Geomembrane Wrinkles in Containment Applications

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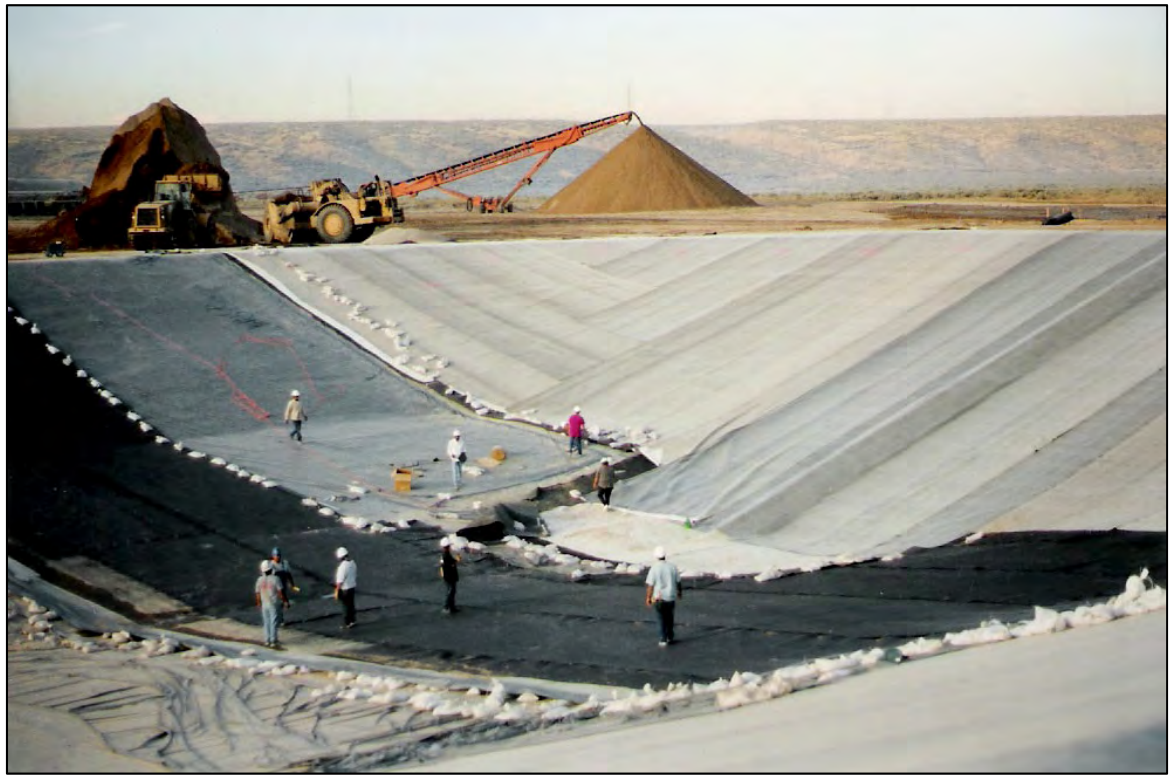
Importance of Wrinkles

- Subtitle D Liner System Requirements
- Composite Liner System
- Field Intimate Contact
- Wrinkle Behavior & Leakage
- State Regulations
- Thermal Expansion
- Summary



Subtitle D Liner System

- CHAPTER 4 SUBPART D DESIGN CRITERIA
- 4.3.3 Technical Considerations:
- **Standard Composite Liner System:**
- "The composite liner system is an effective hydraulic barrier because it combines the complementary properties of two different materials into one system: 1) compacted soil with a low hydraulic conductivity; and 2) a FML (FMLs are also referred to as geomembranes). Geomembranes may contain defects including tears, improperly bonded seams, and pinholes. In the absence of an underlying low-permeability soil liner, flow through a defect in a geomembrane is essentially unrestrained. The presence of a low-permeability soil liner beneath a defect in the geomembrane reduces leakage by limiting the flow rate through the defect."

Subtitle D Liner System

- CHAPTER 4 SUBPART D DESIGN CRITERIA
- 4.3.3 Technical Considerations:
- **Geomembranes:**
- "The polymeric materials used most frequently as geomembranes are HDPE, PVC, CSPE, and CPE. The thicknesses of geomembranes range from 20 to 120 mil (1 mil = 0.001 inch) (U.S. EPA, 1983 and U.S. EPA, 1988e). The recommended minimum thickness for all geomembranes is 30 mil, with the exception of HDPE, which must be at least 60 mil to allow for proper seam welding. Some geomembranes can be manufactured by a calendering process with fabric reinforcement, called scrim, to provide additional tensile strength and **dimensional stability**." (emphasis added)
- Subtitle D – USEPA regs in 1988 and effective in 1991!!!

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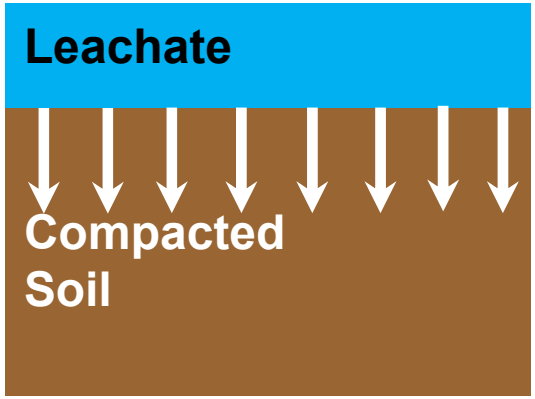
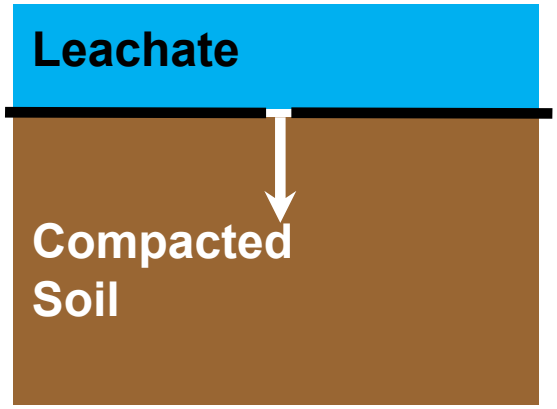
Enhanced Composite Liner System

Subtitle D Liner System



- ***Darcy's Law:***
- ***Q = kiA***
- Q = **Seepage/Leakage Rate (m^3/sec)**
  k = hydraulic conductivity
  i = hydraulic gradient
  A = area of seepage

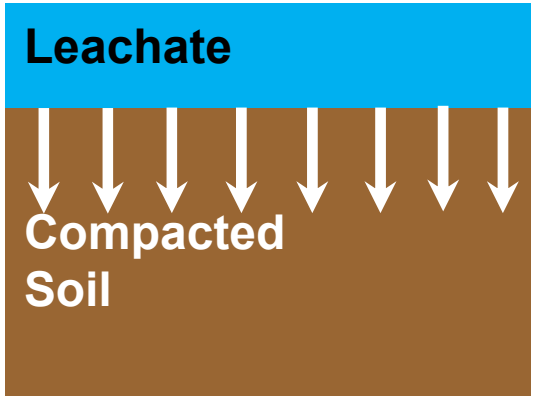


- ***Darcy's Law:***
- ***Q = kiA***
  A = area of defect if
  Intimate Contact

Construction Defects

- Giroud (2017)
- 3rd Party CQA – 5 to 6 holes/hectare
- Random CQA – 20 to 25 holes/hectare
- Leak Location – possible zero defects

Subtitle D Liner System



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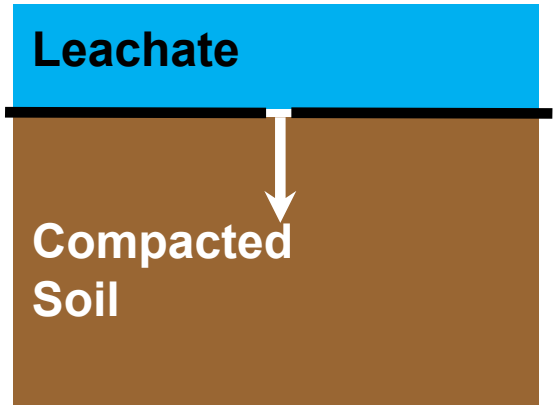

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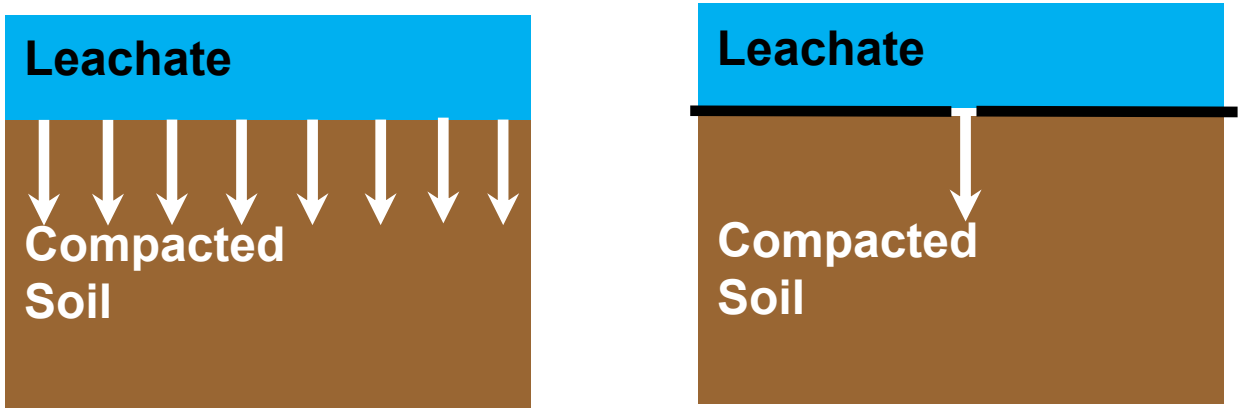
Leakage Rate for Subtitle D Liner System



- **Giroud (2017) – 5th de Melo Lecture - Brazil**

$$Q = 0.21 * \left[1 + 0.1\left(\frac{h_{w-GM}}{t_{soil}}\right)^{0.95}\right] * a^{0.1} * (h_{w-GM})^{0.9} * k^{0.74}$$

Q = Leakage rate through one hole (m^3/sec)
a = hole area (m^2)
t_{soil} = thickness of compacted soil (m)
k_{soil} = hydraulic conductivity of underlying compacted soil (m/sec)
$h_{w\text{-}GM}$ = hydraulic head on geomembrane (m); regulation = 0.3 m

Leakage Rate for Subtitle D Liner Systen

Hole Area* (mm^2/m^2)	Hole diameter (mm/m)	Holes per ha (ha^{-1})	*Int Contact Leakage Q* (m^3/sec/ha)	*Int Contact Leakage Q* (lphd)
$1.0/1x10^{-6}$	1.0/0.001	4	$1.56x10^{-8}$	1.35
$2.0/2x10^{-6}$	2.0/0.002	4	$1.68x10^{-8}$	1.45
$3.0/3x10^{-6}$	3.0/0.003	4	$1.75x10^{-8}$	1.51
$4.0/4x10^{-6}$	2.0/0.002	4	$1.80x10^{-8}$	1.55

Four holes/hectare ~1.5 lphd

Giroud (2017) – 5th de Melo Lecture – Brazil
- 4 holes per hectare
- hole area of 4 mm^2

Other Input Parameters
- h_{GM} = 0.3 m
- k_{soil} = $1x10^{-9}$ m/sec
- t_{soil} = 0.6 m

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Intimate Contact

Non-Intimate Contact

Wrinkles in HDPE geomembrane

- Textured wrinkles remain
- Uncovered slopes – wrinkles at toe

Construction Issues

Photo from Koerner and Koerner (2013)
GSI White Paper #27, 21 p.

- Two different temperatures
- Weld rolls installed on same day

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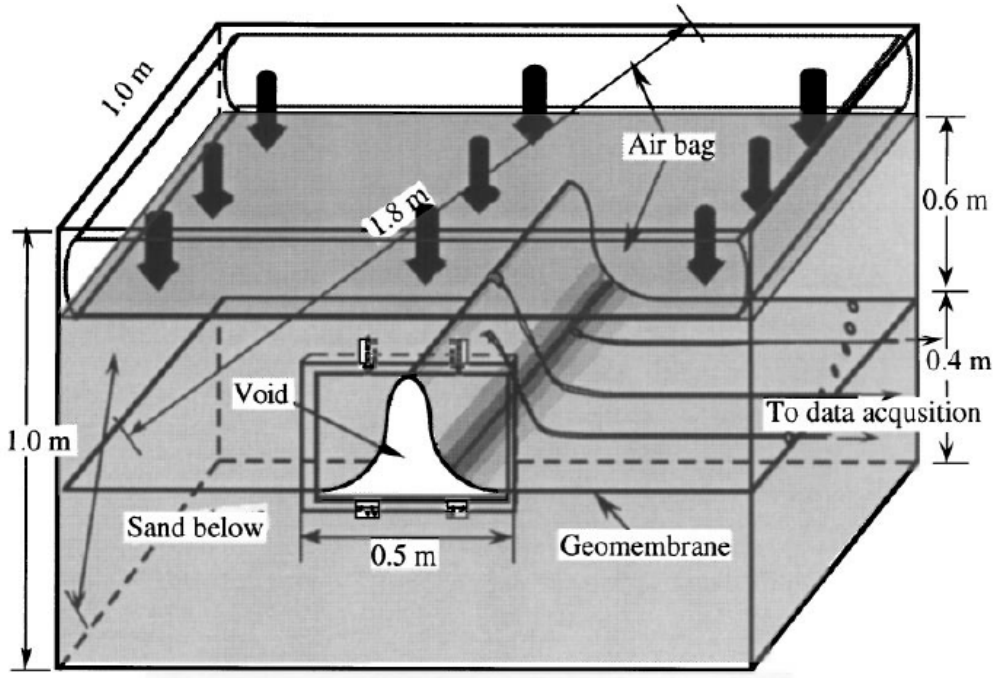
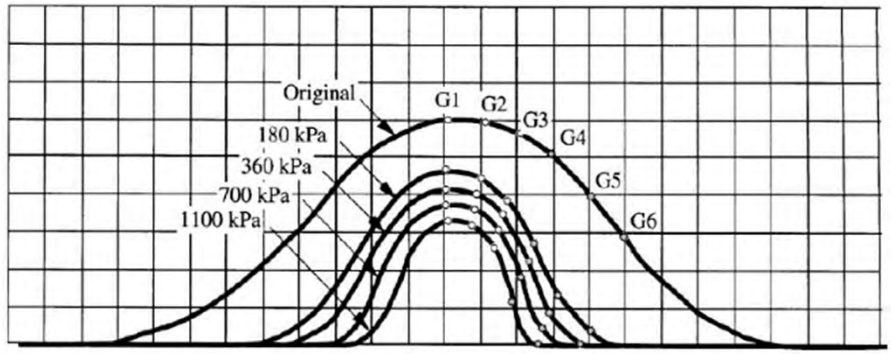
Wrinkle Behavior





Sand below 40 mil HDPE

- Wrinkles as small as 0.5” do not flatten
- Wrinkles fold over and create creases

Soong, T.-Y., and Koerner, R. M. 1998. “Laboratory study of high density polyethylene waves.” *Proc., 6th Int. Conf. on Industrial Fabrics Association International, Geosynthetics*, St. Paul, Minn., 301–306.

Wrinkle Behavior

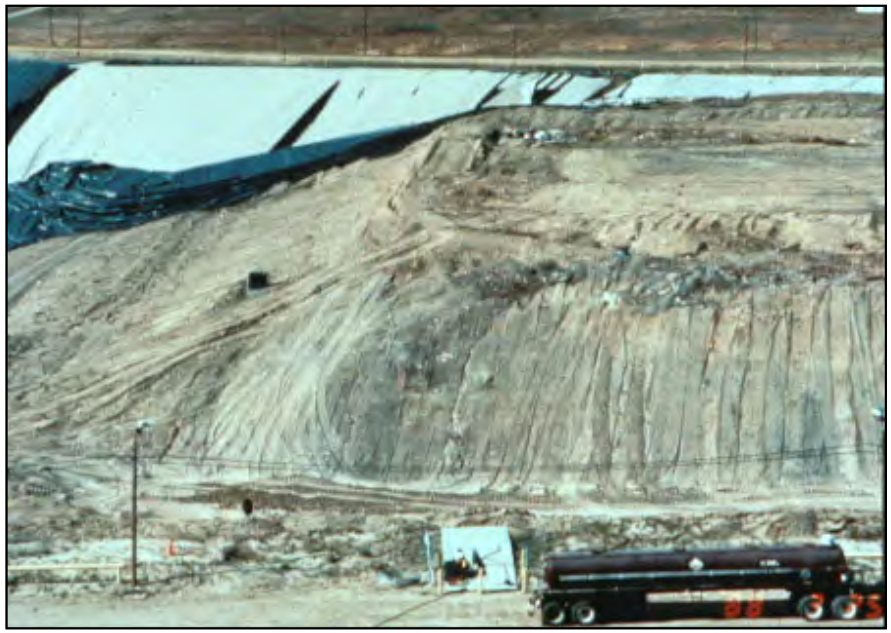
Wrinkle being entombed- Dam

Exhumed wrinkles

Koerner, R. M. and Koerner, G.R. 2013. “The Intimate Contact Issue of Field Placed Geomembranes with Respect to Wave (or Wrinkle) Management.” *GSI White Paper #27,* 21 p.

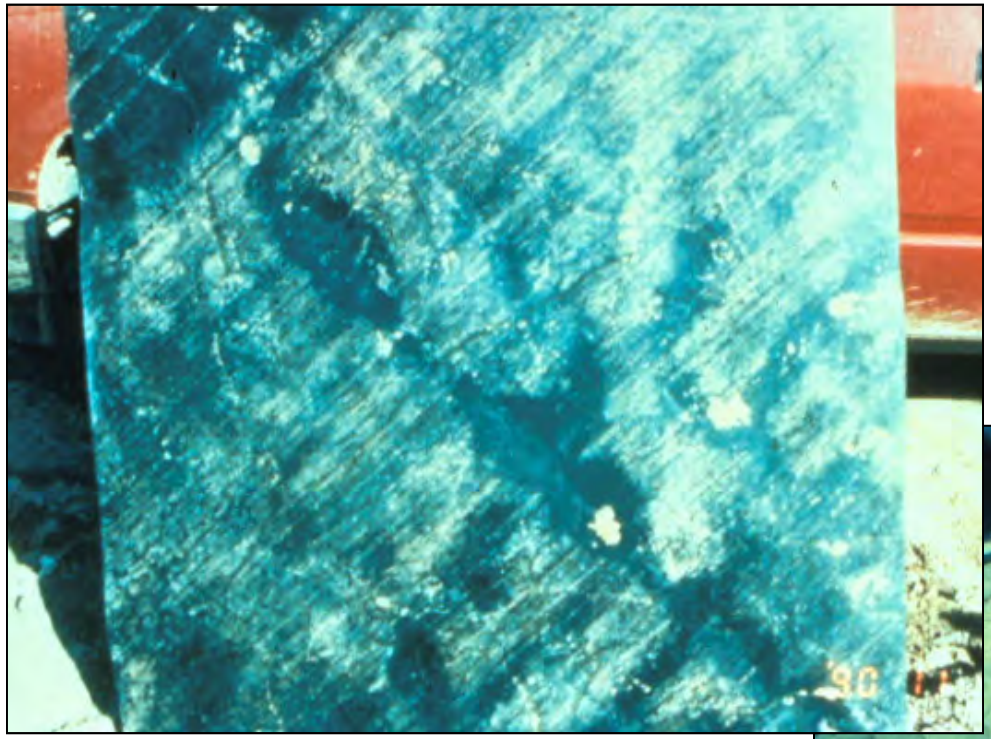
Wrinkle Behavior

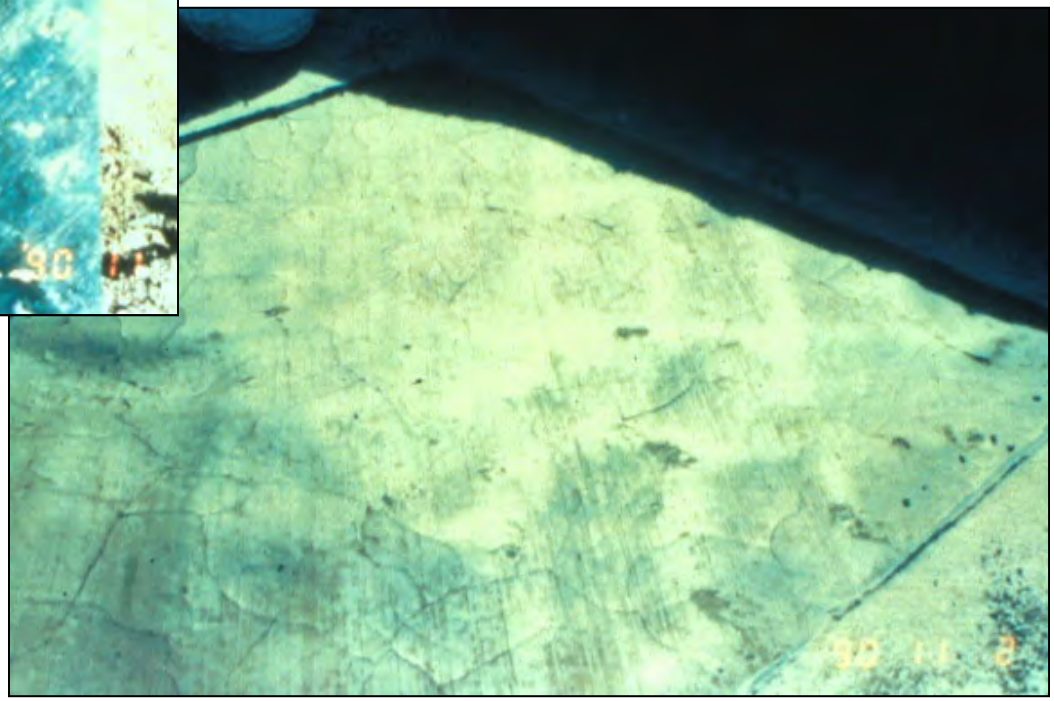
Kettlemen Hills Hazardous Waste Repository



Wrinkle Behavior

Kettlemen Hills Hazardous Waste Repository





HDPE Wrinkle Summary

- R.K. Rowe (2017):
- Typical wrinkle width: 0.2 to 0.3 m (0.7 to 1.0 ft)
- Typical wrinkle height: 0.06 to 0.2 m (0.2 to 0.7 ft)
- Wrinkle area: 2 to 30% of entire area
- Typical wrinkle length if 5% of area has wrinkles: 200 m (655 ft) - interconnected

Interconnected Wrinkles

- **R.K. Rowe (2017):**

Interconnected Wrinkles

- **R.K. Rowe (2017):**

- **Interconnected**

Importance of Wrinkles

- R.K. Rowe (2017):
- If there are 5 holes/ha and:
  - 20% of entire area is occupied by wrinkles, there is 67% probability that 5% of entire area is occupied by wrinkles and there is 23% probability that at least one hole is coincident with a wrinkle.
- Wrinkles dominate leakage

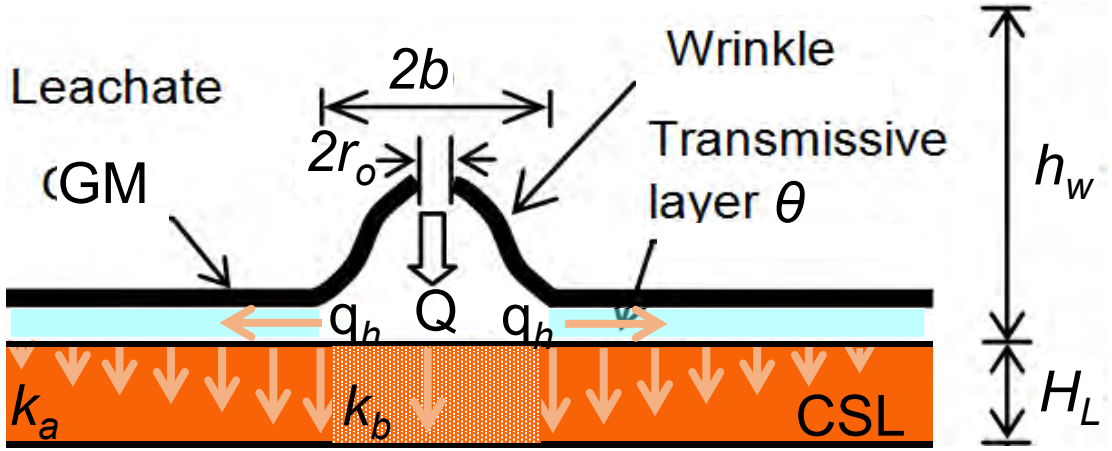
State Requirements for Wrinkles

- 36 States – Intimate/Direct Contact
- 4 States – Minimize
- 7 States - Vague

Data summarized from Koerner, R. M. and Koerner, G.R. 2013. “The Intimate Contact Issue of Field Placed Geomembranes with Respect to Wave (or Wrinkle) Management.” *GSI White Paper #27,* 21 p.

Leakage Rate for Subtitle D Liner w/Wrinkles

Slide from R.K. Rowe



$$Q = (2b\ L\ k_b\ h_d/H_L) + 2q_h$$

$$q_h = L\ \theta\ i_h$$

$$Q = L\ [2b^{*}k_b + 2(k_a\ H_L\ \theta)^{0.5}]\ h_d / H_L$$

Rowe (1998):

Q: flow through GM

$2b$: width of wrinkle

L: wrinkle length

k_b: hyd. conductivity of CSL/GCL below wrinkle

k_a: hyd. conductivity in contact with GM

h_d: Head loss ($h_d=h_w+H_L$)

h_w: Water/leachate level

H_L: Soil liner thickness

θ: transmissivity b/t GM and compacted soil liner (CSL)/GCL

Intimate Contact Categories

- Giroud (1997)
- **Good Contact is:**
  - GM w/as few wrinkles as possible on smooth compacted soil
  - Rowe (1998) $\theta = 1.6 \times 10^{-8}$ m^2/s
- **Poor Contact is:**
  - GM w/a number of wrinkles on rough compacted soil
  - Rowe (1998) $\theta = 1.0 \times 10^{-7}$ m^2/s

Leakage Rate for Subtitle D Liner System

Wrinkle Length (m/ha)	Wrinkle Width (m)	Holes per Wrinkle	*Leakage* Q (m^3/sec/ha)	*Leakage* Q (lphd)
60	0.2	1	4.7×10^{-8}	4.1
230	0.4	1	2.5×10^{-7}	22.0
500	0.6	1	7.1×10^{-7}	60.9
1000	0.8	1	1.7×10^{-6}	149.0

Intimate contact & four holes/hectare ~1.5 lphd
One wrinkle & one hole ~ 100*no wrinkle

Rowe (2012):

GCL k_b = 5×10^{-11}m/s, GCL k_a = 2×10^{-10}m/s, H_L = 0.01m, θ = 3×10^{-11} m^2/s;

CSL k_b = 1×10^{-9} m/s, CSL k_a = 2×10^{-10}m/s, H_L = 0.6m, θ = 1.0×10^{-7} m^2/s;

Defects and Wrinkles on Leakage Rates

Geomembrane Defect and Wrinkle Leakage Calculator - August, 2020

By: Timothy D. Stark, Ph.D., P.E., D.GE, F.ASCE
Fabricated Geomembrane Institute
University of Illinios at Urbana-Champaign

STEP ONE (General Calculations & Summary)

For a pond with the following dimensions: Top Width	400	feet
Pond Top Length	600	feet
Pond Depth,	25	feet
Total/overall volume of the pond is:	31,852,428.2	gallons
with a compacted soil hydraulic conductivity of *	1.00E-07	cm/sec
and a geomembrane hydraulic conductivity of **	1.00E-12	cm/sec
Leakage through the compacted soil liner is:	2,286.4	gallons/day
Leakage through a geomembrane is ONLY:	1.4	gallons/day
Cost of water is:	US$25,000.00	/acre-foot
Lost Money due to Compacted Soil Leakage:	64,675.4	$/year
Lost Money due to Geomembrane Leakage:	0.0	$/year

NOTES:

*Compacted soil hydraulic conductivty is 1x10-7 cm/sec based on Subtitles D and C landfill requirements

**Geomembrane hydraulic conductivty ranges from 1x10-10 to 1x10-14 cm/sec for typical products based on vapor transmission testing

Defects and Wrinkles on Leakage Rates

STEP TWO (Detailed Information)					
Leakage Rate Calculator from a Water Pond					
Input Parameters					
Pond Geometry	Depth	=	25	ft.	
	Pond Freeboard	=	2	ft.	Water Below Pond Surface
	Pond Top Width	=	400	ft.	
	Pond Top Length	=	600	ft.	
	Side Slope Geometry				
	H		V		
	3	:	1		
Material Properties	Compacted Soil	=	5	ft.	Thickness
	Hydraulic Conductivity, k	=	1.00E-07	cm/sec	
	Geomembrane	=	1	in.	Thickness
	Hydraulic Conductivity, k	=	1.00E-12	cm/sec	
	Geomembrane Defects				
	# of holes per hectare	=	4	with "high Inspection"	
	Number of holes	=	9	For the total leakage Area	
	Area of a hole	=	4.00E-06	m^2	
	Hydraulic head on GM	=	0.3	m	
	Wrinkle dimensions		Width (ft.)		Length (ft.)
	HDPE	=	0.85		655
	LLDPE	=	0.5		300
	PVC	=	0.1		12.5
	Flexible PP	=	0.15		15
	Head Loss	=	27	ft.	
	Transmissivity	=	1.6E-08	m^2/s	Good Contact
		=	1.00E-07	m^2/s	Poor Contact

Defects and Wrinkles on Leakage Rates

Calculations			
Area of Pond Bottom	=	112,500.0	$ft.^2$
Area of Four Sideslopes	=	121,899.5	$ft.^2$
Total Leakage Area	=	234,399.5	$ft.^2$
Total Volume of Pond	=	31,852,428.2	gallons
Compacted Soil Liner			
Hydraulic Gradient, i	=	4.6	
Leakage Rate, q	=	2,286.4	gallons/day
Geomembrane			
Hydraulic Gradient, i	=	276	
Leakage Rate No Defects, q	=	1.4	gallons/day
Geomembrane with Defects			
Leakage Rate for one hole	=	1.37	gallons/day
Leakage Rate for all holes	=	11.95	gallons/day
Leakage Rate, GM w. defects, q	=	13.33	gallons/day
Geomembrane with Wrinkles			
Good Intimate Contact			
(HDPE)	=	249.35	gallons/day
(LLDPE)	=	113.00	gallons/day
(PVC)	=	4.65	gallons/day
(FLEXIBLE PP)	=	5.59	gallons/day
Poor Intimate Contact			
(HDPE)	=	613.80	gallons/day
(LLDPE)	=	279.93	gallons/day
(PVC)	=	11.61	gallons/day
(FLEXIBLE PP)	=	13.94	gallons/day

Effect of Wrinkles

- Observed leakage 100 to 1,000* greater than calculated
- Causes localized stresses and strains
- Location of stress cracks (Soong and Koerner, 1997)
- Interference with drainage above
- Bentonite migration if GCL present
- Increase construction damage potential
- Leak location surveys = ?

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Leak Location Requirements

- NJ, NY, CA, WA, WI, MN, TX (Part B), FL

- Ohio
  - Must leak locate
  - Wrinkles less than 4 inches

Wrinkle Observations

- HDPE
- Large wrinkles ~ 7 to 9 inches tall
- - 10 to 20 feet apart
  - impede flow
  - stress cracking

Wrinkle Observations

- Low stiffness
- PVC Geomembranes
- Small & Close together wrinkles
- 1 to 2 inches tall
- Not Connected

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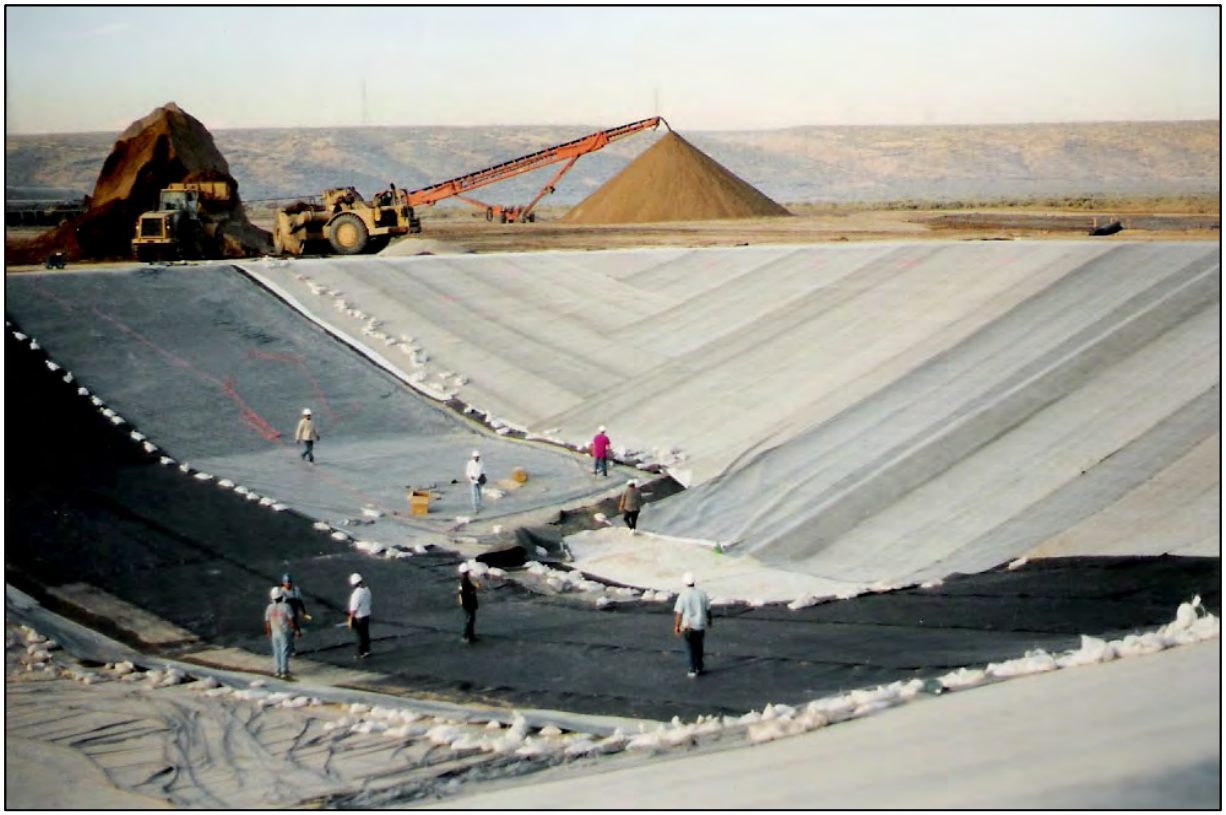
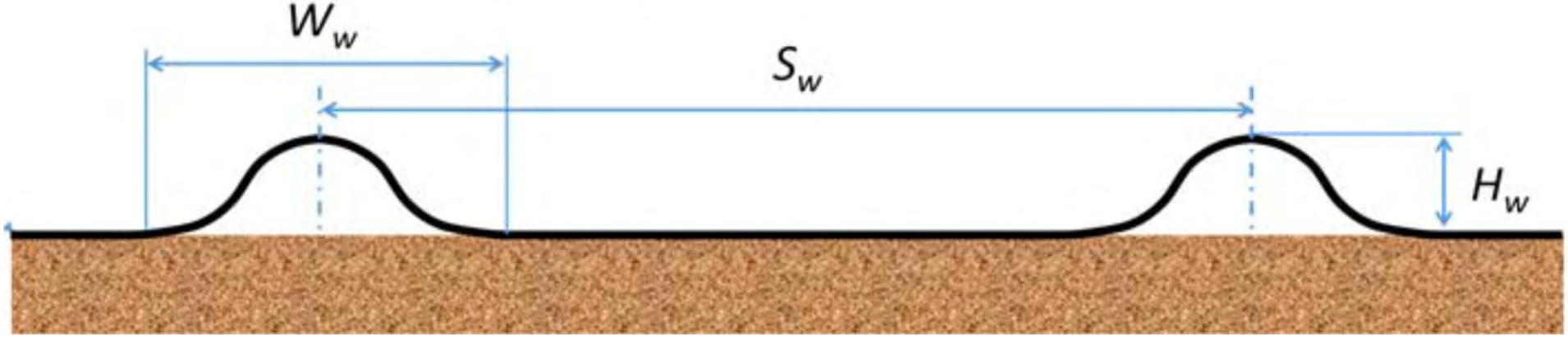


GM Thermal Expansion

- Giroud & Wallace (2016) – Geo-Americas



- **Unreinforced GMs**

$$H_w = \frac{1}{2} * \left[\frac{\alpha * \Delta T * E * t_{GM}^2}{\rho * g * \tan(\delta)}\right]$$

$\boldsymbol{H_w = wrinkle\ height\ (m)}$,
$\alpha = \boldsymbol{GM\ coefficient\ of\ thermal\ expansion}\ (^0\boldsymbol{C} - \boldsymbol{1})$,
$\Delta\boldsymbol{T = change\ in\ Temperature}\ (^0\boldsymbol{C})$,
$\boldsymbol{E = Young's\ Modulus\ (Pa)}$,
$\mathbf{t}_{\boldsymbol{m}} = \boldsymbol{GM\ thickness\ (m)}$,
$\boldsymbol{g = 9.81\ m/s^2}$,
$\rho = \boldsymbol{GM\ density}\ (\boldsymbol{kg/m^3})$, and
$\delta = \boldsymbol{CSL\ or}\ \frac{\boldsymbol{GCL}}{\boldsymbol{GM}}\ \boldsymbol{interface\ friction\ angle}\ (^0)$.

GM Thermal Expansion

Unreinforced GM Polymer (Black)	Coeff. Thermal Exp. ($^0C^{-1}$)	GM Bending Modulus (MPa)	GM Density (kg/cm^3)	GM Thick-ness (mm)	GM Inter-face friction (deg)	*Wrinkle Height,* H_w (mm)
HDPE-S	$1.9x10^{-4}$	250	940	1.5	10	92
LLDPE-S	$1.9x10^{-4}$	200	850	1.0	10	58
fPP	$8.9x10^{-5}$	150	750	1.0	22	27
PVC#1-Grey	$1.3x10^{-4}$	125	700	0.75	20	12

$\boldsymbol{g = 9.81\ m/s^2}$
$\boldsymbol{\Delta T = 45^0C}$

HDPE ~ 8* higher wrinkle than PVC

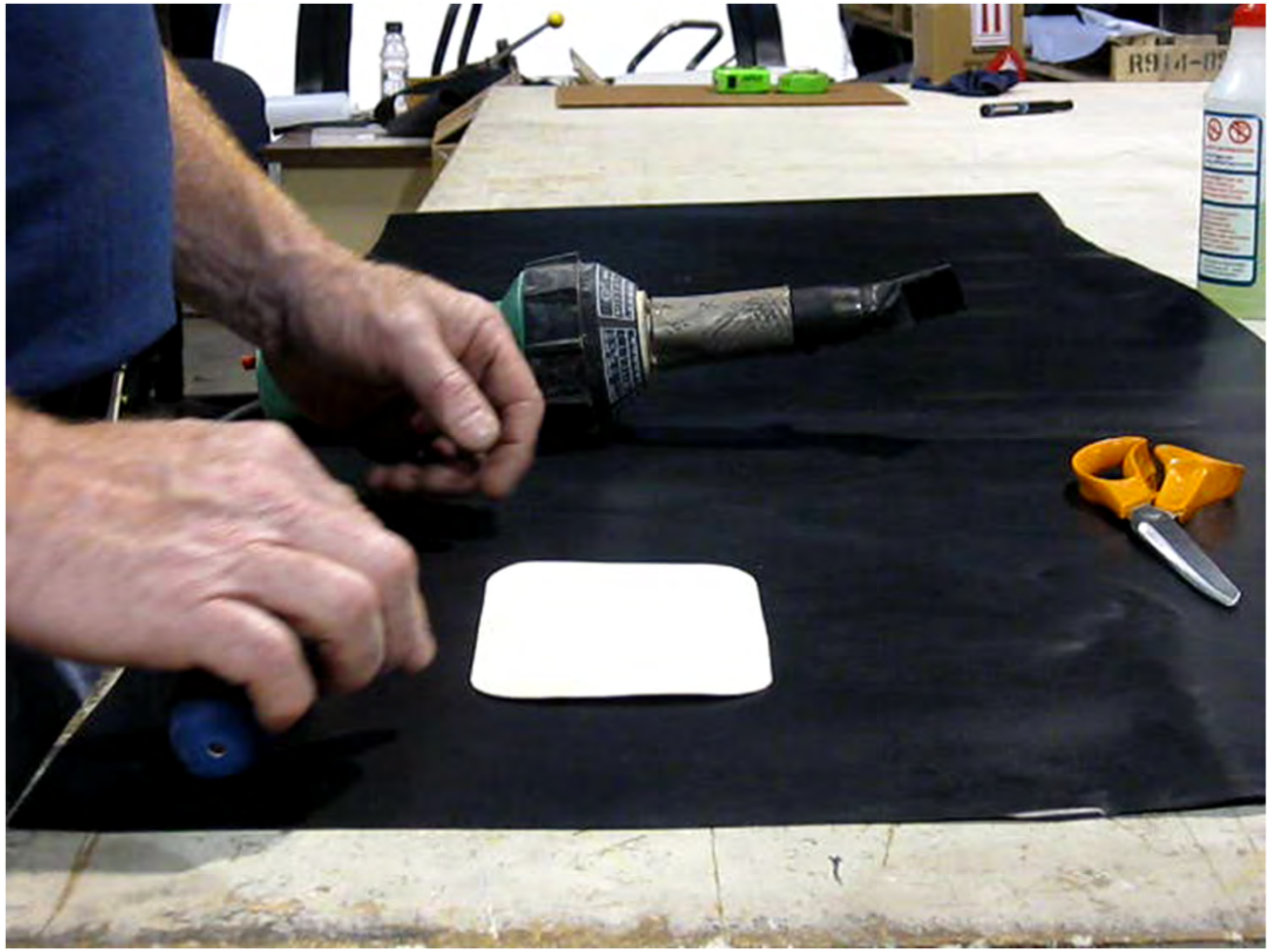
Other Flexible Membrane Liners (FMLs)

- Factory: No destructive seam testing on production liner – Consistent welds
- Field: One every 500 lineal feet

Extrusion Patches

- From Brian Queen (OEPA) (2017)
  - ~5 holes/acre
  - ~5% due to extrusion welds
  - ~85% due to cover soil placement
  - ~10% due to welding and waste placement

Flexible GM Thermal Patching



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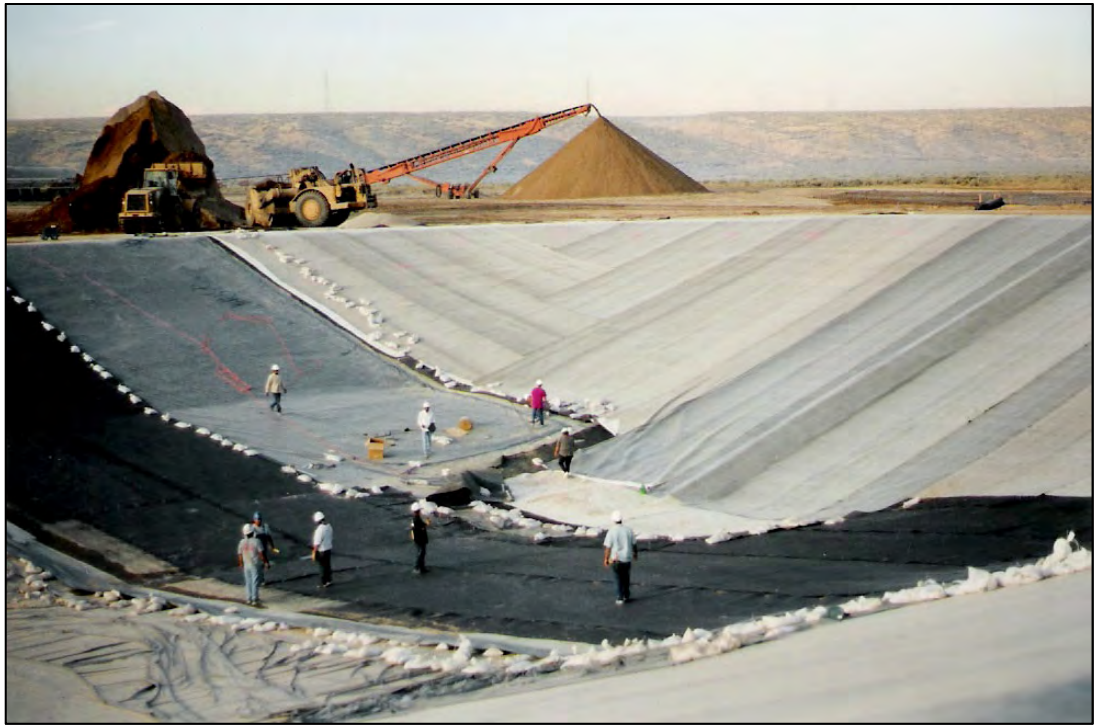
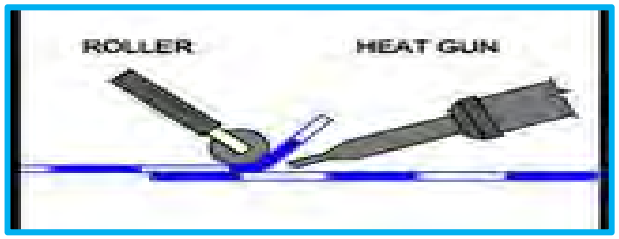


Summary

- Wrinkles:
  - Remain
  - No intimate contact
  - Pond liquid
  - Increase leakage
  - Impact leak location surveys
- New Regulations
  - More leak location
  - Wrinkles less than 4 inches (2-3 inches)

Recommendations

- Use flexible or reinforced geomembranes – 9090 Testing
- Backfill at night
- Light colored geomembranes??
- Do not push and cut out wrinkles
- Hot air patches



Questions???

Thank you for attending!

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Next FGI Webinar

US EPA Reconsideration of CCR Regulations Impacting the Geosynthetics Industry

Thursday, October 8, 2020 at 11 a.m. Central Time

Free to Industry Professionals

1.0 PDH

Presenters

Harold (J.R.) Register, P.E.

Andrew Bittner, P.E.

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- Pond Leakage Calculator
- Panel Weight Calculator
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