Effect of Wrinkles on Geomembrane Performance

R. Kerry Rowe

Professor and Canada Research Chair in Geotechnical and Geoenvironmental Engineering, Queen's University

Kingston

Canada

The Geo Engineering Centre at Queen's-RMC

www.geoeng.ca

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)

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

GMB in Direct Contact with GCL

GMB with no wrinkles

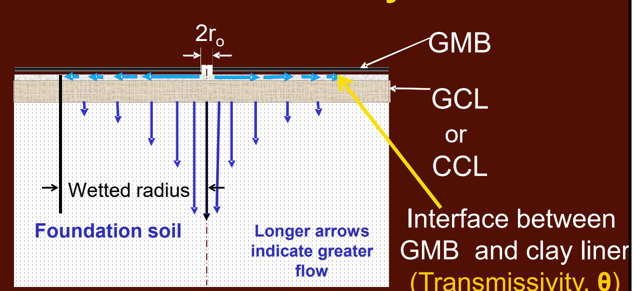
Geomembranes (GMB)

- 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

Leakage through GMB in Direct Contact with Clay Liner



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 can not be modeled as an interface transmissivity (very small and local "wrinkles" < 1cm high may be included in the Giroud definition)

Rowe (1998) inferred transmissivities of:

- good contact θ = 1.6x10^{-8} m^2/s
- poor contact θ = 1x10^{-7} m^2/s

© R.K. Rowe 2018

Calculated Leakage for Direct contact

	GMB/GCL	GMB/CCL	GMB
h_w (m)	Q (lphd)	Q (lphd)	Q (lphd)
0.3	0.2	2	10,000

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

GCL: H_L = 0.01 m, k_L = 1x10^{-11} m/s, θ = 2x10^{-8} m^2/s

CCL: H_L = 0.6 m, k_L = 1x10^{-9} m/s, θ = 2 x10^{-8} m^2/s

© R.K. Rowe 2018

Rowe (2012)

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: 2x10^{-11} ≤ θ ≤ 4x10^{-11} m^2/s for water or MSW leachate σ_v' ≥ 50kPa (i.e., 3 to 4 orders of magnitude lower than for a CCL)

© R.K. Rowe 2018

Rowe (2012)

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?**

© R.K. Rowe 2018

Calculated Leakage for GMB alone

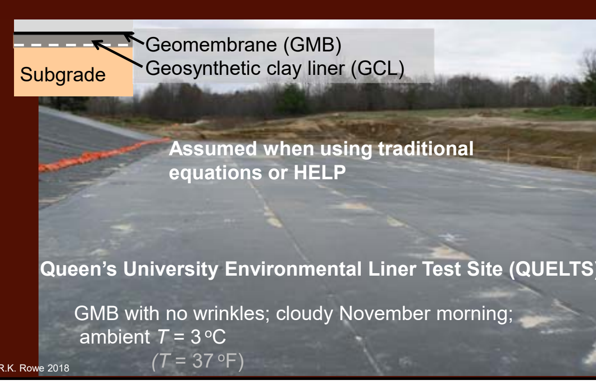
Hole Area* (mm^2)	Hole diameter (mm)	Number per ha (ha^{-1})	Q (lphd)
1.5	1.4	1	750
2.5	1.8	1	1250
4	2.3	2	4000
8	3.2	1	4000
Total			10,000

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

© R.K. Rowe 2018

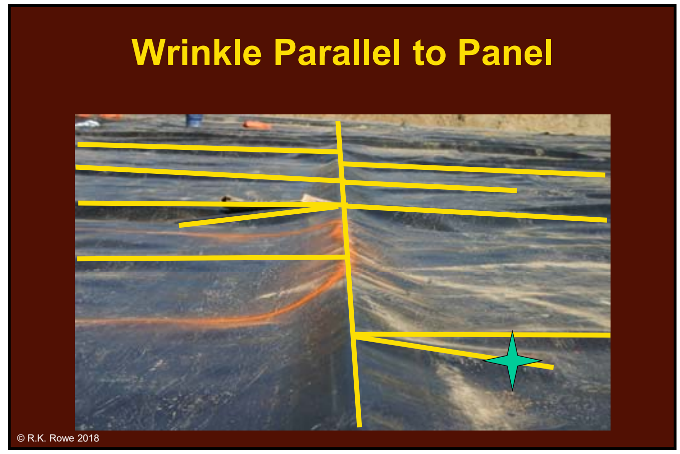
Rowe (2018)

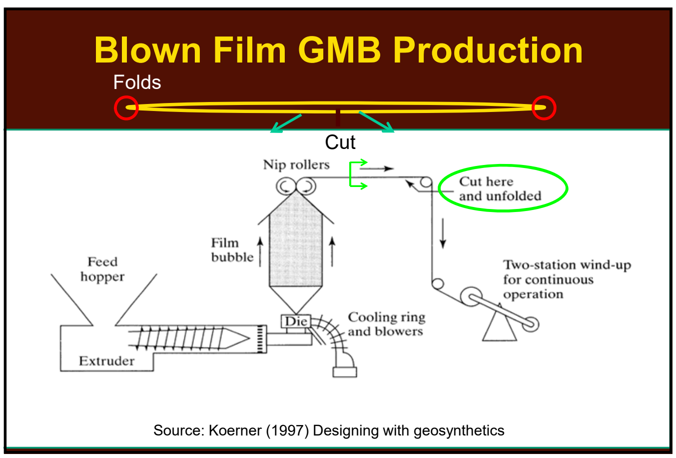
GMB in direct contact with GCL

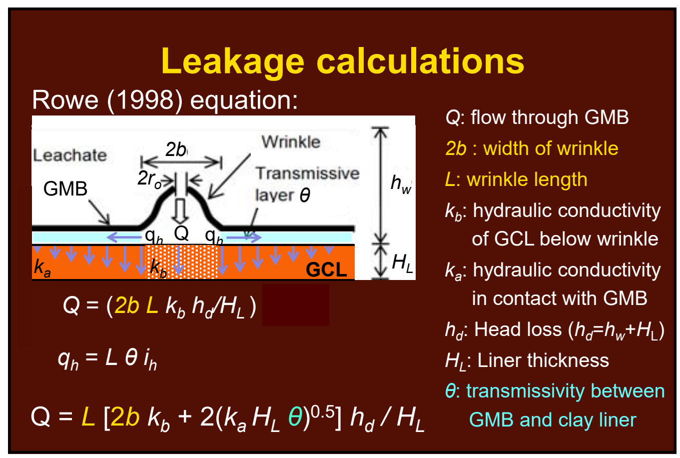


© R.K. Rowe 2018

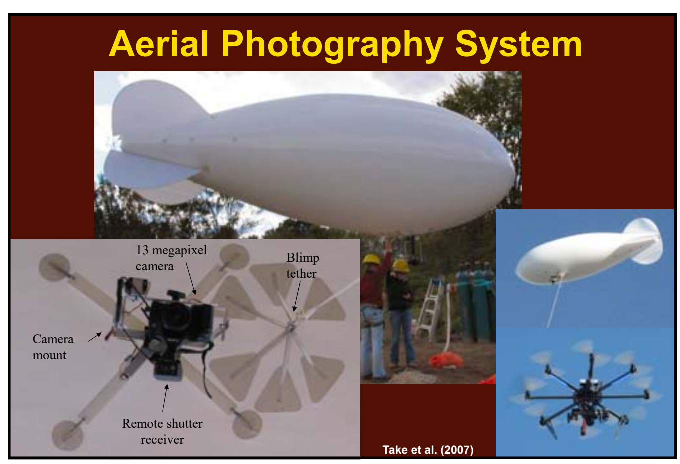

GMB Wrinkles
Roll-parallel wrinkle at fold
GMB $T \approx 45\ ^oC$ ($110\ ^oF$)
GMB with wrinkles; midmorning when ambient T = 17 ^{o}C (63^{o}F) same location as shown in earlier slide)
© R.K. Rowe 2018
Rowe et al. (2012)

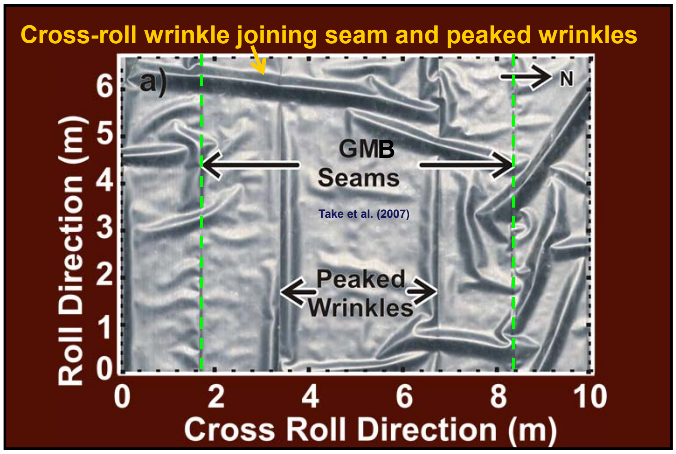

Wrinkle Parallel to Panel
© R.K. Rowe 2018

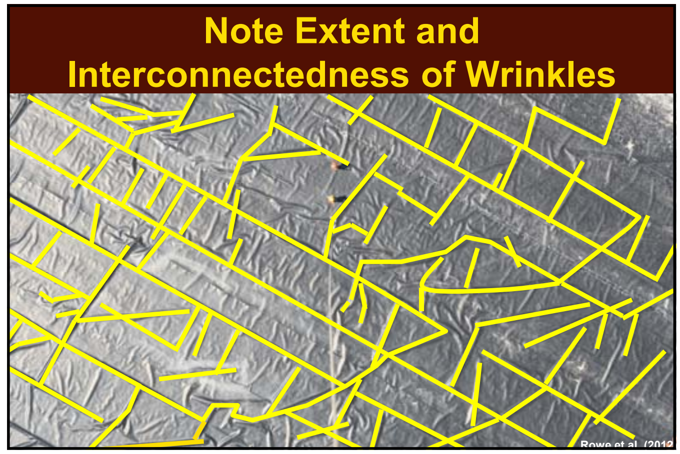

Blown Film GMB Production
Folds
Cut
Nip rollers
Cut here and unfolded
Film bubble
Feed hopper
Two-station wind-up for continuous operation
Cooling ring and blowers
Die
Extruder
Source: Koerner (1997) Designing with geosynthetics

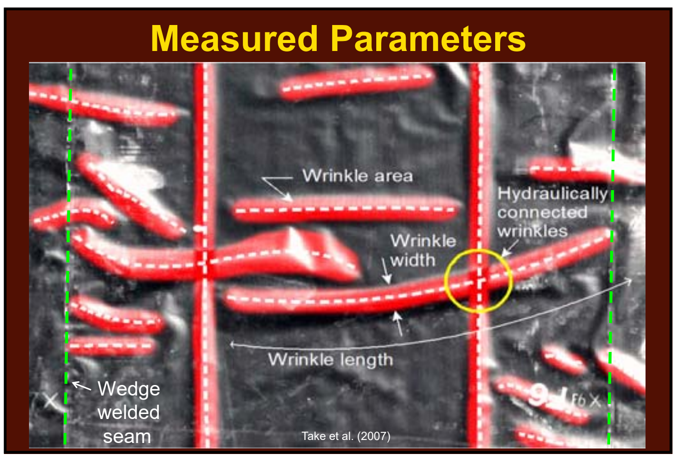

Leakage calculations
Rowe (1998) equation:
Leachate
GMB
$2b$
$2r_o$
Wrinkle
Transmissive layer θ
h_w
q_h Q q_h
k_a
k_b
GCL
H_L
$Q = (2b\ L\ k_b\ h_d/H_L)$
$q_h = L\ \theta\ i_h$
$Q = L\ [2b\ k_b + 2(k_a\ H_L\ \theta)^{0.5}]\ h_d / H_L$
Q: flow through GMB
$2b$: width of wrinkle
L: wrinkle length
k_b: 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
θ: transmissivity between GMB and clay liner

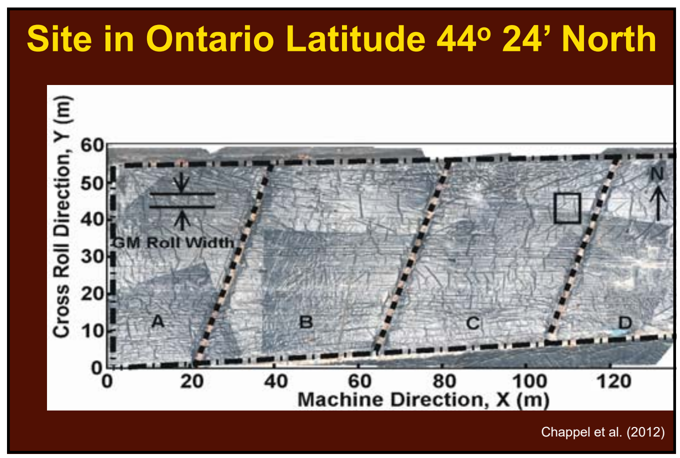

Wrinkle Parallel to Panel
Wedge welded seam
Cross-roll wrinkle intersecting seam
"V shaped" roll-parallel wrinkle at fold
© R.K. Rowe 2018

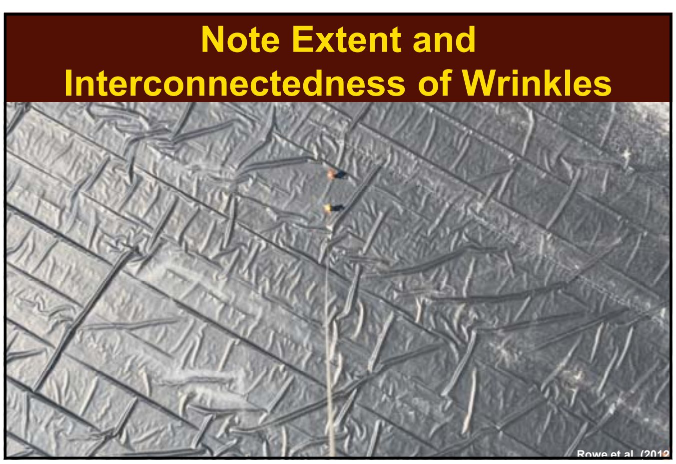

Aerial Photography System
13 megapixel camera
Blimp tether
Camera mount
Remote shutter receiver
Take et al. (2007)


Cross-roll wrinkle joining seam and peaked wrinkles
a)
N
GMB
Seams
Take et al. (2007)
Peaked
Wrinkles
Roll Direction (m)
0
1
2
3
4
5
6
0
2
4
6
8
10
Cross Roll Direction (m)


Note Extent and
Interconnectedness of Wrinkles


Measured Parameters
Wrinkle area
Hydraulically
connected
wrinkles
Wrinkle
width
Wrinkle length
Wedge
welded
seam
Take et al. (2007)


Site in Ontario Latitude 44o 24' North
Cross Roll Direction, Y (m)
0
10
20
30
40
50
60
GM Roll Width
N
A
B
C
D
0
20
40
60
80
100
120
Machine Direction, X (m)
Chappel et al. (2012)


Note Extent and
Interconnectedness of Wrinkles


Site in Ontario Latitude 44o 24' North
Early morning
Chappel et al. (2012)

Site in Ontario Latitude 44º 24’ North

Midday

Chappel et al. (2012)

Significance of holes and wrinkles

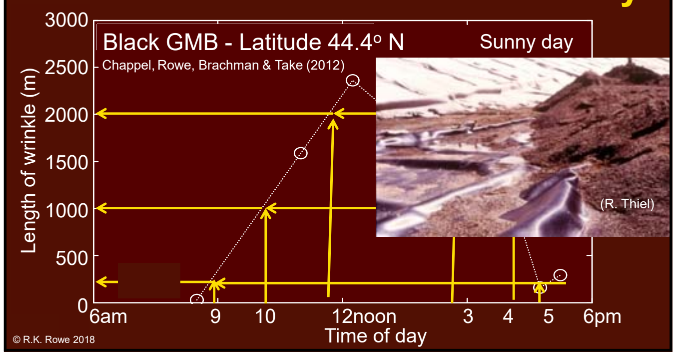
If there are 5 holes / ha and

- 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

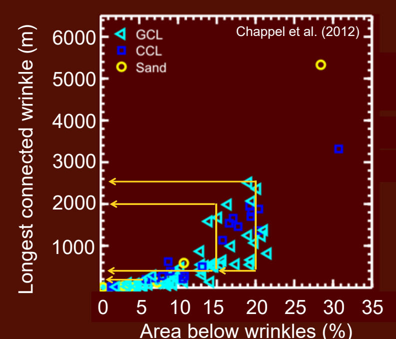
at least one of those holes is coincident with a wrinkle.

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

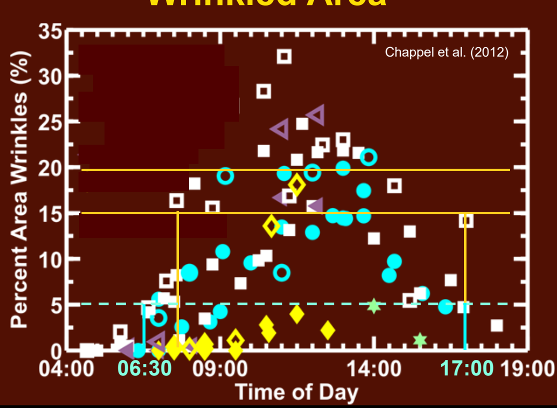
Change in length of longest connected wrinkle with time of day



Longest Length vs Area of Wrinkles



Wrinkled Area

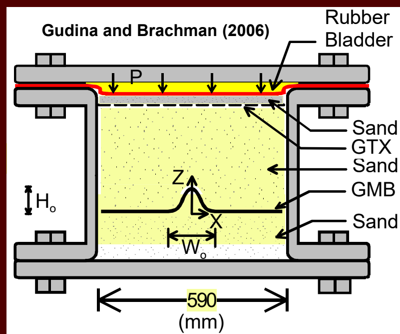


HDPE Wrinkle Summary

- Wrinkling related to solar radiation and GMB temperature (may be 20-40ºC > 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

Burial beneath waste

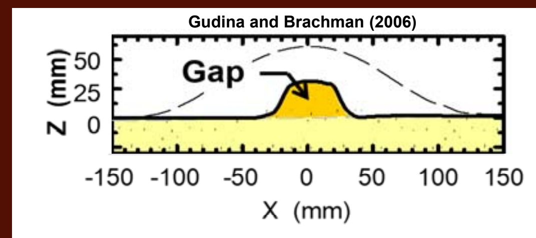
SP / GMB / SP



HDPE Wrinkle on Loading

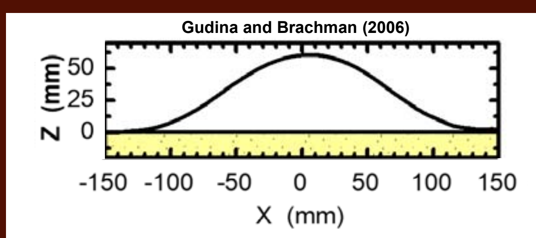
SP / GMB / SP
1100 kPa

80 m waste
γ = 13 kN/m³



HDPE Wrinkle on Loading

SP / GMB / SP
Initial



Summary: wrinkles

- as many as 5000 wrinkles / ha
- max length over 5400 m long
- NEED to limit time of day place cover
- may get smaller but do not go away
  - after cover soil
  - after buried beneath waste

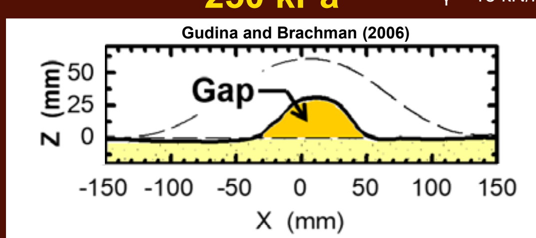
© R.K. Rowe 2018

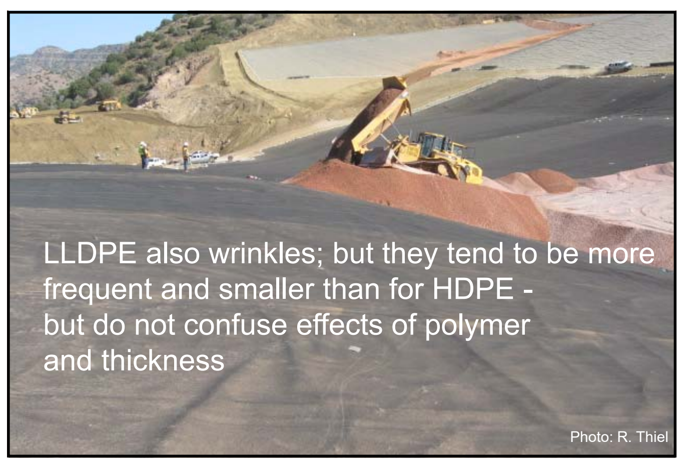
26:00

HDPE Wrinkle on Loading

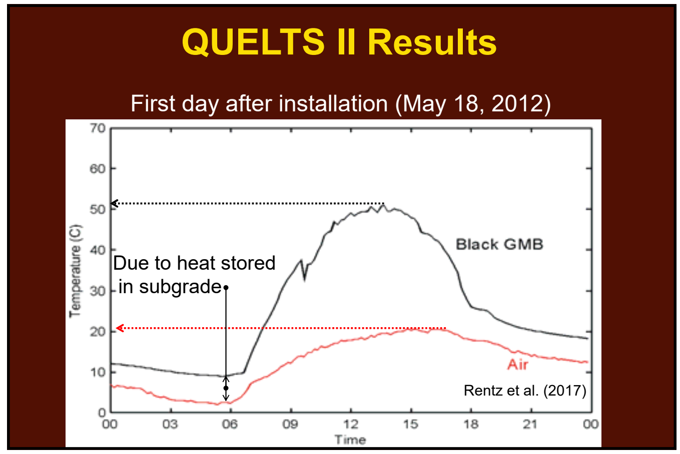
SP / GMB / SP
250 kPa

18 m waste
γ = 13 kN/m³

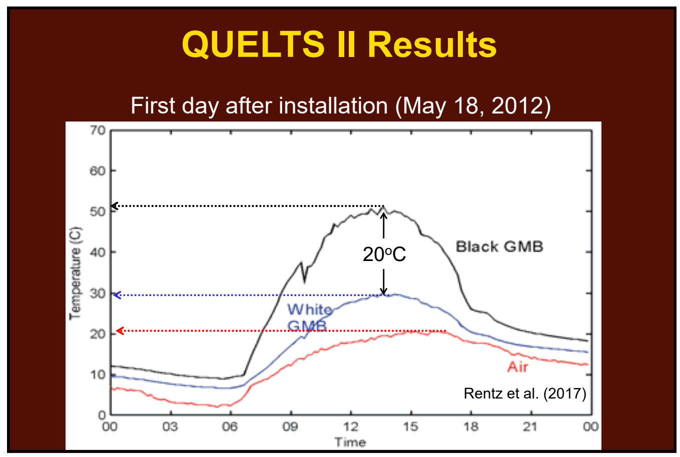


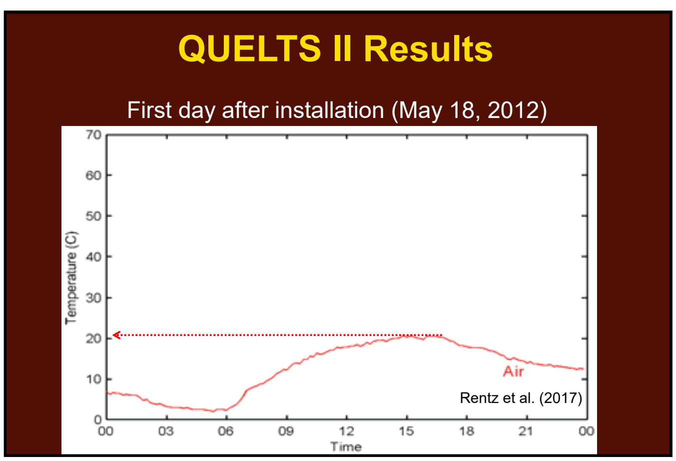


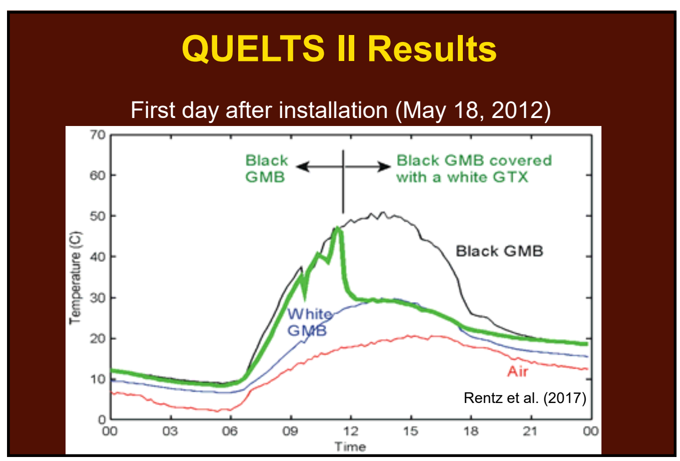

LLDPE Wrinkles
Photo: R. Thiel


QUELTS II Results
First day after installation (May 18, 2012)
Temperature (C)
Time
Due to heat stored
in subgrade
Black GMB
Air
Rentz et al. (2017)

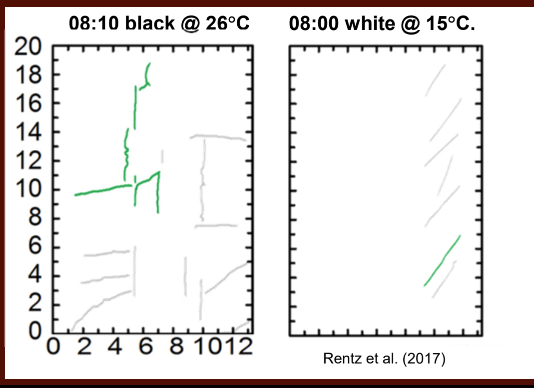

Queen's University Experimental Liner Test Site (QUELTS): Godfrey, ON
0.3m gravel
Geotextile
GMB + GCL
Exposed
White GMB
+ GCL
Exposed
Black GMB
+ GCL
Rentz et al. (2017)


QUELTS II Results
First day after installation (May 18, 2012)
Temperature (C)
Time
20°C
Black GMB
White GMB
Air
Rentz et al. (2017)


QUELTS II Results
First day after installation (May 18, 2012)
Temperature (C)
Time
Air
Rentz et al. (2017)


QUELTS II Results
First day after installation (May 18, 2012)
Temperature (C)
Time
Black GMB
Black GMB covered with a white GTX
Black GMB
White GMB
Air
Rentz et al. (2017)

Longest Connected Wrinkle

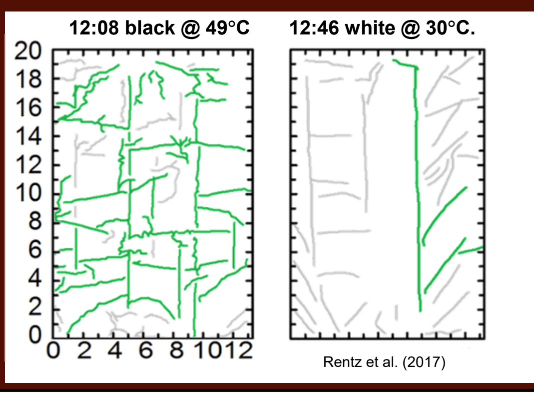


Black vs White GMB Wrinkles

- 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

Rentz et al. (unp)

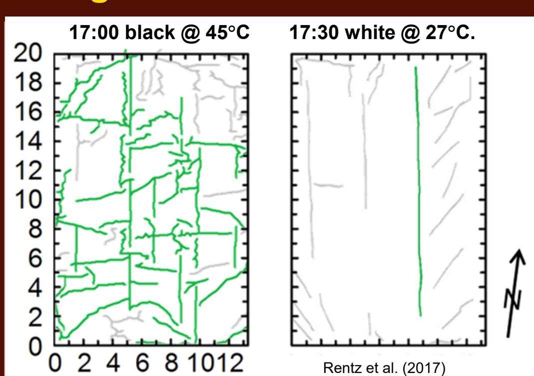
Longest Connected Wrinkle



Significance of holes and wrinkles

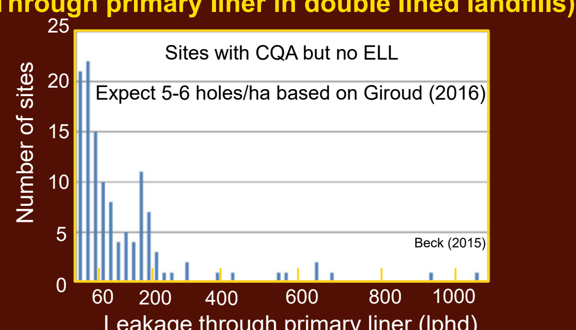
Number of holes per ha	% of area with wrinkles	Probability of a hole in a wrinkle
5	5	23%
	10	41%
	15	**56%**
	20	67%
6	10	47%
	15	**62%**
10	5	40%
	10	65%
	15	**80%**
	20	89%

Longest Connected Wrinkle

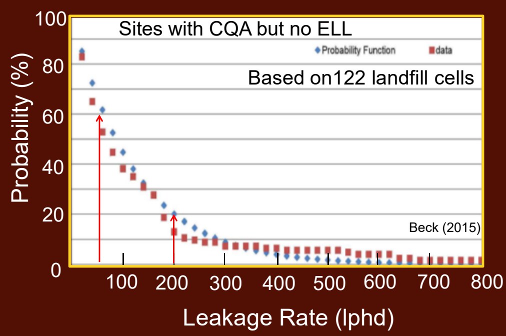


Observed Leakage

(Through primary liner in double lined landfills)

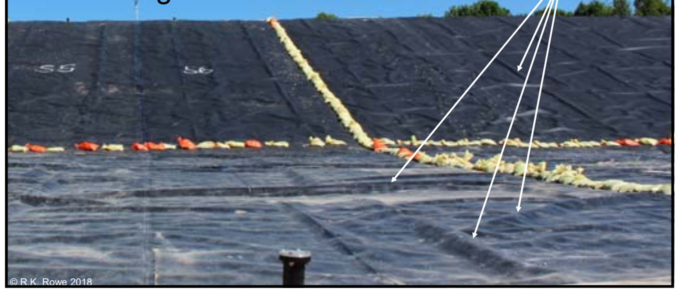


Probability of Exceeding Leakage Rate



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

Liner	L (m/ha)	Leakage (lphd)		Probability leakage is higher with no ELLS
GMB/CCL	1000	830		< 3
GMB/CCL	230	190	20 gpad	20
GMB/CCL	60	50	5 gpad	60
GMB/GCL	1000	130		35
GMB/GCL	400	50	5 gpad	60
GMB/GCL	60	8		> 85

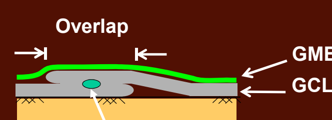
One wrinkle with hole: length, *L*; width, *2b* = 0.2 m

GCL $k_b = 5\times10^{-11}$ m/s, GCL $k_a = 2\times10^{-10}$ m/s, $H_L = 0.01$ m, $\theta = 3\times10^{-11}$ m²/s;
CCL $k_L = 1\times10^{-9}$ m/s, $H_L = 0.6$ m, $\theta = 1.6\times10^{-8}$ m²/s;

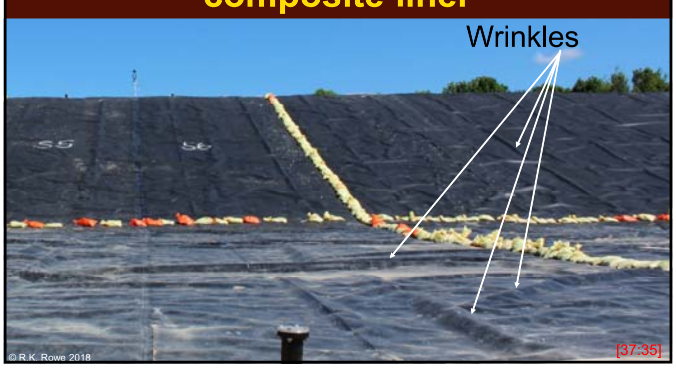
Rowe (2012)

GCL Overlap as Designed

Consider interaction between system and climate

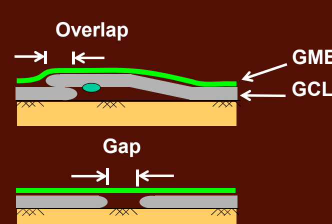


What happens if we leave a composite liner



Defective GCL Overlap

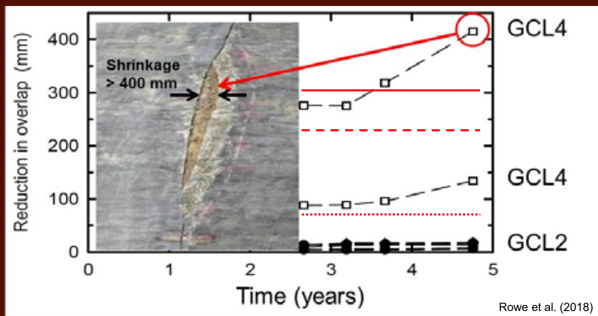
Consider interaction between system and climate



Overlap loss due to shrinkage

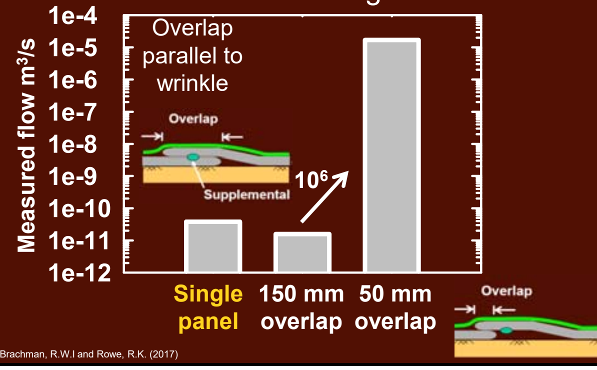
Shrinkage

Maximum reduction in overlap – Base



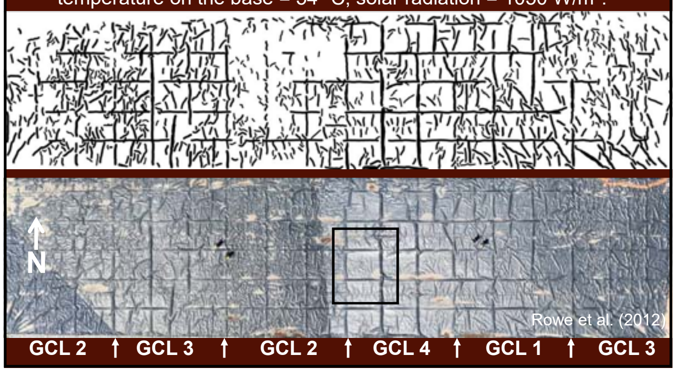
Shrinkage

Measured leakage



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.



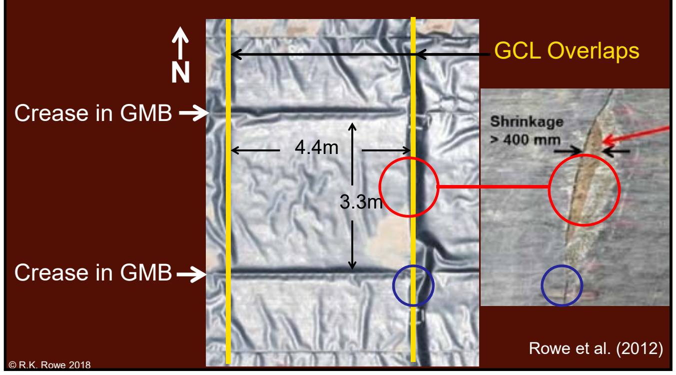
Shrinkage

Consider interaction between system and climate

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**

GMB Wrinkles on Base QUELTS



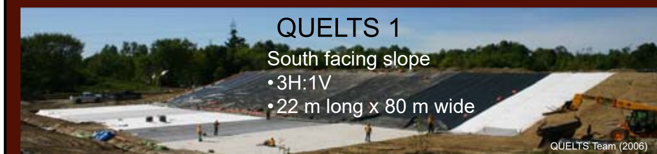
Queen's University Environmental Liner Test Sit QUELTS

QUELTS Team (2006)

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

[44:30]

Queen's U. Environmental Liner Test Site



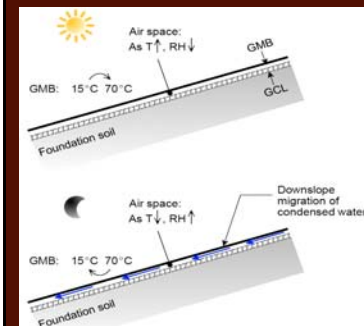
Base: 3% grade to south; 20 m long x 80 m wide; 6 sections

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)

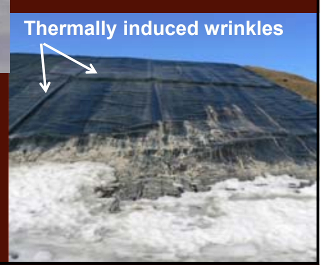
Moisture cycle from thermal cycle when exposed



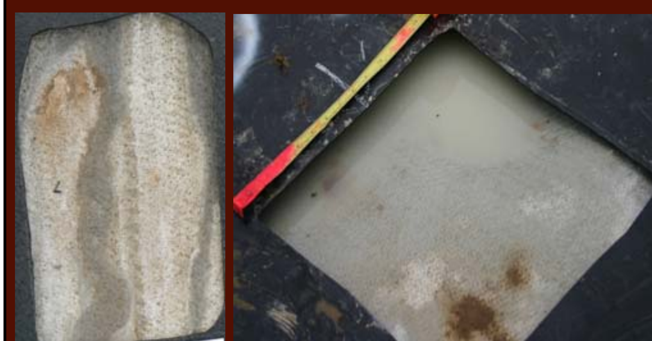
- GCL hydrates with moisture from subsoil
- on heating:
  - GCL loses moisture to GMB/GCL interface
  - vapour migrates towards wrinkles
- on cooling:
  - vapour condenses on underside of GMB
  - condensed moisture trickles downslope

Differential exposure

Black GMB get hot; even when partly snow covered



The first hint of a problem QUELTS I

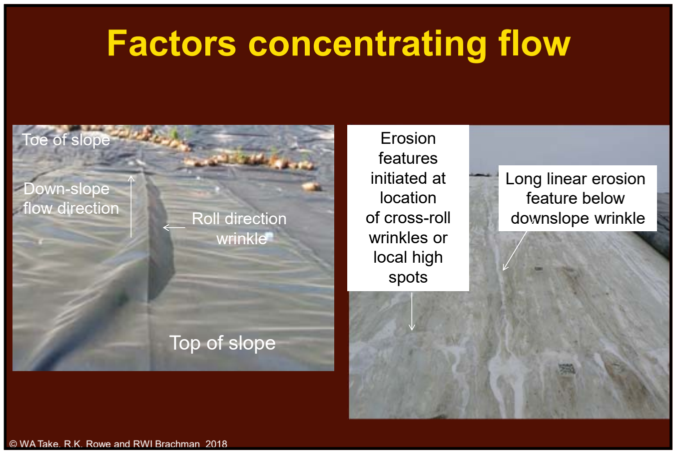


Wrinkles

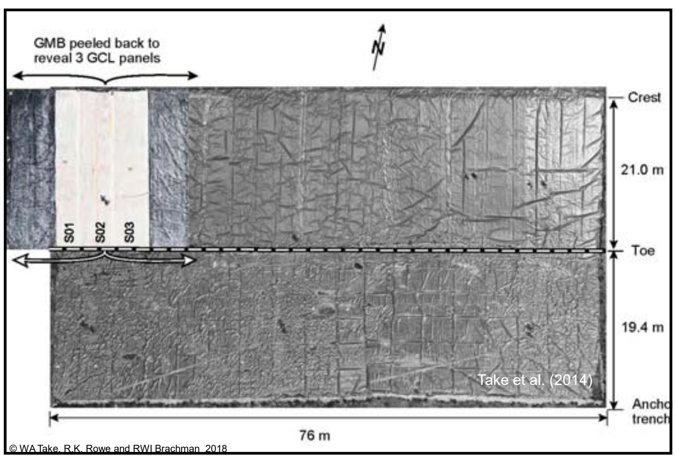
Early morning – no thermally induced wrinkles

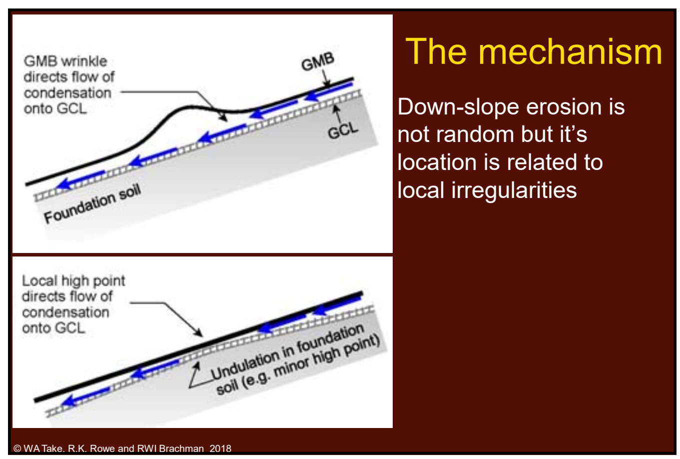
Later in partially cloudy day Many thermally induced wrinkles

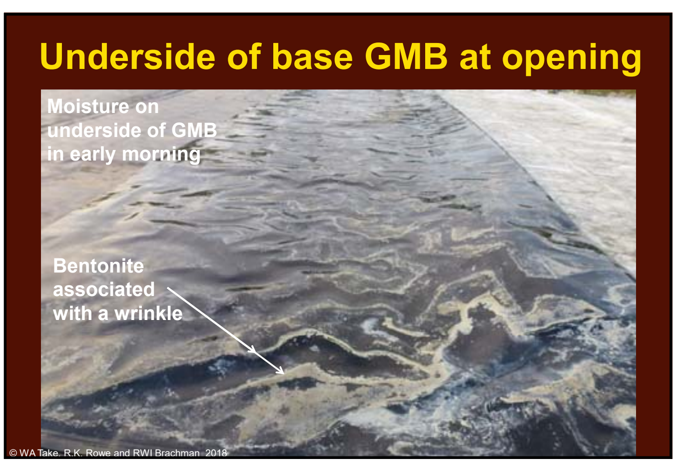
A bigger clue


Factors concentrating flow
Toe of slope
Down-slope flow direction
Roll direction wrinkle
Top of slope
Erosion features initiated at location of cross-roll wrinkles or local high spots
Long linear erosion feature below downslope wrinkle
© WA Take, R.K. Rowe and RWI Brachman 2018


Bentonite: underside of slope GMB
Dried bentonite trail on underside of GMB
© WA Take, R.K. Rowe and RWI Brachman 2018

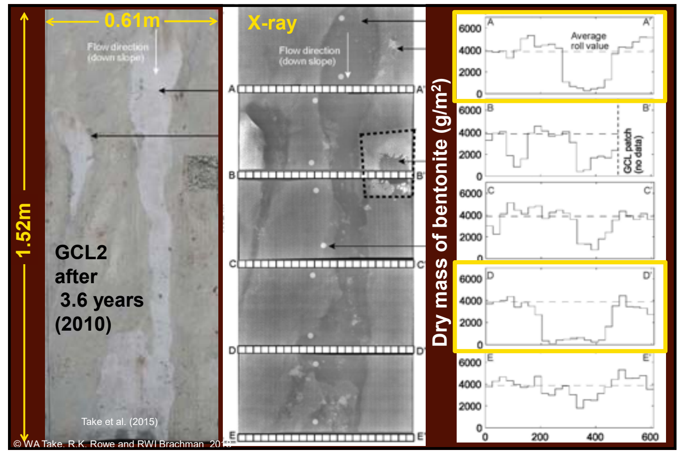

GMB peeled back to reveal 3 GCL panels
N
Crest
21.0 m
S01
S02
S03
Toe
19.4 m
Take et al. (2014)
Ancho trench
76 m
© WA Take, R.K. Rowe and RWI Brachman 2018


The mechanism
GMB wrinkle directs flow of condensation onto GCL
GMB
GCL
Foundation soil
Local high point directs flow of condensation onto GCL
Undulation in foundation soil (e.g. minor high point)
Down-slope erosion is not random but it's location is related to local irregularities
© WA Take, R.K. Rowe and RWI Brachman 2018

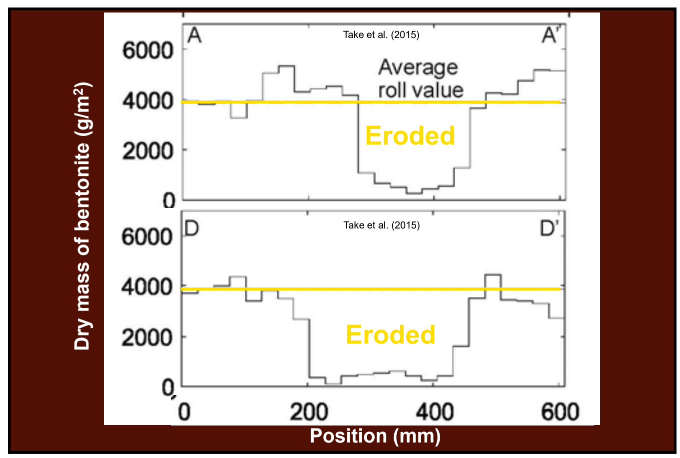

Underside of base GMB at opening
Moisture on underside of GMB in early morning
Bentonite associated with a wrinkle
© WA Take, R.K. Rowe and RWI Brachman 2018

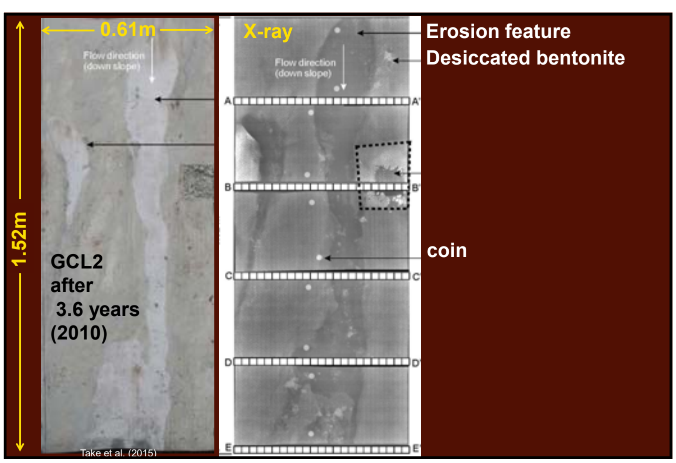

Bentonite at bottom of slope
© WA Take, R.K. Rowe and RWI Brachman 2018


Early morning trail on base
© WA Take, R.K. Rowe and RWI Brachman 2018


0.61m
1.52m
Flow direction (down slope)
GCL2
after
3.6 years
(2010)
Take et al. (2015)
X-ray
A A'
B B'
C C'
D D'
E E'
Dry mass of bentonite (g/m²)
Average roll value
GCL patch (no data)
6000
4000
2000
0
200
400
600
© WA Take, R.K. Rowe and RWI Brachman 2018


When geomembrane was removed
after 3.6 years
Eroded locations
Direction down-slope water flow
Bentonite on subsoil below eroded zone
Take et al. (2015)

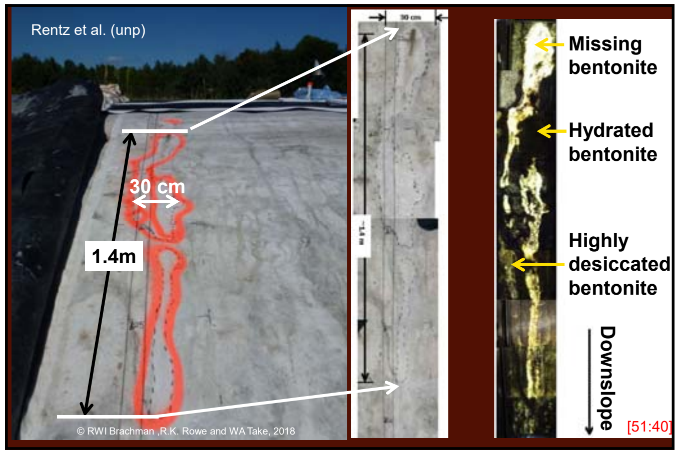

Dry mass of bentonite (g/m²)
A
A'
Take et al. (2015)
Average roll value
Eroded
D
D'
Take et al. (2015)
Eroded
6000
4000
2000
0
0
200
400
600
Position (mm)


0.61m
1.52m
Flow direction (down slope)
GCL2
after
3.6 years
(2010)
Take et al. (2015)
X-ray
A A'
B B'
C C'
D D'
E E'
Erosion feature
Desiccated bentonite
coin


Erosion of a patch in 1 year
Take et al. (2015)
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

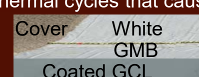


Features on slope and base

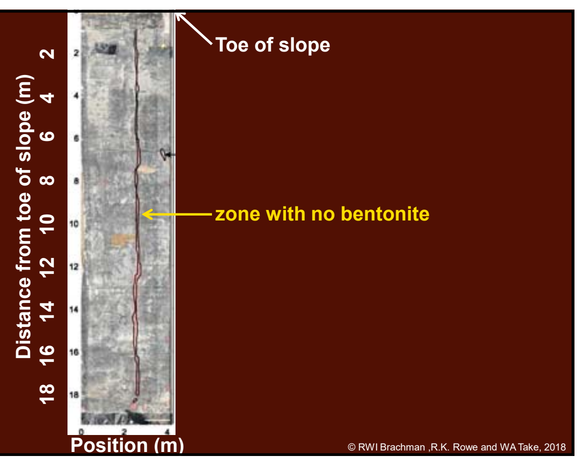
- more features detected on slope than base
- after 4.7 years, most significant feature on base was:
  - maximum 50 mm wide, nearly 20 m long
- features big enough such that they will not heal from swelling or stress effects once covered

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



© R.K. Rowe 2018



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

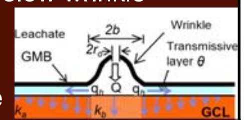
  leakage becomes very large (controlled by Bernoulli's equation
- Probability of this becomes much higher as the number of buried wrinkles increases since winkles may be
  - both perpendicular and parallel & directly over overlaps
  - aligned with location of downslope erosion

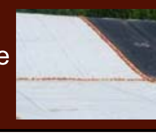
Avoiding excessive leakage

- 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^{o}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

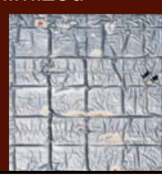




Conclusions

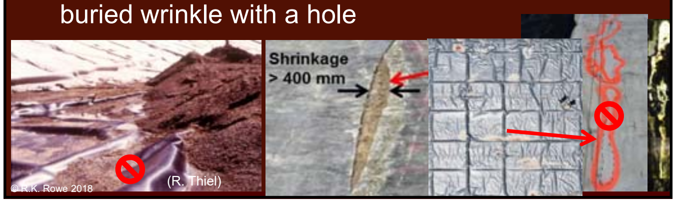
- Nature of required liner depends on level of acceptable leakage
- Leakage can be substantially reduced by a composite liner
- Wrinkles/waves will increase leakage for composite liners and should be minimized


(K. Embree)



Conclusions

- Cover composite liners in a timely manner (or wrinkles contribute to problems with CCL or GCL)
  - desiccation of CCLs
  - shrinkage for some GCL
  - downslope erosion of some GCLs
- All or which become critical if intersected by a buried wrinkle with a hole

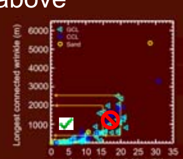


(R. Thiel)

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



Acknowledgements

Queen's-RMC Colleagues: R. Brachman,R. A. Take, G. Siemens

PDFs: Drs. N. Arnepalli, E. Safari. P. Yang

PhD Students: M. Chappel, A. Rentz

MSc Students: L. Ashe, R. Beddoe, L. Bostwick

Natural Sciences and Engineering Research Council of Canada

Terrafix Geosynthetics
Naue GmbH
Solmax/GSE International
Rick Thiel

All comments in this lecture are those of the speaker and are not necessarily shared by any of those listed above

References – Leakage and Overlaps

Beck, A. (2015) "Available Technologies to Approach Zero Leaks", Geosynthetics 2015, Polrtland, 10pp.

Brachman, R.W.I., Rowe, R.K. and Take, W.A. (2018) "Reductions in GCL overlap beneath an exposed geomembrane" ASCE Journal of Geotechnical and Geoenvironmental Engineering, (In press)

Brachman, R.W.I, Joshi, P., and Rowe, R.K. (2016) "Hydraulic performance of overlapped geosynthetic clay liner seams requiring field-applied supplemental bentonite" ASCE Journal of Geotechnical and Geoenvironmental Engineering, 142 (12): 4016067-1 to 11; DOI: 10.1061/(ASCE)GT.1943-5606.0001566

Giroud, J.P. (2016) "Leakage Control using Geomembrane Liners", Soils and Rocks 39(3): 213-235.

Joshi, P., Brachman, R.W.I and Rowe, R.K. (2017) "Hydraulic performance of GCL seams without field-applied supplemental bentonite below a geomembrane wrinkle", ASCE Journal of Geotechnical and Geoenvironmental Engineering, 143(9): 04017086-1 to 10, doi/10.1061/(ASCE)GT.1943-5606.0001756

Joshi, P., Rowe, R.K. and Brachman, R.W.I (2017) "Hydraulic performance of GCL seams with factory-applied powered bentonite below a geomembrane wrinkle" Environmental Geotechnics, http://dx.doi.org/10.1680/jenge.16.00027

Rowe, R.K., Brachman, R.W.I. and Take, W.A. (2018) "Field measurements of overlap reductions for two reinforced fabric-encased GCLs" Canadian Geotechnical Journal, 55(5): 631-639. https://doi.org/10.1139/cgj-2017-0375

Effect of Wrinkles on Geomembrane Performance

R. Kerry Rowe

Professor and Canada Research Chair in Geotechnical and Geoenvironmental Engineering, Queen's University

Kingston

Canada

www.geoeng.ca

The GeoEngineering Centre at Queen's-RMC

Queen's University

References - Winkles

Chappel, M.J., Brachman, R.W.I., Take, W.A. and Rowe, R.K. (2012). "Large-scale quantification of wrinkles in a smooth, black, HDPE geomembrane", ASCE J. Goetech. Geoenvir. Eng., 138 (6): 671-679.

Chappel, M.J., Rowe, R.K., Brachman, R.W.I. and Take, W.A. (2012). "A comparison of geomembrane wrinkles for nine field cases", Geosynthetics International, 19(6): 453-469.

Rentz, A., Brachman, R.W.I, Take, W.A. and Rowe, R.K. (2017) "Comparison of Wrinkles in White and Black HDPE Geomembranes",ASCE J. Goetech. Geoenvir. Eng., 143(8): 04017033-1 to 8

Rowe, R.K. (1998). "Geosynthetics and the minimization of contaminant migration through barrier systems beneath solid waste", 6th International Conference on Geosynthetics, Atlanta, March, 1, pp. 27-103.

Rowe, R.K. (2005). "Long-term performance of contaminant barrier systems", 45th Rankine Lecture, Geotechnique, 55(9):631-678.

Rowe, R.K (2012). "Short and long-term leakage through composite liners", The 7th Arthur Casagrande Lecture", Canadian Geotechnical Journal, 49(2): 141-169. https://doi.org/10.1139/t11-092

Rowe, R.K. (2018) "Protecting the environment with geosynthetics: Successes and challenges", 53rd Karl Terzaghi Lecture, paper in preparation

Rowe, R.K., Chappel, M.J., Brachman, R.W.I. and Take, W.A. (2012). "Field monitoring of geomembrane wrinkles at a composite liner test site", Canadian Geotechnical Journal, 49(10): 1196-1211.

Rowe, R.K., Yang, P., Chappel, M.J., Brachman, R.W.I. and Take, W.A. (2012). "Wrinkling of a geomembrane on a compacted clay liner on a slope", Geotechnical Engineering, Journal of the South East Asian Geotechnical Society, 43(3): 11-18.

Take, W.A., Chappel, M.J., Brachman, R.W.I. and Rowe, R.K. (2007). "Quantifying geomembrane wrinkles using aerial photography and digital image processing", Geosynthetics International, 14(4) 219-227.

References- Down-slope Erosion

Brachman, R.W.I., Rentz, A., Rowe, R.K. and Take W.A.(2015) "Classification and quantification of downslope erosion from a GCL when covered only by a black geomembrane", Canadian Geotechnical Journal, 52(4): 395-412 (10.1139/cgj-2014-0241)

Rentz, A., Take W.A., Brachman, R.W.I. and Rowe, R.K., (2016) "Effect of geomembrane colour and cover soil on solar-driven down slope bentonite erosion from a GCL", Geosynthetics International, 23(4): 257–270. http://dx.doi.org/10.1680/jgein.15.00050

Rowe, R.K., Ashe, L.E., Take W.A., and Brachman, R.W.I. (2014) "Factors affecting the down-slope erosion of bentonite in a GCL", Geotextiles and Geomembranes, 42(5): 445-456 http://dx.doi.org/10.1016/j.geotexmem.2014.07.002

Rowe, R.K., Brachman, R.W.I, Take, W.A, Rentz, A. and Ashe, L.E., (2016) "Field and laboratory observations of down-slope bentonite migration in exposed composite liners", Geotextiles and Geomembranes, 44(5): 686-706, http://dx.doi.org/10.1016/j.geotexmem.2016.05.004

Rowe, R.K., Rentz, A., Brachman, R.W.I. and Take W.A.(2016) "Effect of GCL type on down-slope bentonite erosion in an exposed liner", ASCE Journal of Geotechnical and Geoenvironmental Engineering, 142(12) 4016074-1 to 10; DOI: 10.1061/(ASCE)GT.1943-5606.0001565

Take, W.A., Brachman, R.W.I., and Rowe, R.K. (2015). "Observations of bentonite erosion from solar-driven moisture migration in GCLs covered only by a black geomembrane", Geosynthetics International, 22(1): 78-92.

Take, W.A., Rowe, R.K, Brachman, R.W.I., and Arnepalli, D.N. (2015). "Thermal exposure conditions for a composite liner with a black geomembrane exposed to solar radiation", Geosynthetics International, 22(1): 93-109.