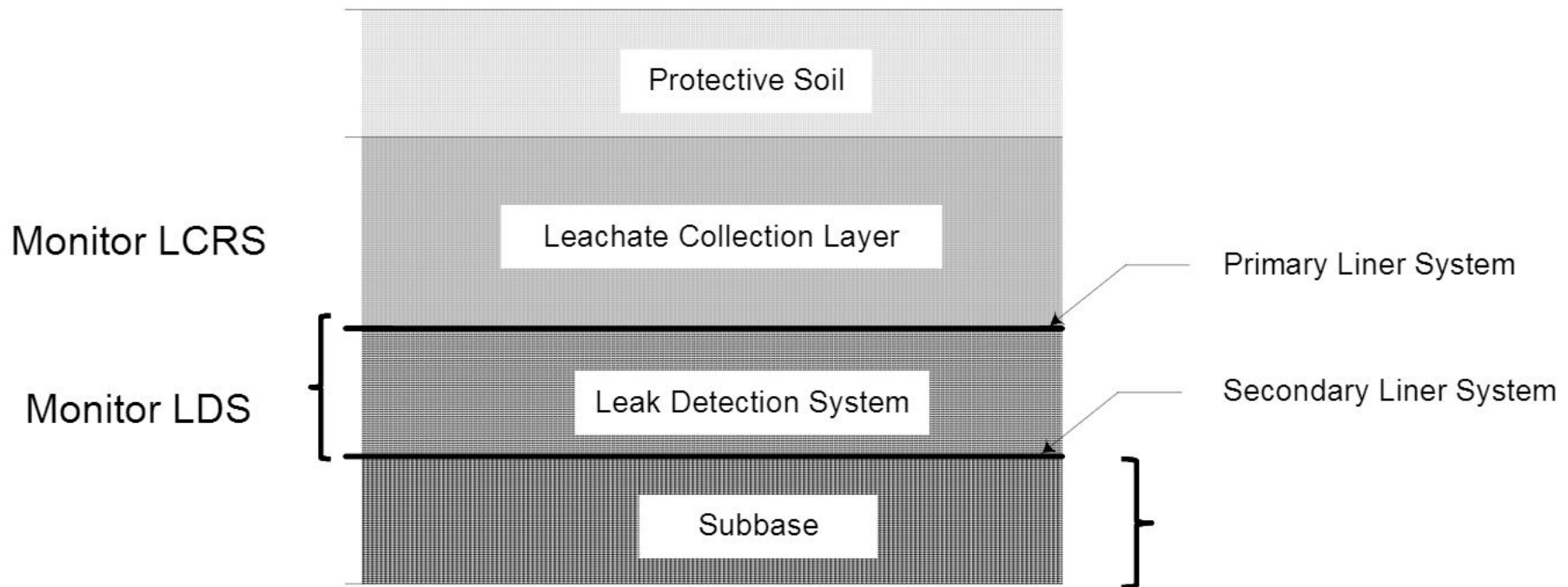
performed under  
EPA Cooperative Agreement Number  
CR-821448-01-0

Project Officer  
Mr. David A. Carson  
United States Environmental Protection Agency  
Office of Research and Development  
National Risk Management Research Laboratory  
Cincinnati, OH 45268

<http://www.epa.gov/ORD/NRMRL/Pubs/600R02099/600R02099.pdf>

# Methodology for Assessing Landfill Liner Performance

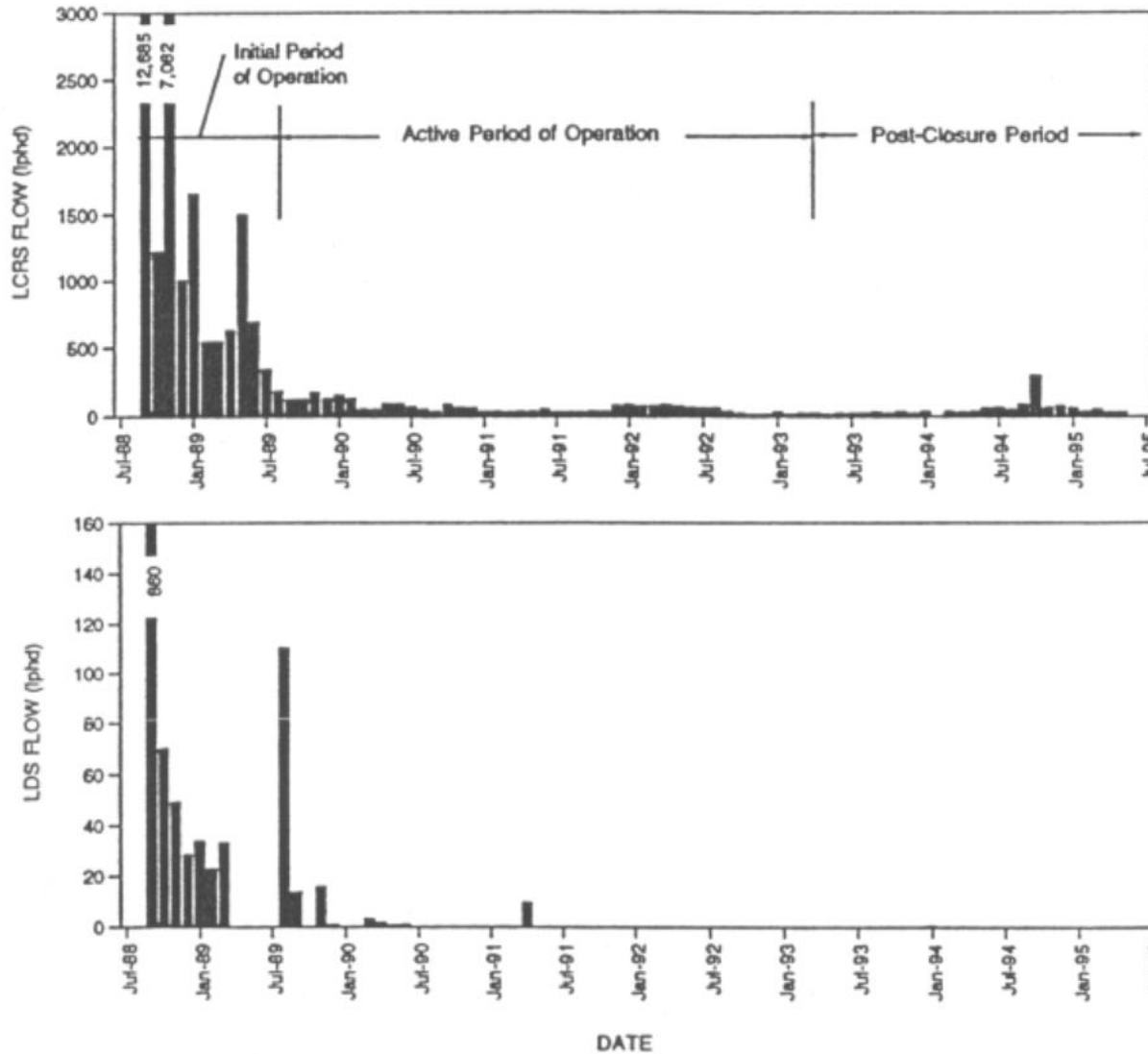
## Double Liner with Lower Composite Liner



(after Fluet, 2000)



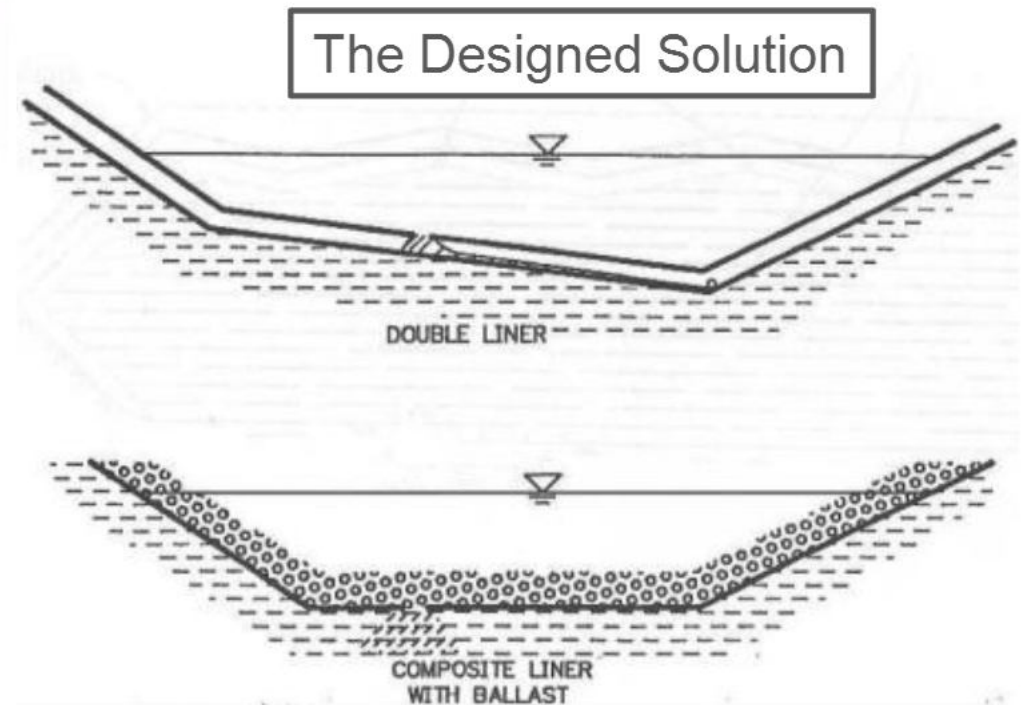
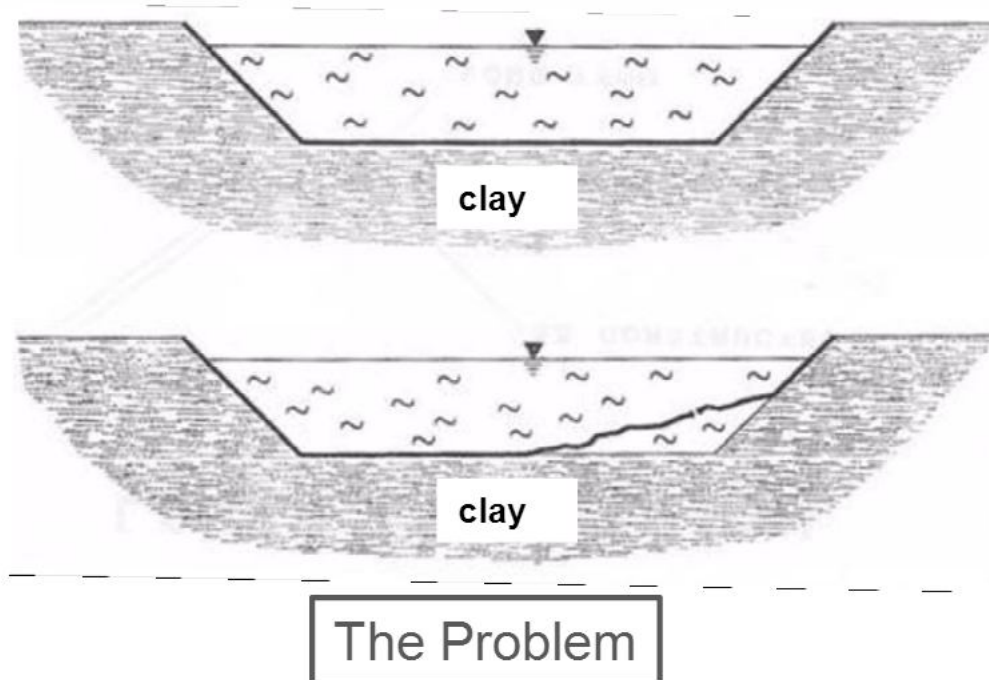
# Data Summary – Operational Life



- Leachate and leakage generation are influenced by waste thickness
- CQA was incorporated and important
- Cover systems are problematic
- Filter geotextiles were sometimes compromised

(after Bonaparte, et al, 2002)

# Example: Geosynthetics in Ponds



(after Giroud and Fluet, 2000)

## 2. CQA Should be Required on All Projects

- **Manufacturer**
  - Quality Control (MQC) – product in compliance with certification and project documents
  - Quality Assurance (MQA) – product meets project requirements
- **Construction**
  - Quality Control (CQC) – installer/contractor testing to assure material and workmanship are appropriate
  - Quality Assurance (CQA) – owners representative to assure constructed product in compliance with specifications



# Geosynthetic Quality Program

- MQC/MQA
  - Manufacturer keeps records
  - Check on manufacturing procedures and controls
  - Quality control concepts
    - Minimum roll properties and average roll/lot properties
    - Minimum average roll values (MARVs)
  - Testing frequency
  - If you (designer) want specific properties, require them, as most manufacturers maintain these records
- CQC/CQA
  - Provide independent check of materials and installation
  - Testing frequency and methods
  - Recordkeeping
  - History has demonstrated the value of CQA testing, even among tried-and-true contractors

# CQA of Geomembrane and Liner Systems



**CQA - Leak Location**

(after GSE, 2014)



**Solution Ponds**



# CQA Should be Required on All Projects



**We know better!!**



# Examples of CQA Lessons

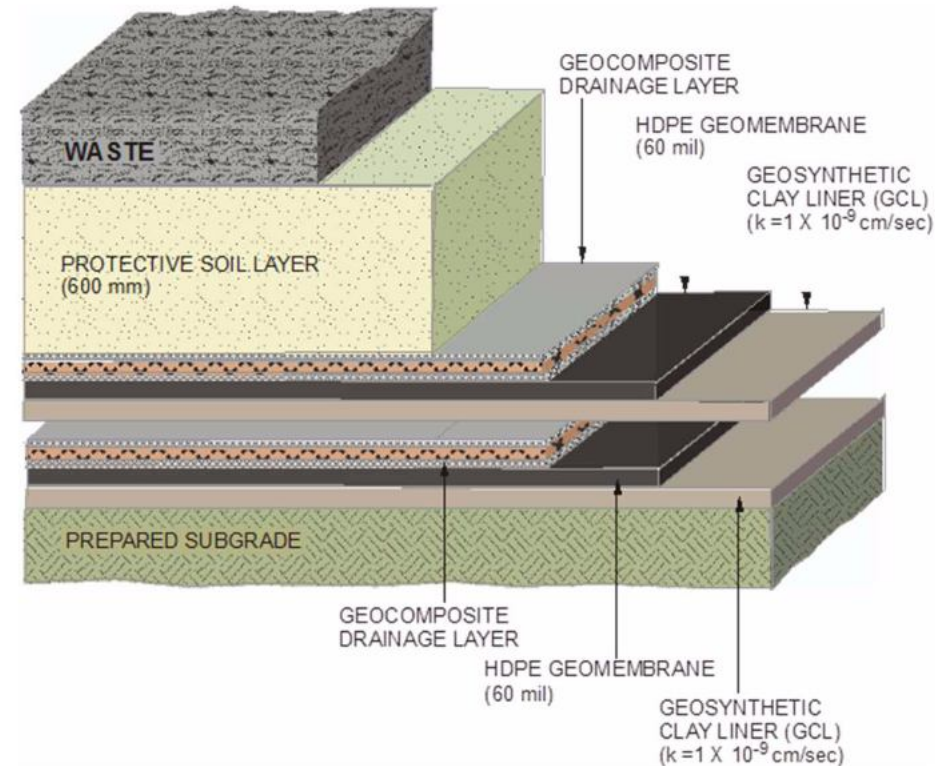


metrospirit.com

**Despite learning lessons, CQA still needed**

### 3. Interfaces are Real... Must be Considered in Design

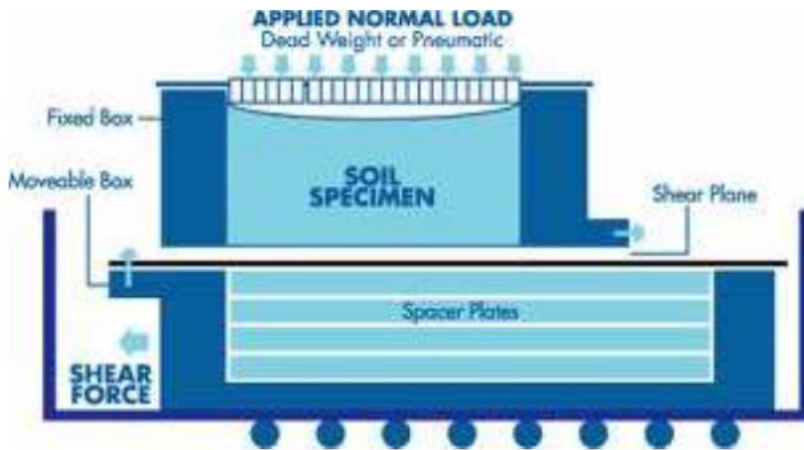
- Interface direct shear strength (most common test concept)
  - ASTM D5321 – Geotextile and Geogrid
  - ASTM D6243 – Geosynthetic Clay Liners
- Test “sandwich” used in design
  - Site-specific soils
    - Geosynthetic
    - Soil
  - Normal stress
  - Large scale ( $>\approx 12$  inches)
  - Peak versus large deformation
- Test conditions
  - Aperture
  - Thickness
  - Moisture and hydration (if soil)
  - Rate of shear



**Landfill Lining Systems ARE Study of Interfaces**

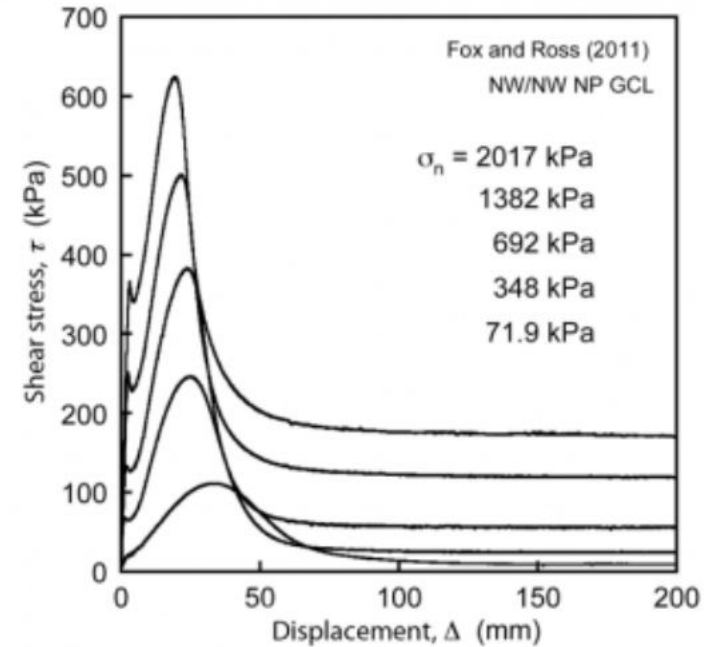


# Soil and Geosynthetic Interface Testing



**Interface Shear Box**

[www.durhamgeo.com](http://www.durhamgeo.com)

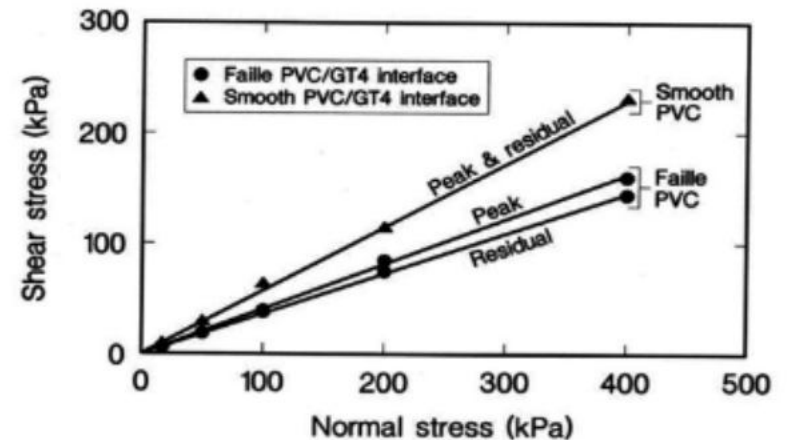


(after Fox and Athanassopoulos, 2012)

## Important to Consider:

- Material configurations
- Normal stress
- Hydration
- Small or large deformation

Unfortunately, there remains machine and size effects to address



(after Hillman and Stark, 2000)



# 4. Composite Action Recognizes Synergy

