Objectives and Limitations

- Introduce concepts to those new to the field
- Present some latest developments
- The material presented is not complete in and of itself; it is intended only to provide direction. Examine published sources for more complete information
- Not all topics are covered

Geomembranes (GMB)

- Are essentially impermeable to flow of aqueous solutions – except for holes.

Giroud (2016):
- “All liners leak”
- With fulltime CQA but no electrical leak location survey expect 5-6 holes per hectare
- With only spot checks and no electrical leak location survey expect 25 holes per hectare

Geomembranes leakage

Depends on
- Number and size of holes – in service (i.e., after GMB is loaded!)
- Head on liner
- Interaction with the climatic conditions and surrounding media (above and below) before and after it is covered

and has been often calculated assuming hole in a GMB in direct contact with a clay liner (e.g., Giroud 1997)
Interface contact GMB/CCL

Giroud (1997) defined:
- **good contact** - GMB with as few “wrinkles” as possible, on low-permeability soil, adequately compacted and a smooth surface
- **poor contact** - GMB with a certain number of “wrinkles”, and/or on low-permeability soil, not well compacted and does not appear smooth

“Wrinkles” as discussed in this presentation cannot be modeled as an interface transmissivity (very small and local “wrinkles” < 1 cm high may be included in the Giroud definition).

Rowe (1998) inferred transmissivities of:
- **good contact** \( \theta = 1.6 \times 10^{-8} \text{ m}^2/\text{s} \)
- **poor contact** \( \theta = 1 \times 10^{-7} \text{ m}^2/\text{s} \)

Interface contact GMB/GCL

- greater potential for obtaining good contact with GCL than with CCL since
  - GCL can be placed flat on a well compacted, smooth and firm foundation
  - bentonite swelling upon hydration may reduce small gaps at the GMB/GCL interface
- typical transmissivity: \( 2 \times 10^{-11} \leq \theta \leq 4 \times 10^{-11} \text{ m}^2/\text{s} \) for water or MSW leachate \( \sigma_v \geq 50 \text{kPa} \) (i.e., 3 to 4 orders of magnitude lower than for a CCL)

Calculated Leakage for Direct contact

<table>
<thead>
<tr>
<th>GMB/GCL</th>
<th>GMB/CCL</th>
<th>GMB</th>
</tr>
</thead>
<tbody>
<tr>
<td>( h_w ) (m)</td>
<td>( Q ) (lphd)</td>
<td>( Q ) (lphd)</td>
</tr>
<tr>
<td>0.3</td>
<td>0.2</td>
<td>2</td>
</tr>
</tbody>
</table>

GMB: 5 holes/ha 1.4-3.2 mm diameter (also for below)

\( \text{GCL}: \ H = 0.01 \text{ m}, k = 1 \times 10^{-11} \text{ m/s}, \theta = 2 \times 10^{-8} \text{ m}^2/\text{s} \)

\( \text{CCL}: \ H = 0.6 \text{ m}, \ k = 1 \times 10^{-9} \text{ m/s}, \theta = 2 \times 10^{-8} \text{ m}^2/\text{s} \)

Findings from field monitoring

- Leakage with composite liners much less than with a single geomembrane
- Composite liners with a GCL perform much better than a composite with a CCL

BUT

- Observed leakages 10 to 10,000 times larger than calculated using traditional equations assuming direct contact and a reasonable number of holes/ha – why?

Calculated Leakage for GMB alone

<table>
<thead>
<tr>
<th>Hole Area* (mm²)</th>
<th>Hole Diameter (mm)</th>
<th>Number per ha</th>
<th>Q (lphd)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>1.4</td>
<td>1</td>
<td>750</td>
</tr>
<tr>
<td>2.5</td>
<td>1.8</td>
<td>1</td>
<td>1250</td>
</tr>
<tr>
<td>4</td>
<td>2.3</td>
<td>2</td>
<td>4000</td>
</tr>
<tr>
<td>8</td>
<td>3.2</td>
<td>1</td>
<td>4000</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>10,000</td>
</tr>
</tbody>
</table>

* Based on Giroud (2016); 5 holes/ha; head \( h_w = 0.3 \text{ m} \)

GMB in direct contact with GCL

Geomembrane (GMB)
Geosynthetic clay liner (GCL)

Assumed when using traditional equations or HELP

Queen's University Environmental Liner Test Site (QUELTS)

GMB with no wrinkles; cloudy November morning; ambient \( T = 3^\circ \text{C} \) \( (T = 37^\circ \text{F}) \)
GMB Wrinkles

Roll-parallel wrinkle at fold

GMB T ≈ 45 °C (110 °F)

GMB with wrinkles; midmorning when ambient T = 17 °C (63 °F)

same location as shown in earlier slide

Rowe et al. (2012)

Wrinkle Parallel to Panel

GMB Wrinkles

Rowe et al. (2012)

Blown Film GMB Production

Folds

Cut here and unfolded

Roll-parallel wrinkle at fold

Source: Koerner (1997) Designing with geosynthetics

Leakage calculations

Rowe (1998) equation:

Q = (2b L k_b h_d / H_L)

q_h = L \theta I_h

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

Q: flow through GMB

2b: width of wrinkle

L: wrinkle length

k_b: hydraulic conductivity of GCL below wrinkle

k_a: hydraulic conductivity in contact with GMB

h_d: Head loss (h_d = h_w + H_L)

H_L: Liner thickness

\theta: transmissivity between GMB and clay liner

Wrinkle Parallel to Panel

"W shaped" roll-parallel wrinkle at fold

Aerial Photography System

13 megapixel camera

Remote shutter receiver

Remote control

Blimp tether

Remote shutter receiver

Take et al. (2007)

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University of Illinois at Urbana-Champaign
Cross-roll wrinkle joining seam and peaked wrinkles

Note Extent and Interconnectedness of Wrinkles

Measured Parameters

Site in Ontario Latitude 44° 24’ North

Note Extent and Interconnectedness of Wrinkles

Site in Ontario Latitude 44° 24’ North

Early morning
Site in Ontario Latitude 44° 24’ North

Significance of holes and wrinkles

If there are 5 holes / ha and
• 20% of the entire area is occupied by wrinkles, there is a 67% probability that
• 5% of the entire area is occupied by wrinkles there is a 23% probability that

Thus, wrinkles will dominate leakage unless covered with essentially no wrinkles.

Change in length of longest connected wrinkle with time of day

Longest Length vs Area of Wrinkles

Wrinkled Area

HDPE Wrinkle Summary

• Wrinkling related to solar radiation and GMB temperature (may be 20-40°C > ambient)
• Typical wrinkle width about 0.2 - 0.3 m
• Typical wrinkle height about 0.06m (up to 0.2m)
• Wrinkles could range from a few % to more than 30% depending on time GMB is covered
• Even on a “small” area (0.15-0.17 ha), wrinkle length exceeded 200m once more than about 5% of area was wrinkles
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QUELTS II Results
First day after installation (May 18, 2012)

Due to heat stored in subgrade

QUELTS II Results
First day after installation (May 18, 2012)

Due to heat stored in subgrade

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First day after installation (May 18, 2012)

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QUELTS II Results
First day after installation (May 18, 2012)

Due to heat stored in subgrade

QUELTS II Results
First day after installation (May 18, 2012)

Due to heat stored in subgrade
Longest Connected Wrinkle

Black vs White GMB Wrinkles
- Significant wrinkles for both black and white GMBs
- Significant wrinkles appeared sooner and remain longer in black GMB than in white GMB
- More wrinkles in black GMB than in white GMB at any time
- Longer connected wrinkles in black GMB than in white GMB

Significance of holes and wrinkles

<table>
<thead>
<tr>
<th>Number of holes per ha</th>
<th>% of area with wrinkles</th>
<th>Probability of a hole in a wrinkle</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>5</td>
<td>23%</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>41%</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>56%</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>67%</td>
</tr>
<tr>
<td>6</td>
<td>10</td>
<td>47%</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>62%</td>
</tr>
<tr>
<td>10</td>
<td>5</td>
<td>40%</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>65%</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>80%</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>89%</td>
</tr>
</tbody>
</table>

Observed Leakage
(Through primary liner in double lined landfills)

Sites with CQA but no ELL
Expect 5-6 holes/ha based on Giroud (2016)
**Probability of Exceeding Leakage Rate**

- **Sites with CQA but no ELL**
  - Based on 122 landfill cells
  - Probability Function

**Queen's Univ. Environmental Liner Test Site**

- When GMB gets hot, moisture evaporates from GCL into airspace (mostly at wrinkles) and does not go back when the GMB cools.

**Calculated leakage through a primary liner**

<table>
<thead>
<tr>
<th>Liner</th>
<th>L (m/ha)</th>
<th>Leakage (lphd)</th>
<th>Probability leakage is higher with no ELLS</th>
</tr>
</thead>
<tbody>
<tr>
<td>GMB/CCL</td>
<td>1000</td>
<td>830</td>
<td>&lt; 3</td>
</tr>
<tr>
<td>GMB/CCL</td>
<td>230</td>
<td>190</td>
<td>20 gpad</td>
</tr>
<tr>
<td>GMB/CCL</td>
<td>60</td>
<td>50</td>
<td>5 gpad</td>
</tr>
<tr>
<td>GMB/GCL</td>
<td>1000</td>
<td>130</td>
<td>35</td>
</tr>
<tr>
<td>GMB/GCL</td>
<td>400</td>
<td>50</td>
<td>60</td>
</tr>
<tr>
<td>GMB/GCL</td>
<td>60</td>
<td>8</td>
<td>&gt; 85</td>
</tr>
</tbody>
</table>

One wrinkle with hole: length, $L$; width, $2b = 0.2$ m

- GCL: $k_L = 5 \times 10^{-10} \text{ m/s}$, $L_0 = 2 \times 10^{-10} \text{ m/s}$; $h_{CL} = 0.01 \text{ m}$, $B = 3 \times 10^{-11} \text{ m/s}$
- CCL: $k_c = 1 \times 10^{-9} \text{ m/s}$, $L_0 = 0.6 \text{ m}$, $B = 1.6 \times 10^{-7} \text{ m/s}$

**GCL Overlap as Designed**

- Consider interaction between system and climate
- Overlap as Designed

**Defective GCL Overlap**

- Consider interaction between system and climate
- Overlap loss due to shrinkage

**What happens if we leave a composite liner**

- Wrinkles

**Overlap GMB/GCL**

- Supplemental bentonite

- Overlap loss due to shrinkage
Shrinkage
Maximum reduction in overlap – Base

- Observed shrinkage in GCL overlaps over time.
- Shrinkage appears to depend on:
  - method of GCL manufacture
  - local site conditions
  - Considering interaction between system and climate

GM Wrinkles on Base QUELTS
28 May 2008 at 13:00 - air temperature = 14°C, the geomembrane temperature on the base = 54°C, solar radiation = 1050 W/m²

GCL Overlaps

Crease in GMB

GCL Overlaps

Crease in GMB

女王科技大学环境衬里测试站
QUELTS

What we are examining:
- Geosynthetic Clay Liner (GCL) Hydration
- Geomembrane (GMB) Wrinkles
- Geosynthetic Clay Liner (GCL) Shrinkage
- Down-slope erosion

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Observations
- Shrinkage appears to depend on:
  - method of GCL manufacture
  - local site conditions
- Effects can be minimized by:
  - covering as quickly as possible; if not possible, by
  - selecting a GCL with the best performance, and
  - ensuring 300mm overlap at seams, and
  - heat tacking seam where practical, and
  - using a white geomembrane, but still
  - cover as quickly as possible

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Shrinkage
Consider interaction between system and climate

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Queen's U. Environmental Liner Test Site

QUELTS 1
South facing slope
• 3H:1V
• 22 m long x 80 m wide

Base: 3% grade to south; 20 m long x 80 m wide; 6 sections
QUELTS I constructed September 2006 and left exposed for 5 years
• Four commonly used GCLs (GCL1-4) experienced down-slope bentonite erosion
• Erosion developed within 1 year

Take, Brachman & Rowe (2015)

Moisture cycle from thermal cycle when exposed

• GCL hydrates with moisture from subsoil
• on heating:
  • GCL loses moisture to GMB/GCL interface
  • vapour migrates towards wrinkles
• on cooling:
  • vapour condenses on underside of GMB
  • condensed moisture trickles downslope

Differential exposure

Black GMB get hot; even when partly snow covered
Thermally induced wrinkles

The first hint of a problem
QUELTS I

A bigger clue

Bentonite on top of black upper GTX on GCL

Wrinkles

Early morning – no thermally induced wrinkles
Later in partially cloudy day
Many thermally induced wrinkles

© R. Kerry Rowe - Effect of Wrinkles on Geomembrane Performance

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Factors concentrating flow

Bentonite: underside of slope GMB

Underside of base GMB at opening

Bentonite at bottom of slope

The mechanism

Down-slope erosion is not random but its location is related to local irregularities.
When geomembrane was removed after 3.6 years

Bentonite on subsoil below eroded zone

Direction downslope water flow

Dry mass of bentonite (g/m²)

Position (mm)

Erosion of a patch in 1 year

Patch placed after 3.6 years May 2010

Eroded zone after 4.7 years
The Problem

- GCLs covered only by a black GMB was intentionally left exposed for long periods of time at Queen’s test site
- observed of features where there was little/no bentonite remaining in the GCL
- arises from cumulative effects of bentonite migration with small amounts of condensed water trickling on the GCL

Features on slope and base

- more features detected on slope than base
- after 4.7 years, most significant feature on base was:
  - maximum 50 mm wide, nearly 20 m long
- features big enough such that they will not heal from swelling or stress effects once covered

QUELTS 1 & 2 summary

- White GMB prolonged time to erosion
- Bentonite in some GCLs was more resistant to down-slope erosion than others
- Multi-component GCL, no erosion after 28 months
  - coating prevented loss of moisture to GMB/GCL interface
- 0.3 m gravel cover, no erosion after 28 months
  - cover prevented thermal cycles that cause down-slope erosion and shrinkage

Buried wrinkles with shrinkage or downslope erosion

- If a hole in the GMB aligns with a
  - seam that shrinks to disengage supplemental bentonite
  - seam gap
  - location of down-slope erosion
- leakage becomes very large (controlled by Bernoulli’s equation)
- Probability of this becomes much higher as the number of buried wrinkles increases since wrinkles may be
  - both perpendicular and parallel & directly over overlaps
  - aligned with location of downslope erosion
Avoiding excessive leakage

- Cover the composite liner in a timely manner. Important
  – for most common GCLs; and
  – for compacted clay which can desiccate (increasing interface transmissivity)
- If composite must be left exposed, use a GCL with proven good resistance to shrinkage and downslope erosion (there are some but they cost more than the cheaper commonly used GCLs)
- Minimize the number of buried wrinkle (less that 5%)
- Use a leak location survey to minimize number of holes after the cover soil is placed.

Conclusions

- Composite liner leakage less with GCL than CCL, BUT advantage reduced as wrinkle % increases because of low stress on GCL below wrinkle (higher k)
- Mid-day temperature below wrinkle ~ 15°C above elsewhere
- White GMB gives longer period when one can cover but does not eliminate the issue
- Cover soil and loading reduced wrinkle width but they remain

Conclusions

- Nature of required liner depends on level of acceptable leakage
- Leakage can be substantially reduced by a composite liner
- Wrinkles/waves will increase leakage for composite liners and should be minimized

Conclusions

- As % area with wrinkles increases above 5%, probability that
  – a hole will intersect a wrinkle
  – the wrinkle will be long
  – leakage will exceed ALR increases significantly

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All comments in this lecture are those of the speaker and are not necessarily shared by any of those listed above.
Effect of Wrinkles on Geomembrane Performance

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References – Leakage and Overlaps


References – Winkles


