Short Course on

GEOMEMBRANES AND COMPOSITE LINERS IN LANDFILLS AND MINING: MOVING FORWARD

Sunday 17 Sept. 2023

2. Leakage through liners

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Geomembranes

- Essentially impermeable –
  - unless they have holes

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Short-term processes that can increase fluid ingress or egress

- Greatest short-term risk is due to hole formation:
  - During construction - minimized by good design, CQC/CQA
  - Due to activities above completed liner
  - Possibly due to animals (e.g., rodents, bears)

  \- both minimized by good design and site-use restrictions
  - Caused by excessive differential settlement
  - Due to nature of materials above/below GMB and applied pressures

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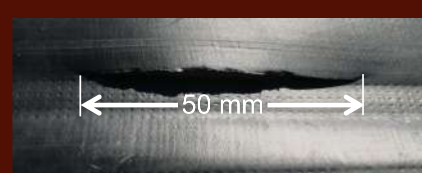
Constrction-related holes in GMB

- 2.5 – 10 holes/ha typical design value
- 3 holes/ha after installation*
- 12 holes/ha after placement of drainage layer*
- 5 holes/ha assumed in presentation
- Median equivalent radius – 5.6mm (typical)



* Nosko & Touze-Foltz (2000)

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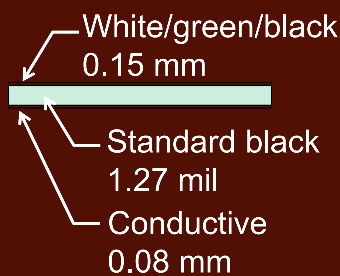
Spark testing

1.5mm Conductive white GMB



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Holes in Geomembranes (GMBs)

To minimize holes in geomembranes (GMBs) need:

- High-quality CQA ,and
- Leak detection
  - Puddle method: exposed GMB detect holes ≥ 1 mm

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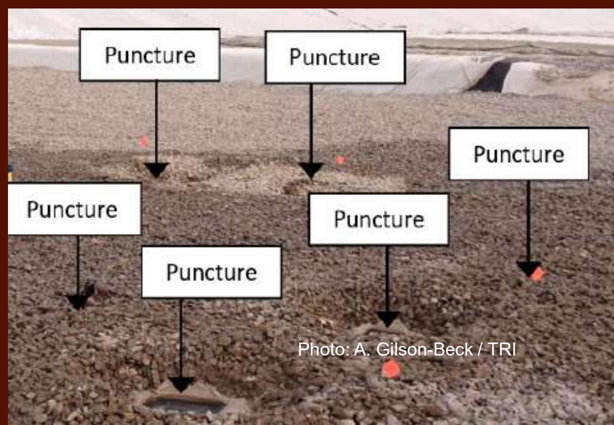
Geomembranes (GMBs)

- Holes in geomembranes occur
  - during installation (mostly eliminated by good CQA)
  - with placement of cover soil over the GMB there can be >20 holes/ha (Giroud 2017)



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Bituminous Geomembranes (BGMs)

(Bremner et al. 2016)

- 230,600 m^2 of BGM + soil used to cover tailings and waste rock in Canada
- 39 holes/ha (5 mm to 150 mm diameter) in 2011
- 18.4 holes/ha in 2012

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Holes in Geomembranes (GMBs)

Locating holes in geomembranes (GMBs) need:

- High-quality CQA ,and
- Leak detection
  - Puddle method: exposed GMB detect holes ≥ 1 mm

- Double Dipole Survey:
  - Water covered GMB
  - Soil covered GMB detect holes ≥ 6 mm under 0.6 m soil

[:0]

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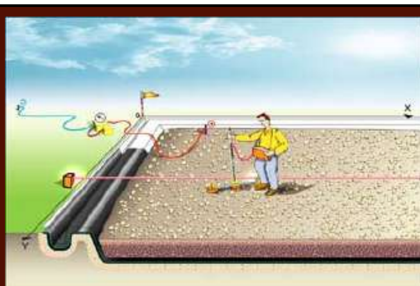
Leak detection survey



Source: Darilek and Laine (2007)

- electrically conductive medium above and below GMB
  - wet gravel or geotextile over GMB
- induce voltage difference between top and bottom
- passed electrodes over top to measure electrical potential
- anomalies in electrical potential indicate holes in GMB
  - caused by flow of current along conductive path through the hole

ASTM D7002 or D7007

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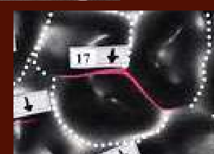
Geomembranes (GMBs)

- Holes in geomembranes occur
  - during installation (mostly eliminated by good CQA)
  - with placement of cover soil (may be detected & eliminated)
  - post-construction (shorter- and longer-term))

Short-term puncture

Longer-term stress crack



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Puncture and excessive strain due to applied pressures

- Short-term puncture
- Strains generate longer-term failure
- Vertical pressure ≤ 3000 kPa

Geosynthetic liner longevity simulator GLLS

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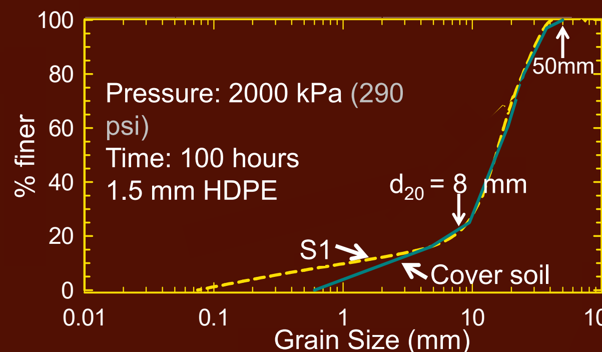
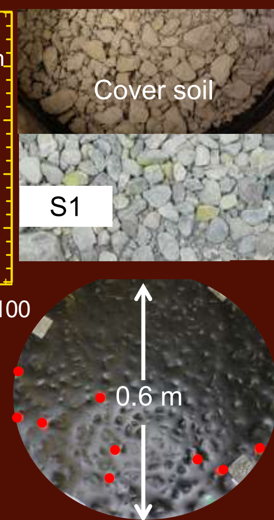
Effect of subgrade grain size





Subgrade	GMB	Holes	Hole/ha
S1	HDPE	9	320,000

Holes adjacent to red dots

Rowe, Brachman, Irfan, Smith & Thiel (2013)

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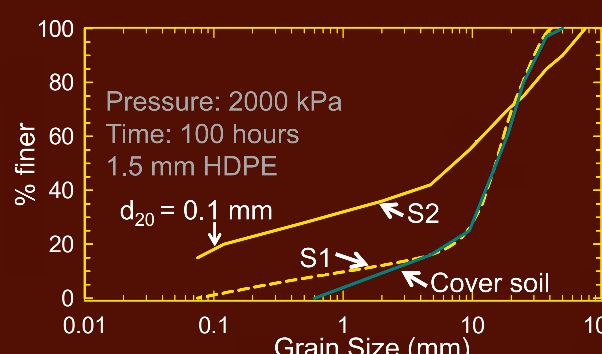
Effect of subgrade grain size



Subgrade	GMB	Holes	Hole/ha
S1	HDPE	9	320,000
S2	HDPE	5	180,000

Rowe, Brachman, Irfan, Smith & Thiel (2013)

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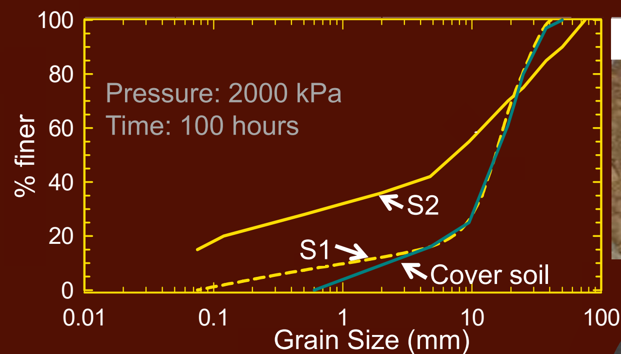
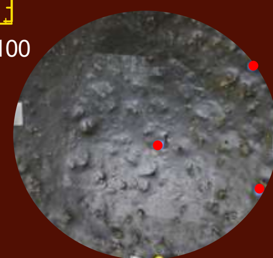
Effect of subgrade grain size





Subgrade	GMB	Holes	Hole/ha
S1	HDPE	9	320,000
S2	HDPE	5	180,000
S2	LLDPE	3	110,000

Rowe, Brachman, Irfan, Smith & Thiel (2013)

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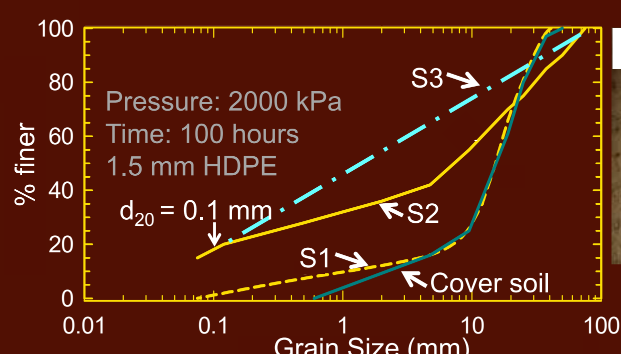
Effect of subgrade grain size



Subgrade	GMB	Holes	Hole/ha
S1	HDPE	9	320,000
S2	HDPE	5	180,000
S3	HDPE	0	0

→ BUT: short-term strains ≈13%

Rowe, Brachman, Irfan, Smith & Thiel (2013)

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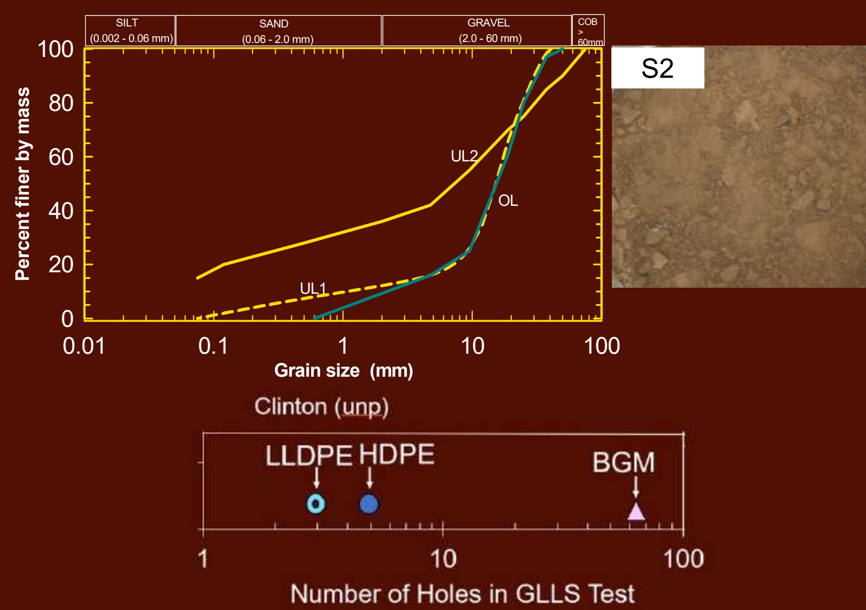
Effect of GMB



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Post-construction hole summary

- Isolated stones in finer grained subgrade may be worse than packed gravel
- Puncture likely when with a coarse gap graded cover soil and subgrade
- Even if no puncture with coarse cover soil (and finer subgrade), short-term strains ≈13%
- Shape of the grading curve of soil adjacent to GMB has a much greater effect on puncture and strains than the maximum particle size

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GMB thermally induced wrinkles/waves
Subgrade
Geomembrane (GMB)
Geosynthetic clay liner (GCL)
GMB T ≈ 45 °C
(110 °F)
SAME GMB with wrinkles a few hours later when ambient T = 17 °C
(63 °F)
Rowe, Chappel, Brachman & Take (2012)

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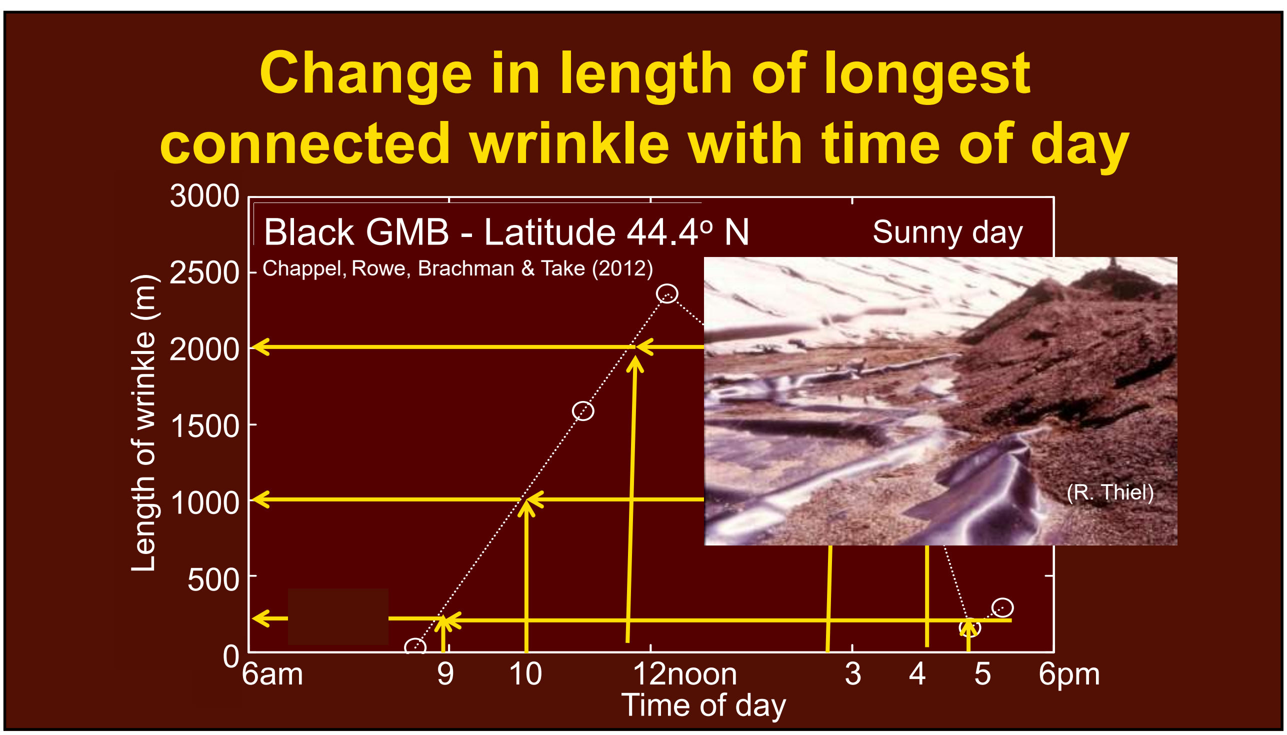
Change in length of longest connected wrinkle with time of day
Black GMB - Latitude 44.4° N
Sunny day
Chappel, Rowe, Brachman & Take (2012)
Length of wrinkle (m)
3000
2500
2000
1500
1000
500
0
6am
9
10
12noon
3
4
5
6pm
Time of day
(R. Thiel)

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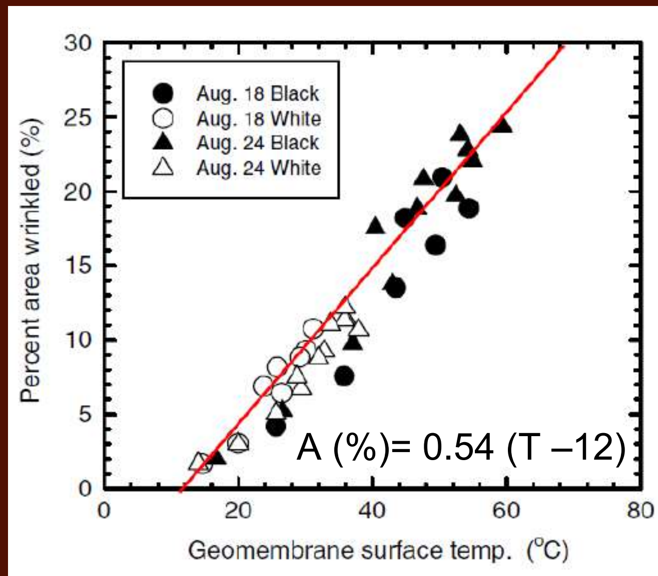
Effect of GMB Colour on Wrinkles



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Covered Wrinkles get Holes

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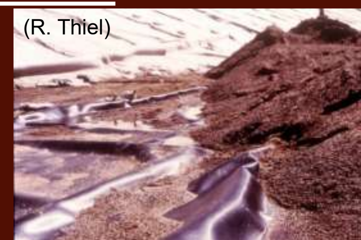
Probability of a holed-wrinkle
(Good CQA but no ELLS)

Wrinkle length (m)	Probability (%)
≥ 100	70
≥ 200	50
≥ 500	15
≥ 1000	4



(Based on New York leakage data; Beck 2015) Rowe (2018)

Message: You will grossly underestimate leakage if you do not consider holes in wrinkles

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How to decrease the number of wrinkles in your liner?

- Cover the GMBs early in the morning
- Use white GMB

What are the consequences of having too many wrinkles in your liner?

- Increased leakage
- Stress cracking

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Warning

- The material presented is not complete in and of itself; it is intended only to provide direction aNd examples. Examine published sources for more complete information.
- The reader is responsible for assessing the relevance and usefulness for any project
- Typical ranges are for typical conditions - many non-typical conditions exist.
- Average or typical values may have 50% above and 50% below

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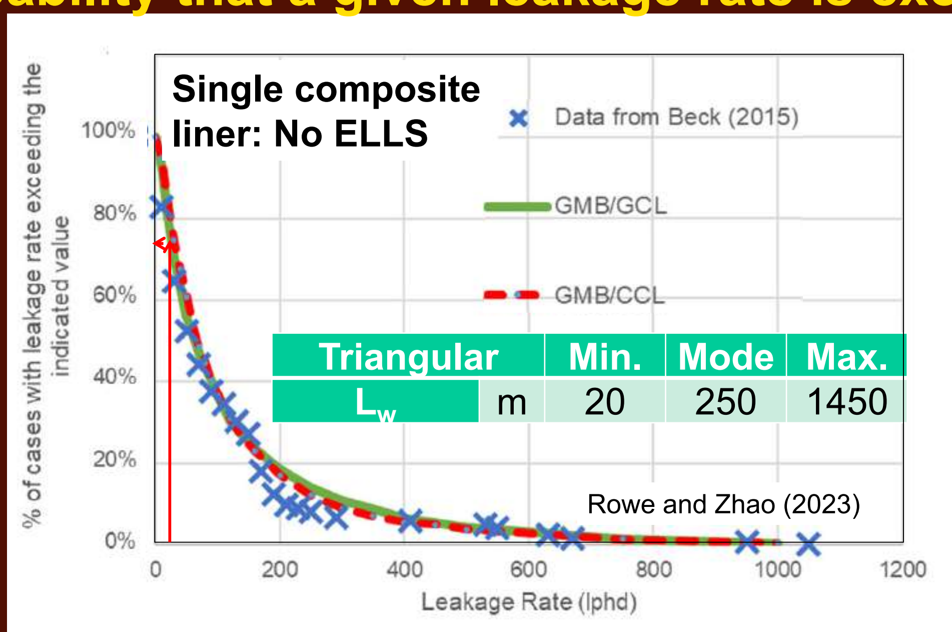
Probability that a given leakage rate is exceeded



Triangular		Min.	Mode	Max.
L_w	m	20	250	1450

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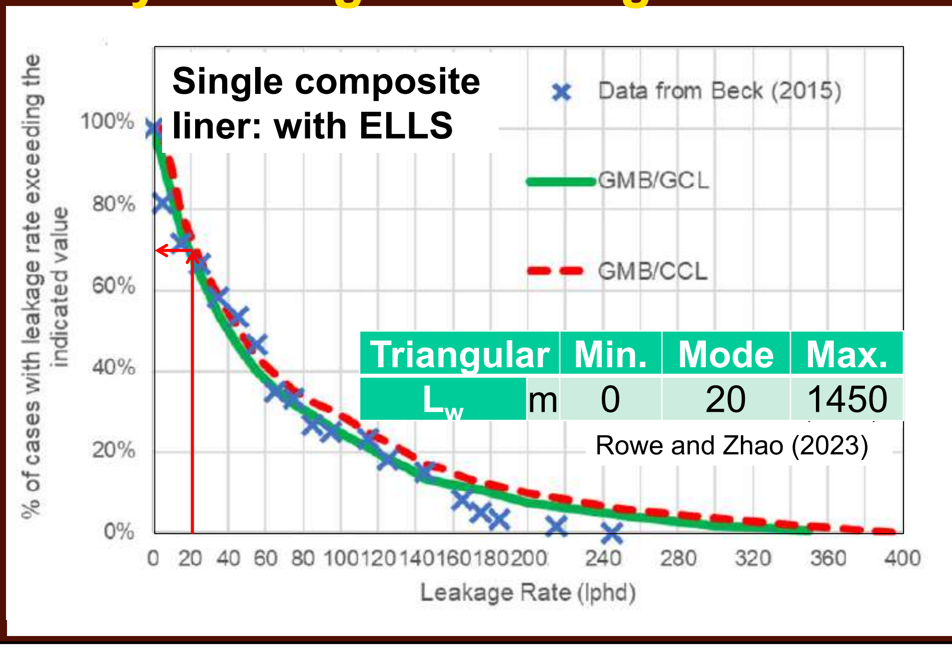
Probability that a given leakage rate is exceeded



Triangular		Min.	Mode	Max.
L_w	m	0	20	1450

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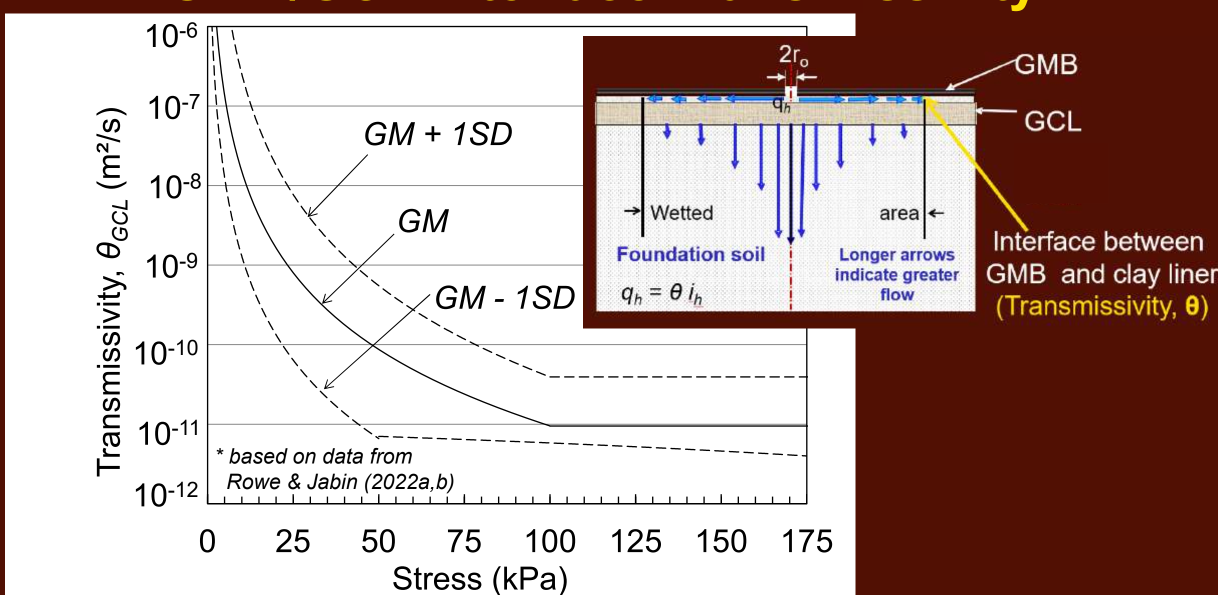
GMB/GCL Interface Transmissivity



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Example liner parameters	σ_{va} < 5 kPa Pond [1]	σ_{va} ~ 15 kPa Cover [2]	σ_{va} ≥ 150 kPa bottom liner[3]
Head on liner, h (m)	5	0.15	0.2
Hole area, a (mm^2)	100	100	100
Holed wrinkle length, L_w (no ELLS) (m)	530	530	530
Holed wrinkle length, L_w (ELLS) (m)	430	430	430
Holed wrinkle average width, 2b (m)	0.2	0.2	0.1
Liner thickness, GCL, H_{GCL} (m)	0.015	0.01	0.007
Hydraulic conductivity below wrinkle, k_{bGCL} (m/s)	2×10^{-10}	6×10^{-8} to 2×10^{-10}	6×10^{-8} to 2×10^{-10}
Hydraulic conductivity below wrinkle, k_{aGCL} (m/s)	5×10^{-11}	2×10^{-10}	3×10^{-11}
Hydraulic conductivity MGCL, k_{GCL} (m/s)	5×10^{-11}	5×10^{-11}	5×10^{-11}
GMB/GCL interface transmissivity, θ_{GCL} (m^2/s)	1×10^{-8}	3×10^{-9}	3×10^{-11}
Liner thickness, CCL, H_{GCL} (m)	0.6	0.6	0.6
Hydraulic conductivity below wrinkle, k_{CCL} (m/s)	1×10^{-9}	1×10^{-8}	2×10^{-10}
GMB/GCL interface transmissivity, θ_{CCL} (m^2/s)	1×10^{-6}	1×10^{-7}	2×10^{-9}

[1] Submerged and about 0.3 m cover soil; [2] About 1 m cover soil; [3] MSW Landfill about 0.3 m gavel drainage layer.

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Leakage through a clay liner alone

1. Darcy's law $Q = A\,k\,h/H$ *A=area (m^2) , h =head (m), H= thickness (m)*

	σ_{va} < 5 kPa Pond [1]	σ_{va} ~ 15 kPa Cover [2]	σ_{va} ≥ 150 kPa bottom liner[3]
Head on liner, h (m)	5	0.15	0.2
Liner thickness, GCL, H_{GCL} (m)	0.015	0.01	0.007 m
Hydraulic conductivity normal GCL, k_{GCL} (m/s)	2×10^{-10}	6×10^{-8} m/s	2×10^{-10} m/s
Leakage with Darcy Equation (lphd)	57,800	829,000	5,100
Hydraulic conductivity MGCL, k_{GCL}	5×10^{-11} m/s	5×10^{-11} m/s	5×10^{-11} m/s
Leakage with Darcy Equation (lphd)	14,400	700	1300
Liner thickness, CCL, H_{GCL}	0.6 m	0.6 m	0.6 m
Hydraulic conductivity k_{CCL}	1×10^{-9} m/s	1×10^{-8} m/s	2×10^{-10} m/s
Leakage with Darcy Equation (lphd)	8,000	11,000	230

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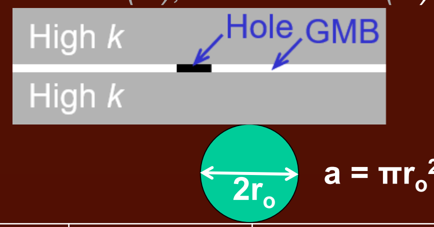
Leakage through a geomembrane defect

1. Darcy's law $Q = A\,k\,h/H$ *A=area (m²) , h =head (m), H= thickness (m)*
2. Bernoulli's equation *a= area of hole (m²)*

   $Q = 2.6\,a\,\sqrt{h}$ h = head (m)

   Q= leakage (m³/s)



	σ_{va} < 5 kPa Pond [1]	σ_{va} ~ 15 kPa Cover [2]	σ_{va} ≥ 150 kPa bottom liner[3]
Head on liner, *h* (m)	5	0.15	0.2
Leakage with Darcy Equation, **MGCL** alone (lphd)	14,400	700	1,300
Leakage with Darcy Equation, **CCL** alone (lphd)	8,000	11,000	230
Hole area, a (mm²)	100	100	100
Leakage from Bernoulli's Eq. Q (lphd)	51,000	8,900	10,300

Maximum leakage possible through this hole in a wrinkle

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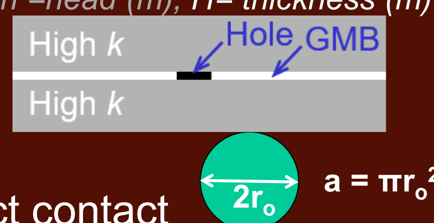
Leakage through a geomembrane defect

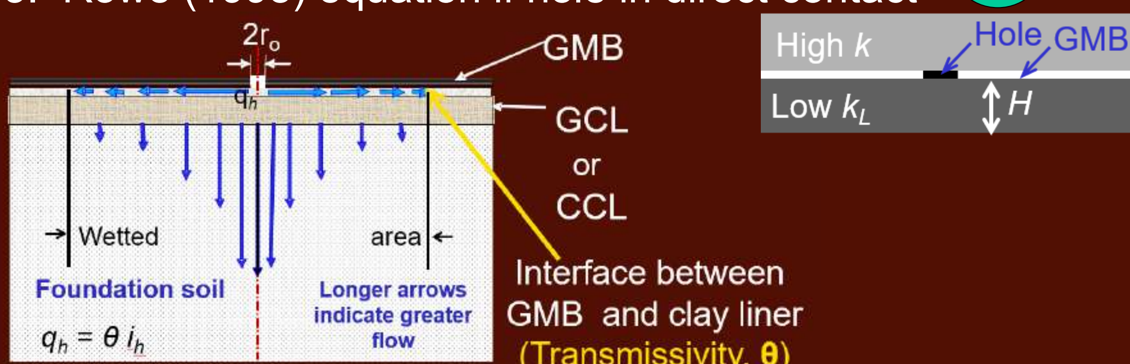
1. Darcy's law $Q = A\,k\,h/H$ *A=area (m²) , h =head (m), H= thickness (m)*
2. Bernoulli's equation *a= area of hole (m²)*

   $Q = 2.6\,a\,\sqrt{h}$ h = head (m)

   Q= leakage (m³/s)



3. Rowe (1998) equation if hole in direct contact



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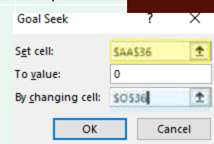
Rowe (1998) equation if hole in direct contact

Spread sheet: Data > what-if analysis>goal seek (dh/dr, 0, R)

Input	Input	Input	Input	Input	$O	Output	$AA
Hole radius r_o (m)	Permeability of liner k_L (m/s)	Thickness of Liner H_L (m)	h_w (m)	θ (m^2/s)	Wetted radius R (m)	$Q_{calculated}$ (L/d)	dh/dr
0.005642	5.00E-11	0.015	5	1.00E-08	7.544	4.667	0.00
0.005642	2.00E-10	0.015	5	1.00E-08	3.804	5.268	0.00
0.005642	2.00E-10	0.01	0.15	3.00E-09	0.808	0.059	0.00
0.005642	6.00E-08	0.01	0.15	3.00E-09	0.065	0.166	0.00
0.005642	3.00E-11	0.007	0.2	3.00E-11	0.243	0.001	0.00
0.005642	3.00E-11	0.007	0.2	3.00E-11	0.243	0.001	0.00
0.005642	1.00E-09	0.6	5	1.00E-06	31.452	560.33	0.00
0.005642	1.00E-08	0.6	0.15	1.00E-07	0.814	3.60	0.00
0.005642	2.00E-10	0.6	0.2	2.00E-09	0.919	0.092	0.00



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	σ_{va} < 5 kPa Pond [1]	σ_{va} ~ 15 kPa Cover [2]	σ_{va} ≥ 150 kPa bottom liner[3]
Head on liner, *h* (m)	5	0.15	0.2
Leakage with Darcy Equation, **MGCL** alone (lphd)	14,400	700	1,300
Hole area, a (mm^2)	100	100	100
Leakage from Bernoulli's Eq. Q (lphd)	51,000	8,900	10,300
Liner thickness, *GCL*, H_{GCL} (m)	0.015	0.01	0.007
Hydraulic conductivity, k_{GCL} (m/s)	2×10^{-10}	6×10^{-8}	3×10^{-11}
GMB/GCL interface transmissivity, θ_{GCL} (m^2/s)	1×10^{-8}	3×10^{-9}	3×10^{-11}
Leakage with Rowe (1998) Equation for DC (lphd)	≤ 5.3	< 0.2	0.001
Liner thickness, CCL, H_{GCL} (m)	0.6	0.6	0.6
Hydraulic conductivity below wrinkle, k_{CCL} (m/s)	1×10^{-9}	1×10^{-8}	2×10^{-10}
GMB/GCL interface transmissivity, θ_{CCL} (m^2/s)	1×10^{-6}	1×10^{-7}	2×10^{-9}
Leakage with Rowe (1998) Equation (lphd)	560	3.6	0.09

[1] Submerged and about 0.3 m cover soil; [2] About 1 m cover soil; [3] MSW Landfill about 0.3 m gavel drainage layer.

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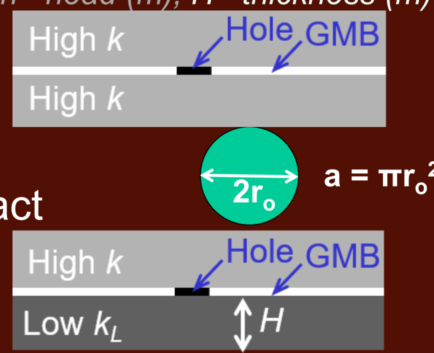
Leakage through a geomembrane defect

1. Darcy's law $Q = A\,k\,h/H$ *A=area (m²), h =head (m), H= thickness (m)*
2. Bernoulli's equation $Q = 2.6\,a\sqrt{h}$ *a= area of hole (m²)*; h = head (m); Q= leakage (m³/s)



4. Giroud's (1997) if hole in direct contact

$$Q = C_q\,[1 + 0.1(h/H)^{0.95}]\,a^{0.1}\,h^{0.9}\,k_L^{0.75}$$

- Valid within strict limits
- Most misused equation (outside of limits on hole size and head – see Giroud's paper)
- Assumes direct intimate contact

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	σ_{va} < 5 kPa Pond [1]	σ_{va} ~ 15 kPa Cover [2]	$\sigma_{va} \geq$ 150 kPa bottom liner[3]
Head on liner, h (m)	5	0.15	0.2
Leakage with Darcy Equation, **MGCL** alone (lphd)	14,400	700	1300
Leakage with Darcy Equation, **CCL** alone (lphd)	8,000	11,000	230
Hole area, a (mm²)	100	100	100
Leakage from Bernoulli's Eq. Q (lphd)	51,000	8,900	10,300
Liner thickness, GCL, H_{GCL} (m)	0.015	0.01	0.007 m
Hydraulic conductivity, k_{GCL} (m/s)	2×10^{-10}	6×10^{-8}	3×10^{-11}
GMB/GCL interface transmissivity, θ_{GCL} (m²/s)	1×10^{-8}	3×10^{-9}	3×10^{-11}
Leakage with Rowe (1998) DC Eq. (lphd)	≤ 5.3	< 0.2	0.001
Leakage with Giroud (1997) DC Eq.(lphd)	na	14	0.06
Liner thickness, CCL, H_{GCL} (m)	0.6 m	0.6 m	0.6 m
Hydraulic conductivity below wrinkle, k_{CCL} (m/s)	1×10^{-9} m/s	1×10^{-8} m/s	2×10^{-10} m/s
GMB/GCL interface transmissivity, θ_{CCL} (m²/s)	1×10^{-6} m²/s	1×10^{-7} m²/s	2×10^{-9} m²/s
Leakage with Rowe (1998) DC Eq. (lphd)	560	3.6	0.09
Leakage with Giroud (1997) DC Eq. (lphd)	na	1.6(g)-8.9(p)	0.4(g)

[1] Submerged and about 0.3 m cover soil; [2] About 1 m cover soil; [3] MSW Landfill about 0.3 m gravel drainage layer.

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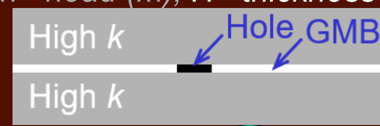
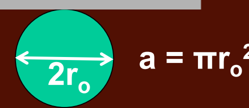
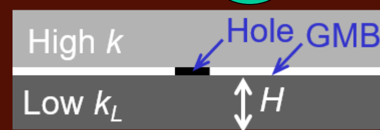
Leakage through a geomembrane defect

1. Darcy's law $Q = A\,k\,h/H$ A=area (m²), h =head (m), H= thickness (m)
2. Bernoulli's equation $Q = 2.6\,a\sqrt{h}$ a= area of hole (m²), h = head (m), Q= leakage (m³/s)



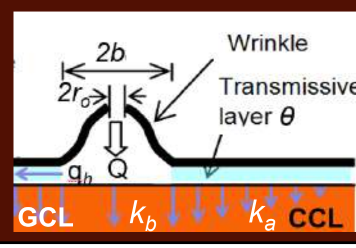


4. Giroud's equation if hole in direct contact $Q = C_q\,[1+ 0.1(h/H)^{0.95}]\, a^{0.1}\, h^{0.9}\, k_L^{0.75}$



5. Rowe's equation if hole in a wrinkle $Q = L\,[2b\,k_b + 2(k_a H\,\theta)^{0.5}]\,h/H$

No ELLS



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Example parameters – GCL	σ_{va} < 5 kPa Pond [1]	σ_{va} ~ 15 kPa Cover [2]	σ_{va} ≥ 150 kPa bottom liner[3]
Head on liner, *h* (m)	5	0.15	0.2
Hole area, a (mm²)	100	100	100
Holed wrinkle length, L_w (no ELLS) (m)	**530**	530	530
Holed wrinkle average width, 2b (m)	0.2	0.15	0.1
Leakage from Bernoulli's Eq. Q (lphd)	**51,000**	**8,900**	**10,300**
Liner thickness, GCL, H_{GCL} (m)	0.015	0.01	0.007
Hydraulic conductivity below wrinkle, k_{bGCL} (m/s)	2×10^{-10}	6×10^{-8} to 2×10^{-10}	6×10^{-8} to 2×10^{-10}
Hydraulic conductivity below wrinkle, k_{aGCL} (m/s)	5×10^{-11}	2×10^{-10}	3×10^{-11}
GMB/GCL interface transmissivity, θ_{GCL} (m²/s)	1×10^{-8}	3×10^{-9}	3×10^{-11}
Leakage with Rowe (1998) DC Eq. (lphd)	≤ 5.3	< 0.2	0.001
Leakage with Rowe (1998) wrinkle Equ. (lphd)	8,700	160 -13,200	60 -16,200
Leakage with Darcy Equation, **MGCL** alone (lphd)	14,400	700	1,300
Hydraulic conductivity of MGCL, k_{GCL} (m/s)	5×10^{-11}	5×10^{-11}	5×10^{-11}
Leakage with Rowe (1998) wrinkle Equ. (lphd)	7,800	67	36

[1] Submerged and about 0.3 m cover soil; [2] About 1 m cover soil; [3] MSW Landfill about 0.3 m gavel drainage layer.

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Example parameters – CCL	***σ_{va} < 5 kPa Pond*** [1]	***σ_{va} ~ 15 kPa Cover*** [2]	***σ_{va} ≥ 150 kPa bottom liner*** [3]
Head on liner, h (m)	5	0.15	0.2
Hole area, a (mm^2)	100	100	100
Holed wrinkle length, L_w (no ELLS) (m)	**530**	530	530
Holed wrinkle average width, 2b (m)	0.2	0.15	0.1
Leakage from Bernoulli's Eq. Q (lphd)	**51,000**	**8,900**	**10,300**
Liner thickness, CCL, H_{GCL} (m)	0.6	0.6	0.6
Hydraulic conductivity below wrinkle, k_{CCL} (m/s)	$1x10^{-9}$	$1x10^{-8}$	$2x10^{-10}$
GMB/GCL interface transmissivity, θ_{CCL} (m^2/s)	$1x10^{-6}$	$1x10^{-7}$	$2x10^{-9}$
Leakage with Darcy Equation, CCL alone (lphd)	8,000	11,000	**230**
Leakage with Rowe (1998) DC Eq. (lphd)	560	3.6	0.09
Leakage with Rowe (1998) wrinkle Equ. (lphd)	21,000	3,000	60

[1] Submerged and about 0.3 m cover soil; [2] About 1 m cover soil; [3] MSW Landfill about 0.3 m gavel drainage layer.

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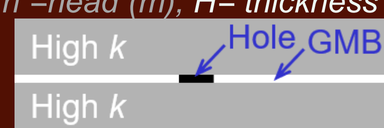
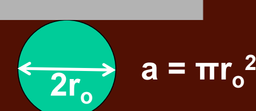
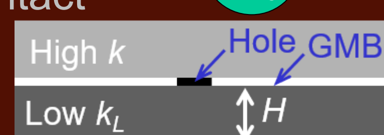
Leakage through a geomembrane defect

1. Darcy's law $Q = A\,k\,h/H$ *A=area (m^2) , h =head (m), H= thickness (m)*
2. Bernoulli's equation *a= area of hole (m^2)*
   $Q = 2.6\,a\,\sqrt{h}$
   h = head (m)
   Q= leakage (m^3/s)



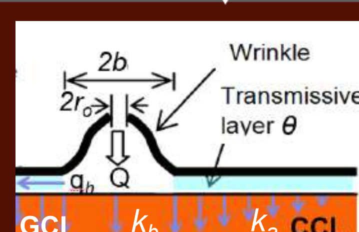


4. Giroud's equation if hole in direct contact
   $Q = C_q\,[1+ 0.1(h/H)^{0.95}]\,a^{0.1}\,h^{0.9}\,k_L^{0.75}$



5. Rowe's equation if hole in a wrinkle
   $Q = L\,[2b\,k_b + 2(k_a\,H\,\theta)^{0.5}]\,h / H$

with ELLS



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Example liner parameters	σ_{va} < 5 kPa Pond [1]	σ_{va} ~ 15 kPa Cover [2]	σ_{va} ≥ 150 kPa bottom liner[3]
Head on liner, *h* (m)	5	0.15	0.2
Hole area, a (mm^2)	100	100	100
Holed wrinkle length, L_w (with ELLS) (m)	**430**	430	430
Holed wrinkle average width, 2b (m)	0.2	0.15	0.1
Leakage from Bernoulli's Eq. Q (lphd)	**51,000**	**8,900**	**10,300**
Liner thickness, GCL, H_{GCL} (m)	0.015	0.01	0.007
Hydraulic conductivity below wrinkle, k_{bGCL} (m/s)	2×10^{-10}	6×10^{-8} to 2×10^{-10}	6×10^{-8} to 2×10^{-10}
Hydraulic conductivity below wrinkle, k_{aGCL} (m/s)	5×10^{-11}	2×10^{-10}	3×10^{-11}
GMB/GCL interface transmissivity, θ_{GCL} (m^2/s)	1×10^{-8}	3×10^{-9}	3×10^{-11}
Leakage with Rowe (1998) direct Equation (lphd)	≤ 5.3	< 0.2	0.001
Leakage with Rowe (1998) wrinkle Equ. (lphd)	7,100	130 -10,800	50 -13,100

[1] Submerged and about 0.3 m cover soil; [2] About 1 m cover soil; [3] MSW Landfill about 0.3 m gavel drainage layer.

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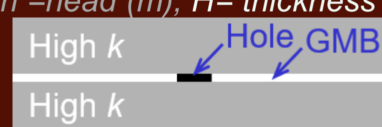
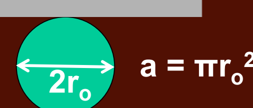
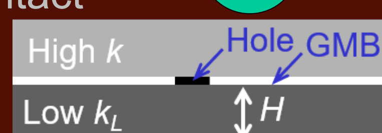
Leakage through a geomembrane defect

1. Darcy's law $Q = A\,k\,h/H$ *A=area (m^2) , h =head (m), H= thickness (m)*
2. Bernoulli's equation *a= area of hole (m^2)*
   $Q = 2.6\,a\,\sqrt{h}$
   h = head (m)
   Q= leakage (m^3/s)





3. Giroud's equation if hole in direct contact
   $Q = C_q\,[1+0.1(h/H)^{0.95}]\,a^{0.1}\,h^{0.9}\,k_L^{0.75}$



4. Rowe's equation if hole in a wrinkle
   $Q = L\,[2b\,k_b + 2(k_a\,H\,\theta)^{0.5}]\,h/H$

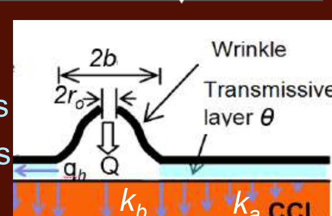
Typical for MSW bottom liners $0.1 \le 2b \le 0.2$ m

$0.007 \le H_{GCL} \le 0.01$ m $6\times10^{-12} \le \theta_{GCL} \le 8\times10^{-11}$ m^2/s

$0.6 \le H_{CCL} \le 1.2$ m $1\times10^{-7} \le \theta_{CCL} \le 3\times10^{-9}$ m^2/s

$2\times10^{-10} \le k_{bGCL} \le 5\times10^{-10}$ m/s $3\times10^{-11} \le k_{aGCL} \le 6\times10^{-11}$ m/s

$1\times10^{-9} \le k_{bCCL} \le 5\times10^{-10}$ m/s $8\times10^{-10} \le k_{bCCL} \le 3\times10^{-10}$ m/s



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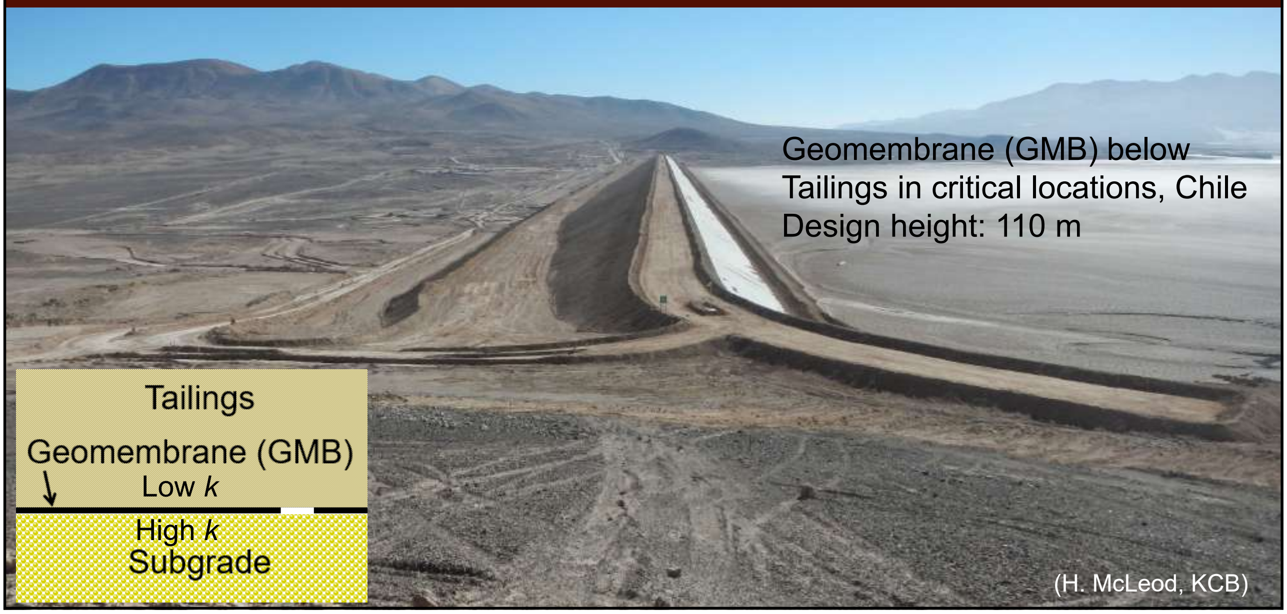
Tailings Storage Facility



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Leakage through a geomembrane defect

1. Darcy's law $Q = A\,k\,h/H$ *A=area (m²) , h =head (m), H= thickness (m)*
2. Bernoulli's equation *a= area of hole (m²)*, *h* = head (m), Q= leakage (m³/s)

   $Q = 2.6\,a\,\sqrt{h}$

4. Giroud's equation if hole in direct contact

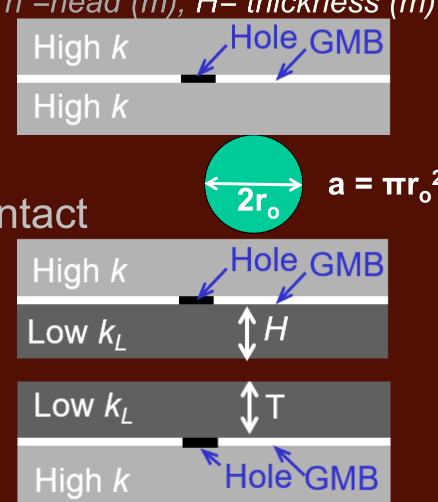
   $Q = C_q\,[1 + 0.1(h/H)^{0.95}]\,a^{0.1}\,h^{0.9}\,k_L^{0.75}$

5. Rowe's equation if hole in a wrinkle

   $Q = L\,[2b\,k_L + 2(k_L\,H\,\theta)^{0.5}]\,h\,/\,H$

6. Rowe and Booker (2000)

$$Q = \{4 + [2.455 + 0.685 \tanh(0.6 \ln (r_o/T))]\, r_o/T\}\, r_o k_L h$$



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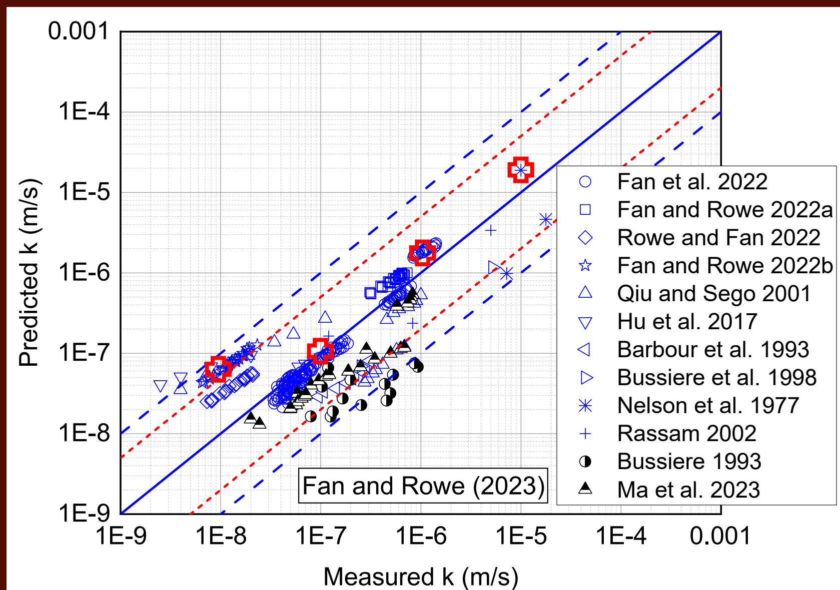
Permeability of tailings



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Leakage through a geomembrane defect in TSF

Head on liner, *h* (m)	**50**	**50**	**50**	**50**	**50**	**50**
Tailings thickness, *H* (m)	48	48	48	48	48	48
Hole area, a (mm^2)	100	100	100	100	100	100
Hydraulic conductivity of tailings at hole, k_T (m/s)	**0**	**$1x10^{-4}$**	**$1x10^{-5}$**	**$1x10^{-6}$**	**$1x10^{7}$**	**$1x10^{-8}$**
Leakage from Rowe-Booker Eq. (2000) (lphd)	162,000	9,750	975	97.5	9.75	0.975
Leakage from Rowe-Fan Eq. (2022a) (lphd)	162,000	6,720	672	67.2	6.7	0.67
Head on liner, *h* (m)	**50**	**100**	**150**	**200**	**250**	**300**
Tailings thickness, *H* (m)	**48**	**98**	**148**	**198**	**248**	**298**
Hole area, a (mm^2)	100	100	100	100	100	100
Hydraulic conductivity of tailings at hole, k_T (m/s)	$1x10^{-6}$	$1x10^{-6}$	$1x10^{-6}$	$1x10^{-6}$	$1x10^{-6}$	$1x10^{-6}$
Leakage from Rowe-Booker Eq. (2000) (lphd)	97.5	195	292	390	487	585
Leakage from Rowe-Fan Eq. (2022) (lphd)	67.2	134	202	269	512	745

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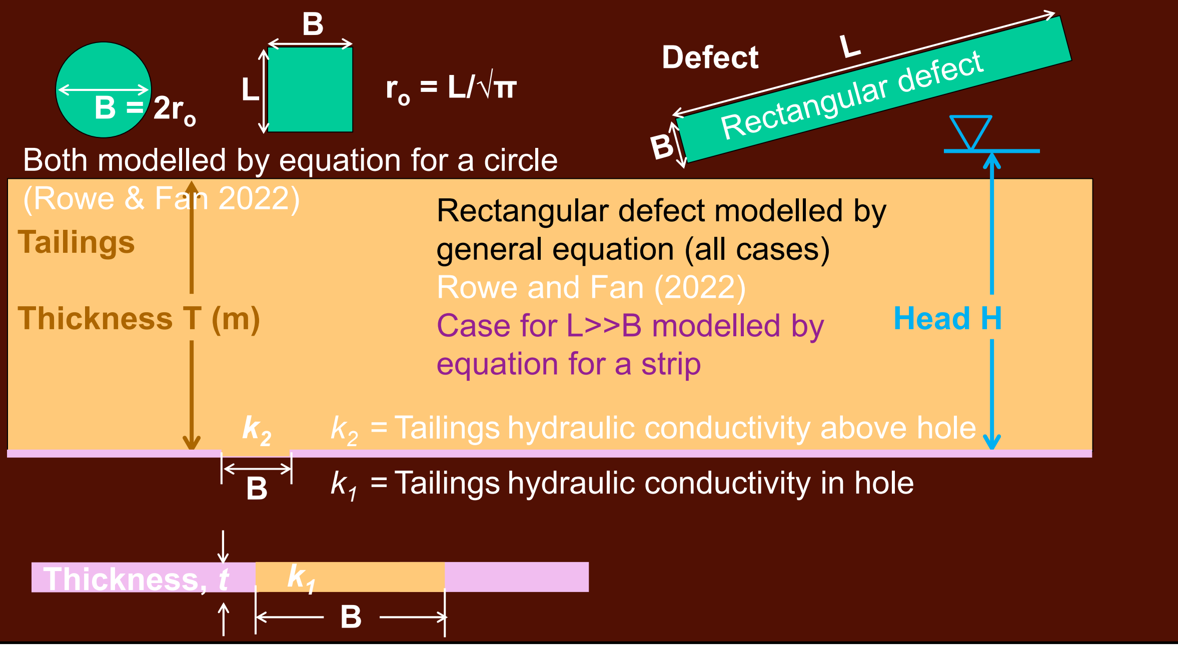
6. Rowe and Fan (2022b) General solution for leak below tailings



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Leakage through a geomembrane defect in TSF

Head on liner, *h* (m)	**50**	**50**	**50**	**50**	**50**	**50**
Tailings thickness, *H* (m)	48	48	48	48	48	48
Hole area, a (mm^2)	100	100	100	10,000	10,000	10,000
Hole length (m)	0.01	0.1	1	0.1	1	10
Hole width (m)	0.01	0.001	0.0001	0.1	0.01	0.001
Hydraulic conductivity of tailings at hole, k_T (m/s)	1x10^{-6}	1x10^{-6}	1x10^{-6}	1x10^{-6}	1x10^{-6}	1x10^{-6}
Leakage from Rowe-Fan Eq. (2022b) (lphd)	71	98	164	1,020	1,670	6,580
Head on liner, *h* (m)	50	50	50	50	300	300
Tailings thickness, *H* (m)	48	48	48	48	298	298
Hole area, a (mm^2)	100,000	100,000	100,000	100,000	100,000	100,000
Hole length (m)	0.316	0.1	0.01	0.001	0.316	0.001
Hole width (m)	0.316	1	10	100	100,000	100
Hydraulic conductivity of tailings at hole, k_T (m/s)	1x10^{-6}	1x10^{-6}	1x10^{-6}	1x10^{-6}	1x10^{-6}	1x10^{-6}
Leakage from Rowe-Fan Eq. (2022b) (lphd)	3,330	4,220	12,400	72,100	19,900	327,000

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Take home message

There are many (all simple) equations – BUT You need to understand which equation is most suitable for your situation

A barrier system design that does not properly calculate and consider the potential consequence of leakage is not a design; it is wishful thinking

Do not destroy composite liner action in a wrong-headed attempt rto solve another problem

[5:00]

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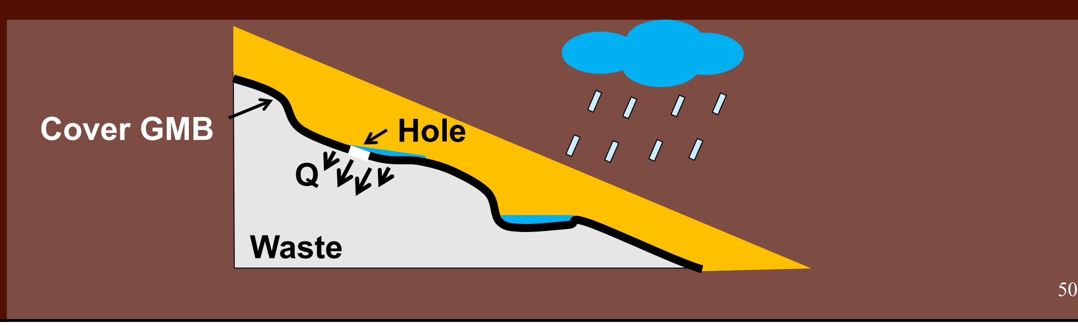
Compared to base liners, GMB strains and leakage for covers may additionally depend on:

1. Weather
2. Differential settlement
3. Slope
4. Wrinkles on slopes
5. Cover soil properties



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Take home messages

- Differential can substantially increase leakage on 4H:1V slopes.
- Care is needed when filling zones of differential settlement not to aggravate the problem.

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Short Course on

GEOMEMBRANES AND COMPOSITE LINERS IN LANDFILLS AND MINING: MOVING FORWARD

Sunday 17 Sept. 2023

2. Leakage through liners

R. Kerry Rowe OC, FRS, FREng, NAE

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