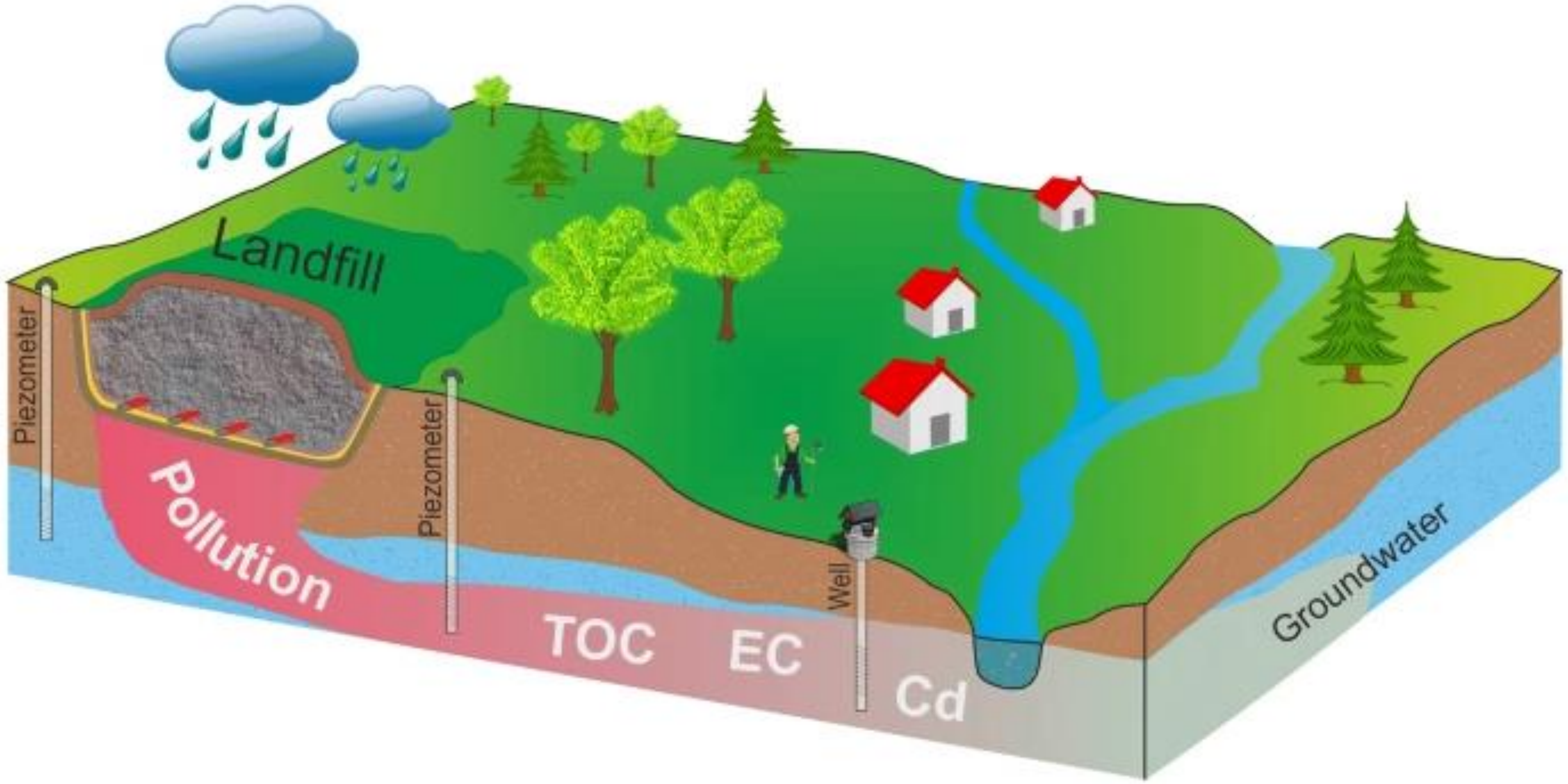
Calculating leakage rates from landfill liner systems

Jonathan Shamrock
Tonkin & Taylor Ltd

Why is calculating the expected leak rate from a landfill lining system important?



Przydated, G., Kanownik, W. 2019

Where we started - Giroud and Bonaparte 1989

Leakage through Liners Constructed with Geomembranes—Part I. Geomembrane Liners*

J. P. Giroud & R. Bonaparte

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(Received 18 June 1987; revised version received and accepted 23 September 1988)

"All liners leak", stated by Giroud & Bonaparte (1989a) at the beginning of their paper. This should not be construed as meaning that there is no way to safely store liquids/waste. In fact, recognizing that all liners may leak is the first step to the safe design of liquid containment systems.

Looked at both single geomembrane on a pervious base, and single geomembrane on a low permeability base, or a composite lining system. The paper determined the leak rate due to permeation through an intact geomembrane, or "coefficient of migration". This value is very low, as geomembranes are very good at limiting flow though them.

TABLE 5
Calculated Unitized Leakage Rates due to Permeation of Water Through an HDPE Geomembrane

	Water depth on top of the geomembrane, h_w					
	0 m (0 ft)	*0·003 m (0·01 ft)*	*0·03 m (0·1 ft)*	*0·3 m (1 ft)*	*3 m (10 ft)*	*>10 m (>30 ft)*
Coefficient of migration, m_g (m^2/s)	0	9×10^{-20}	9×10^{-18}	9×10^{-16}	9×10^{-14}	3×10^{-13}
Unitized leakage rate, q_g						
(m/s)	0	9×10^{-17}	9×10^{-15}	9×10^{-13}	9×10^{-11}	3×10^{-10}
(lphd)	0	8×10^{-5}	0·008	0·8	80	260
(gpad)	0	8×10^{-6}	0·0008	0·08	8	28

Notes: These values of utilized leakage rates were calculated using eqn (5) and assuming a geomembrane thickness of 1 mm (40 mils). The coefficients of migration used to calculate the unitized leakage rates in this table were obtained from eqns (19) and (20), with $C_1 = 1 \times 10^{-22}\ m^4\ kg^{-2}\ s^3$, $n = 2$, and $m_{gmax} = 3 \times 10^{-13}\ m^2/s$. The water depths used here correspond to the typical values defined in Section 1.3.6. (To use eqn (19), it is necessary to know the pressure difference, Δp. According to eqn (1), water depths, h_w, are approximately equal to hydraulic head differences, Δh, which are related by eqn (12) to pressure differences, Δp.)

- Leak rate also directly proportional to head of leachate on the liner
- All examples going forward assume 300 mm, or thickness of a leachate collection layer
- This is also only on the landfill base, side slopes will reduce head and thus leak rates

Leak rate with defects, on permeable base

TABLE 7
Calculated Unitized Leakage Rates Through a Geomembrane Liner

	Water depth on top of the geomembrane, h_w				
	0·003 m (0·01 ft)	*0·03 m (0·1 ft)*	*0·3 m (1 ft)*	*3 m (10 ft)*	*30 m (100 ft)*
Permeation	0·000 1 (0·000 01)	0·01 (0·001)	1 (0·1)	100 (10)	300 (30)
Pinhole	0·01 (0·001)	0·1 (0·01)	1 (0·1)	10 (1)	100 (10)
Small hole	100 (10)	300 (30)	1 000 (100)	3 000 (300)	10 000 (1 000)
Large hole	3 000 (300)	10 000 (1 000)	30 000 (3 000)	100 000 (10 000)	300 000 (30 000)
	Values of unitized leakage rate in lphd (gpad)				

Notes: The geomembrane is assumed to be underlain and overlain by a very pervious medium such as coarse gravel or geonet. The leakage rate calculated for holes would be significantly reduced if the pervious medium in contact with the geomembrane on one or both sides is sand or a less permeable material. The geomembrane is assumed to be made from HDPE with a thickness of 1 mm (40 mils). The unitized leakage rates (i.e. leakage rates per unit area of liner) were obtained assuming one pinhole or one hole per 4000 m^2 (acre). This table has been established by combining Tables 5 and 6 and rounding up. The considered pinhole has a diameter of 0·1 mm (0·004 in); the small hole has a surface area of 3·1 mm^2 (0·005 in^2), i.e. a diameter of 2·0 mm (0·08 in); and the large hole has a surface area of 1 cm^2 (0·16 in^2), i.e. a diameter of 11·3 mm (0·445 in). The water depths used here correspond to the typical values defined in Section 1.3.6.

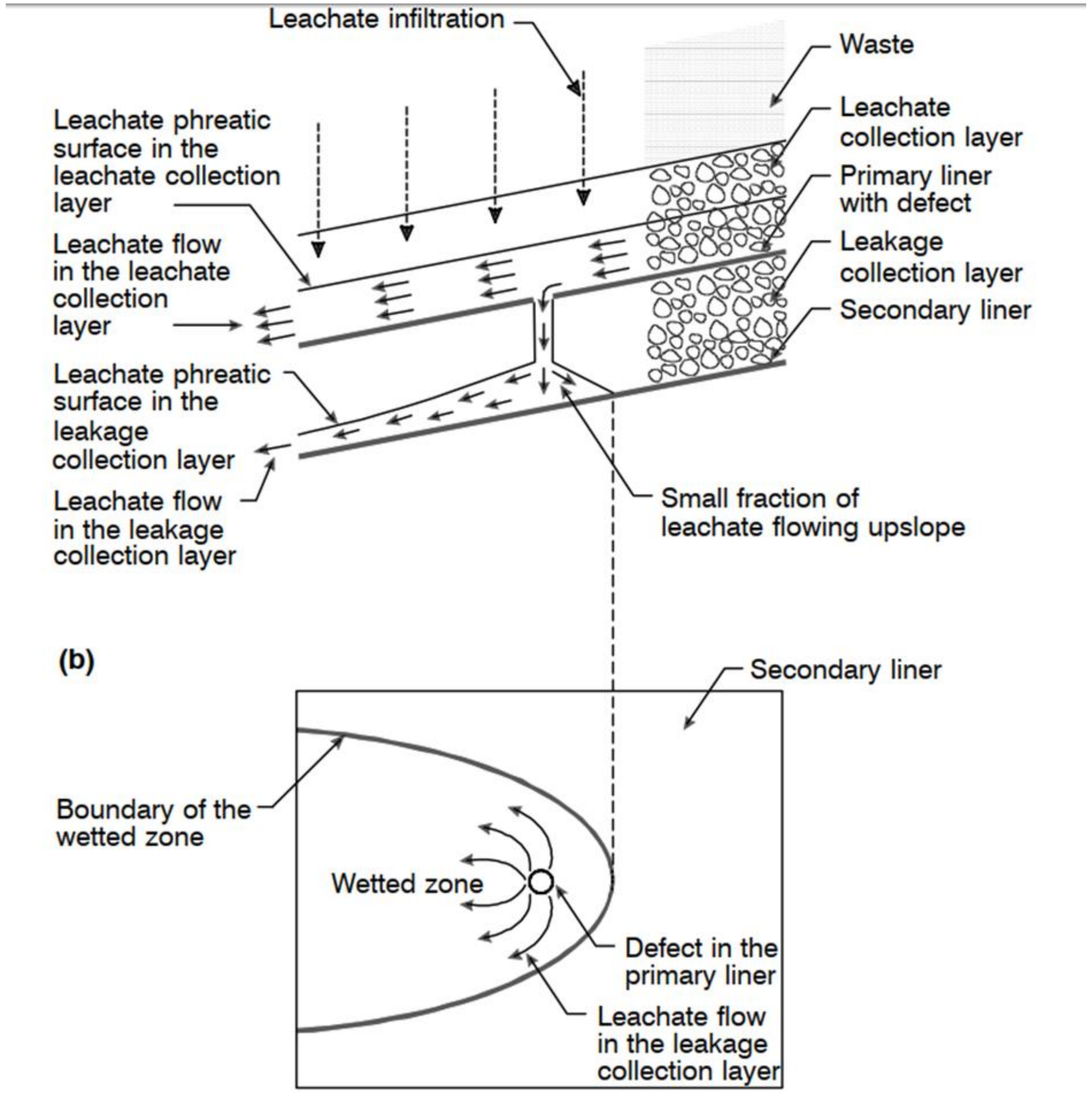
The paper defined frequency and size of holes to be used in the calculation, which are still used as the basis for the calculations today

- One hole per Acre = 2.5 holes per hectare (10,000 m^2)
- 1 cm^2/11.3 mm dia. (Large) for calculations to size the components of the lining system
- 3.1 mm^2/2 mm diam. (Small) for calculation of the lining system performance

Augmented in 1997, looking at leaks through geomembranes in double liner system

Technical Paper by J.P. Giroud, B.A. Gross, R. Bonaparte and J.A. McKelvey

LEACHATE FLOW IN LEAKAGE COLLECTION LAYERS DUE TO DEFECTS IN GEOMEMBRANE LINERS



Key point of this work, limit head on secondary, to limit leakage through lining system, so higher drainage capacity in secondary leachate collection layer is critical.

Table 1. Rate of leachate flow in three different leachate collection layers resulting from a defect in the primary liner.

Leachate thickness (actual or virtual)		Leakage collection layer material					
		Geonet t_{LCL} = 5 mm $k = 1 \times 10^{-1}$ m/s		Gravel t_{LCL} = 300 mm $k = 1 \times 10^{-1}$ m/s		Sand t_{LCL} = 300 mm $k = 1 \times 10^{-3}$ m/s	
t_o		Q		Q		Q	
(m)	(mm)	(m^3/s)	(lpd)	(m^3/s)	(lpd)	(m^3/s)	(lpd)
0.005	5	2.5×10^{-6}	216	2.5×10^{-6}	216	2.5×10^{-8}	2.16
0.01	10	7.5×10^{-6}	648	1.0×10^{-5}	864	1.0×10^{-7}	8.64
0.05	50	4.75×10^{-5}	4,104	2.5×10^{-4}	21,600	2.5×10^{-6}	216
0.1	100	9.75×10^{-5}	8,424	1.0×10^{-3}	86,400	1.0×10^{-5}	864
0.3	300	2.975×10^{-4}	25,704	9.0×10^{-3}	777,600	9.0×10^{-5}	7,776

Notes: The leachate thickness, t_o, can be derived from the leachate head on top of the secondary liner using Equation 4. The leachate thickness, t_o, is the actual leachate thickness if $t_o < t_{LCL}$ and a virtual leachate thickness if $t_o > t_{LCL}$. The tabulated values of the rate of leachate flow, Q, were calculated using Equation 9 when $t_o < t_{LCL}$ and Equation 16 when $t_o > t_{LCL}$. Units: 1 m^3/s = 86,400,000 liters per day (lpd).

Table 2. Rate of leachate migration through a defect in a geomembrane primary liner as a function of the defect diameter and the head of leachate on top of the primary liner.

Leachate head on top of the primary liner, h_{prim} (mm)	Geomembrane primary liner defect diameter, d (mm)							
	1	2	3	5	10	20	50	100
5	13	51	115	319	1,275	5,101	31,881	127,523
10	18	72	162	451	1,803	7,214	45,086	180,345
50	40	161	363	1,008	4,033	16,131	100,816	403,264
100	57	228	513	1,426	5,703	22,812	142,575	570,301
300	99	395	889	2,469	9.878	39,512	246,948	987,790

Note: The tabulated values of the rate of leachate migration, Q, through a geomembrane defect were calculated using Bernoulli's equation (Equation 20) and are expressed in liters per day (lpd).

GRI White Paper # 15, published 2009, produced a summary of expected leak rates, and takes account of impact of composite lining system

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GRI GEI GII GSI GAI GCI

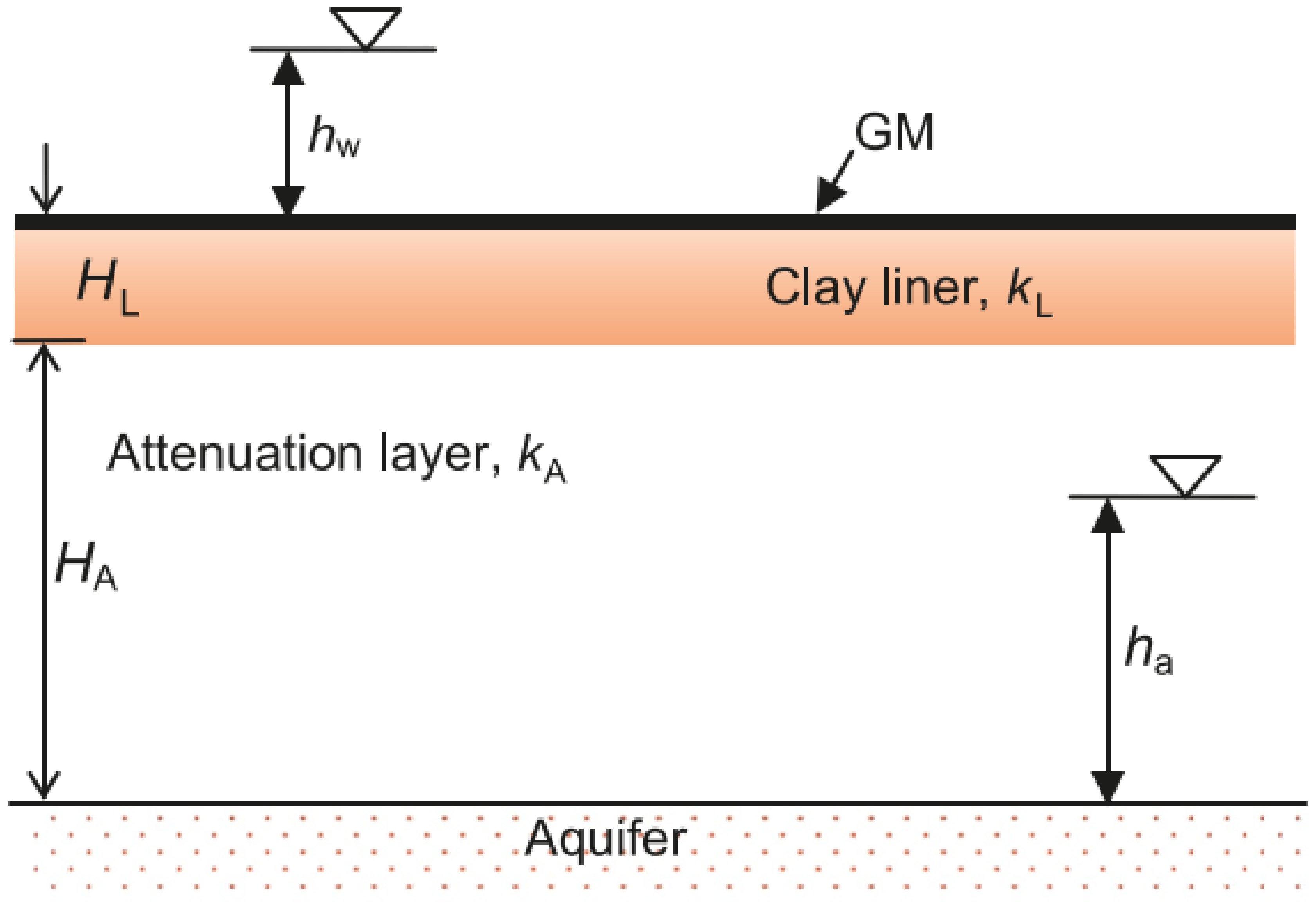
GRI White Paper #15

Survey of U.S. State Regulations on Allowable Leakage Rates in Liquid Impoundments and Wastewater Ponds

Table 1 - Generalized Leakage Rates Through Liners
(ref. Giroud and Bonaparte, Jour. G & G, 1989)

Type of Liner	Leakage Mechanism	Liquid height on top of the geomembrane 0.03 m	0.3 m	3 m	30 m
Geomembrane alone (between two sand layers)	Diffusion	0.01	1	10	300
	Small Holes*	300	1,000	3,000	10,000
	Large Holes*	10,000	30,000	100,000	300,000
Composite liner (poor field conditions, i.e., waves)	Diffusion	0.01	1	100	300
	Small Holes*	0.8	6	50	400
	Large Holes*	1	7	60	500
Composite liner (good field conditions, i.e., flat)	Diffusion	0.01	1	100	300
	Small Holes*	0.15	1	9	75
	Large Holes*	0.2	1.5	11	85
		Values of leakage rate are in lphd (values can be divided by approximately 10 to obtain values expressed in gpad)			

*assumes 3 holes/ha (i.e., 1.0 hole/acre)



Rowe, 2021

Use Darcy on this leak rate to calculate leak rate to environment

Introduced concept of poor/good contact of geomembrane to Compacted Clay Liner. Good contact means limited area for leak to impact CCL.

The next evolution – Rowe 2012

Short- and long-term leakage through composite liners. The 7th Arthur Casagrande Lecture[1]

R. Kerry Rowe

Published in 2012, this paper summarised work on geomembrane wrinkles and their impact on leakage rates. The research was undertaken as "**the calculated leakage through holes in a GM in direct contact with a clay liner is typically substantially smaller than that actually observed in the field**"

The paper also introduces the concept of interface transmissivity, so how a leak can spread under a hole in the geomembrane in a composite lining system.

Table 9. Comparison between observed and calculated leakage (direct contact solution) during the active period for 0.9 m thick CCL and 0.01 m thick GCL in a primary liner over a geonet LDS.

Liner	k_L (m/s)	θ (m^2/s)	Calculated leakage[a]	Observed leakage (lphd)[b] Range[c]	Observed leakage (lphd)[b] Peak[d]
CCL	1×10^{-10}	1.6×10^{-8}	6	60–160[e]	390[e]
	1×10^{-9}	1×10^{-7}	40	60–160	390
GCL	5×10^{-11}	2×10^{-12}	0.001	0–11	54
	2×10^{-10}	2×10^{-10}	0.06	0–11	54

[a]Hole r_o = 5.6 mm; h_w = 0.3 m, h_a = 0 m; H_A = 0 m, 5 holes/ha; calculations rounded to one significant figure.

[b]Bonaparte et al. (2002).

[c]Weighted average flow based on data from Bonaparte et al. (2002).

[d]Maximum peak flow.

[e]Specifically for 0.9 m CCL in Table 4 of Rowe (2005). Note that leakages up to almost 2000 lphd have been reported for other composite liners with a CCL.

The significant step forward this paper highlighted was the impact of wrinkles on leak rate calculations, the cause behind the discrepancy between calculated and field measured leak rates

Fig. 12. Aerial photo showing a small portion of connected wrinkle network on the base liner at QUELTS (same bottom liner as shown in Figs. 8 and 11) (modified from Rowe et al.[2]). Photo taken on 28 May 2008 at 1300; air temperature of 11 °C; GM temperature on the base of 53 °C. Distance between GM seams is approximately 6.7 m as shown.

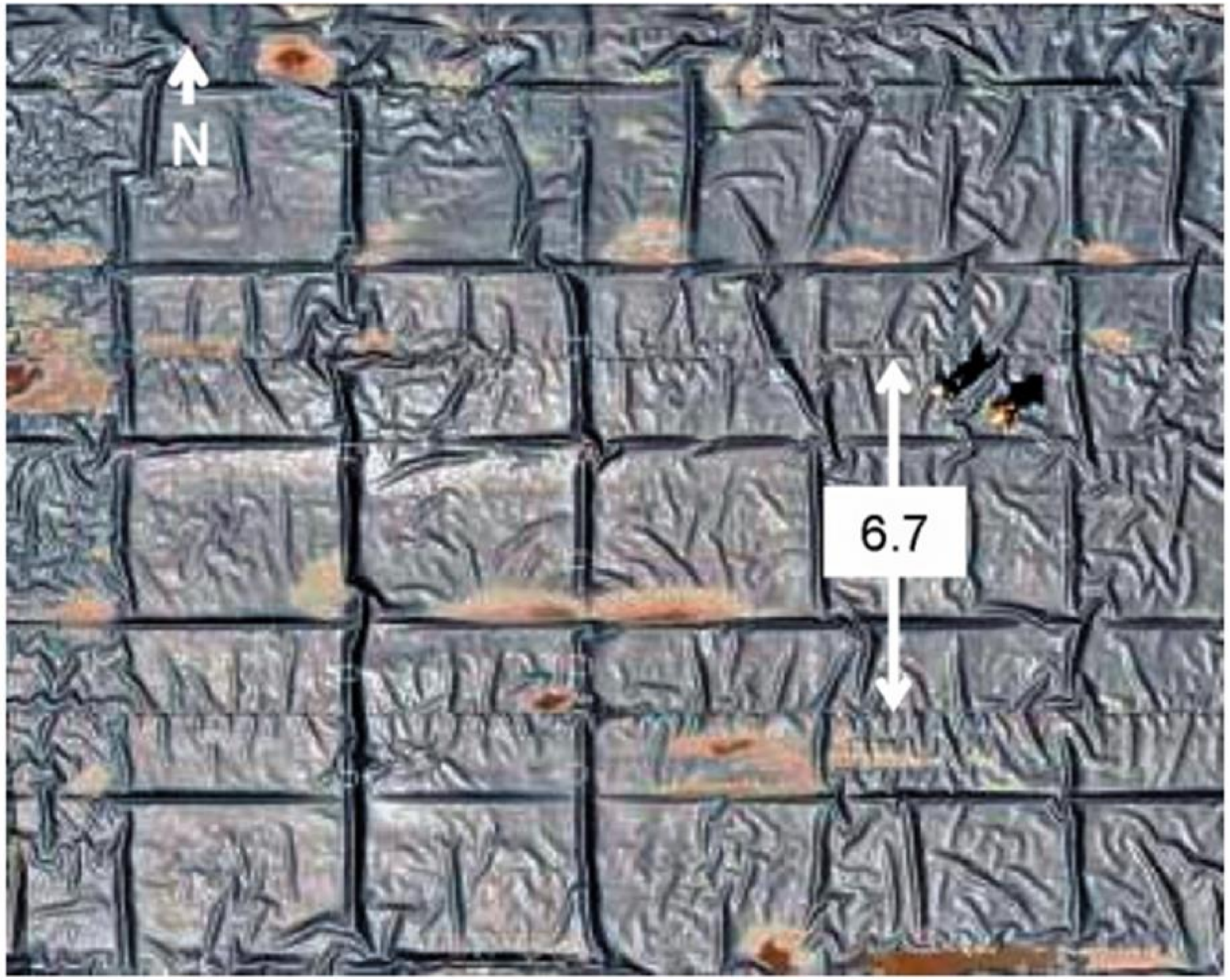


Fig. 10. Schematic showing leakage through a wrinkle of length *L* and width *2b* with a hole of radius r_o (adapted from Rowe 1998).

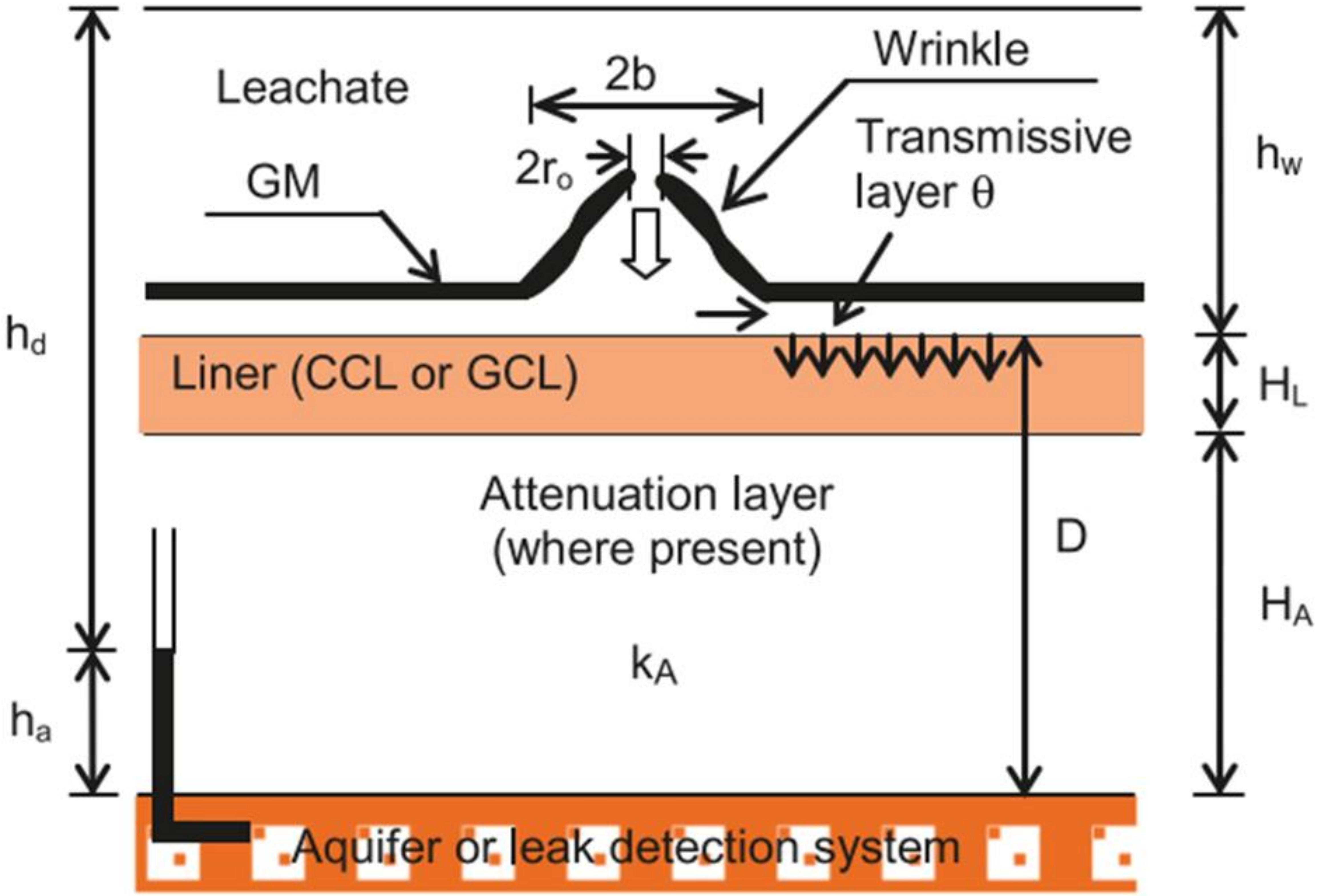


Table 11. Calculated leakage, Q, through selected composite liners for a hole in one connected wrinkle of length L per hectare for $h_w = 0.3$ m.

Case	k_L (m/s)	θ (m²/s)	Q (lphd) L = 100 m	Q (lphd) L = 200 m	Q (lphd) L = 700 m
0.6 m CCL, $H_A = 0$ m[a]	5×10^{-10}	1.6×10^{-8}	58	120	410
	1×10^{-9}	1.6×10^{-8}	83	170	580
0.01 m GCL, $H_A = 0$ m	5×10^{-11}	2×10^{-11}	3	6	21
	2×10^{-10}	2×10^{-11}	9	17	61
	*	2×10^{-11}	7	14	49
0.6 m CCL, $H_A = 3.15$ m[b]	5×10^{-10}	1.6×10^{-8}	67	130	470
	1×10^{-9}	1.6×10^{-8}	94	190	660
0.01 m GCL, $H_A = 3.74$ m[b]	5×10^{-11}	2×10^{-11}	10	20	63
	2×10^{-10}	2×10^{-11}	29	59	210
	*	2×10^{-11}	16	31	110

Note: Leakage calculated using eq. [6] and geometry as per schematic in Fig. 10 with $2b = 0.1$ m, hole r_o = 5.6 mm; calculated leakages have been rounded to two significant digits.

[a] $h_a = 0$ m.

[b] $h_a = 3$ m, $H_A + H_L = 3.75$ m.

*Assuming $k_L = 2 \times 10^{-10}$ m/s below wrinkle and $k_L = 5 \times 10^{-11}$ m/s outside wrinkle.

CCL assumes uniformly mixed and compacted clay, GCL assumes intact GCL layer. Both can however be impacted by desiccation from exposed conditions, waste generated liner temperature increase, and GCL overlaps and panel serration due to shrinkage.

Field validation of leak rate including allowance for wrinkles

Controlling leakage through installed geomembranes using electrical leak location

Abigail Gilson-Beck

TRI Environmental, USA

Published in 2019, this paper examines the likely number and size distribution of holes, based on completed Electrical Leak Location surveys on constructed facilities and double-lined facilities with monitored leak detection layers.

Table 2
Leakage rate calculations for case study site.

Leakage (lphd)[a]				
Column 1	Column 2	Column 3	Column 4	Column 5
Actual Leakage Before Repairs (Recorded Daily)	Good Contact (Giroud Eq.[a])	Poor Contact (Giroud Eq.[a])	Leakage On Wrinkle (Rowe Eq.[b])	Calculated Post-Repair Leakage (Column 1 – Column 4)[c]
280.5	3.8	21.1	244.4	36.1
286.8	4.5	24.5	267.3	19.4
288.8	4.6	25.2	272.2	16.6
270.1	3.5	18.7	227.2	42.9

Notes:

[a] Calculated with observed hole size and geometries and back-calculated hydraulic head at location of leak(s) at time of leakage measurement; assumed GCL thickness of 0.006 m, GCL hydraulic conductivity of 5.0×10^{-11} m/s and GCL thickness of 0.006 m (Giroud (1997) equation).

[b] Back-calculated hydraulic head at location of leak(s) at time of leakage measurement; assumed wrinkle width of 0.31 m, wrinkle length of 190 m, GCL hydraulic conductivity of 5.0×10^{-11} m/s, GCL thickness of 0.006 m and transmissivity of geomembrane/GCL interface of 2.0×10^{-10} m^2/s (for low compressive stress condition) (Rowe, 1998 Equation).

[c] Matches well with observed leakage after repairs of leaks.

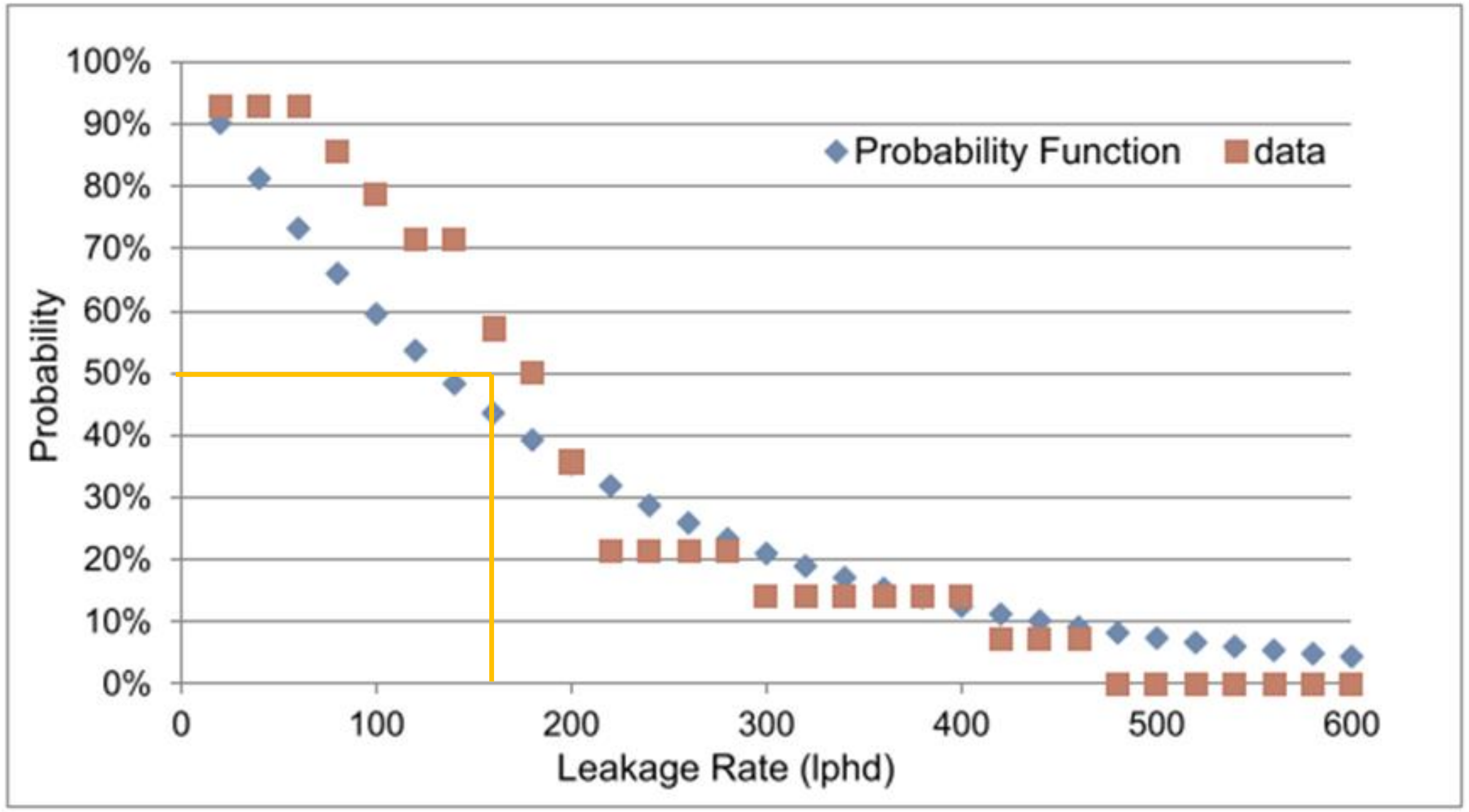


Fig. 12. Probability of Exceeding Given Leakage Rate (both empirical and theoretical).

Dr. Robert Koerner stated "field damage dwarfs manufacturing imperfections!"

Table 1. Location of Holes

No. of Holes	Flat Floor (1)	Corners and Edges (2)	Under Drainage Pipes (3)	Pipe Penetrations (4)	Other (5)
4194	3261	395	165	84	289
100%	77.8%	9.4%	3.9%	2.0%	6.9%

Table 2. Cause of Holes vs. Size of Holes

Size of Holes (cm^2)	Stones	%	Heavy Equip.	%	Welds	%	Cuts	%	Worker Directly	%	Total
<0.5	332	11.1	-	-	115	43.4	5	8.5	195	-	452
0.5-2.0	1720	57.6	41	6.3	105	39.6	36	61.0	105	84.4	2097
2.0-10	843	28.2	117	17.9	30	11.3	18	30.5	36	15.6	1044
>10	90	3.0	496	75.8	15	5.7	-	-	-	-	601
Amount	2985		654		265		59		231		4194
Total	71.17%		15.59%		6.32%		1.41%		5.51%		100%

GSI Webinar Series Quality Control and Quality Assurance of Geosynthetics in Solid and Liquid Waste Containment Systems

Exposed geomembrane ELL

Exposed geomembrane testing, picks up small defects/weld pinholes

Designation: D6747 – 25

Standard Guide for Selection of Techniques for Electrical Leak Location of Leaks in Geomembranes[1]

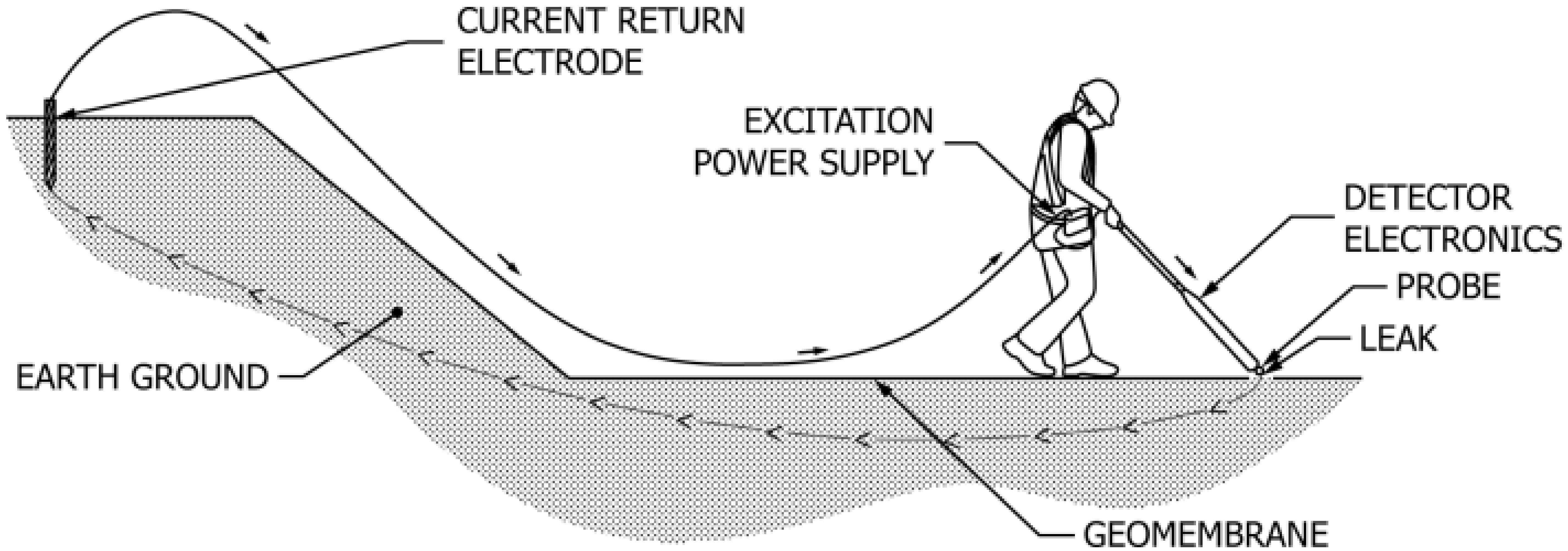
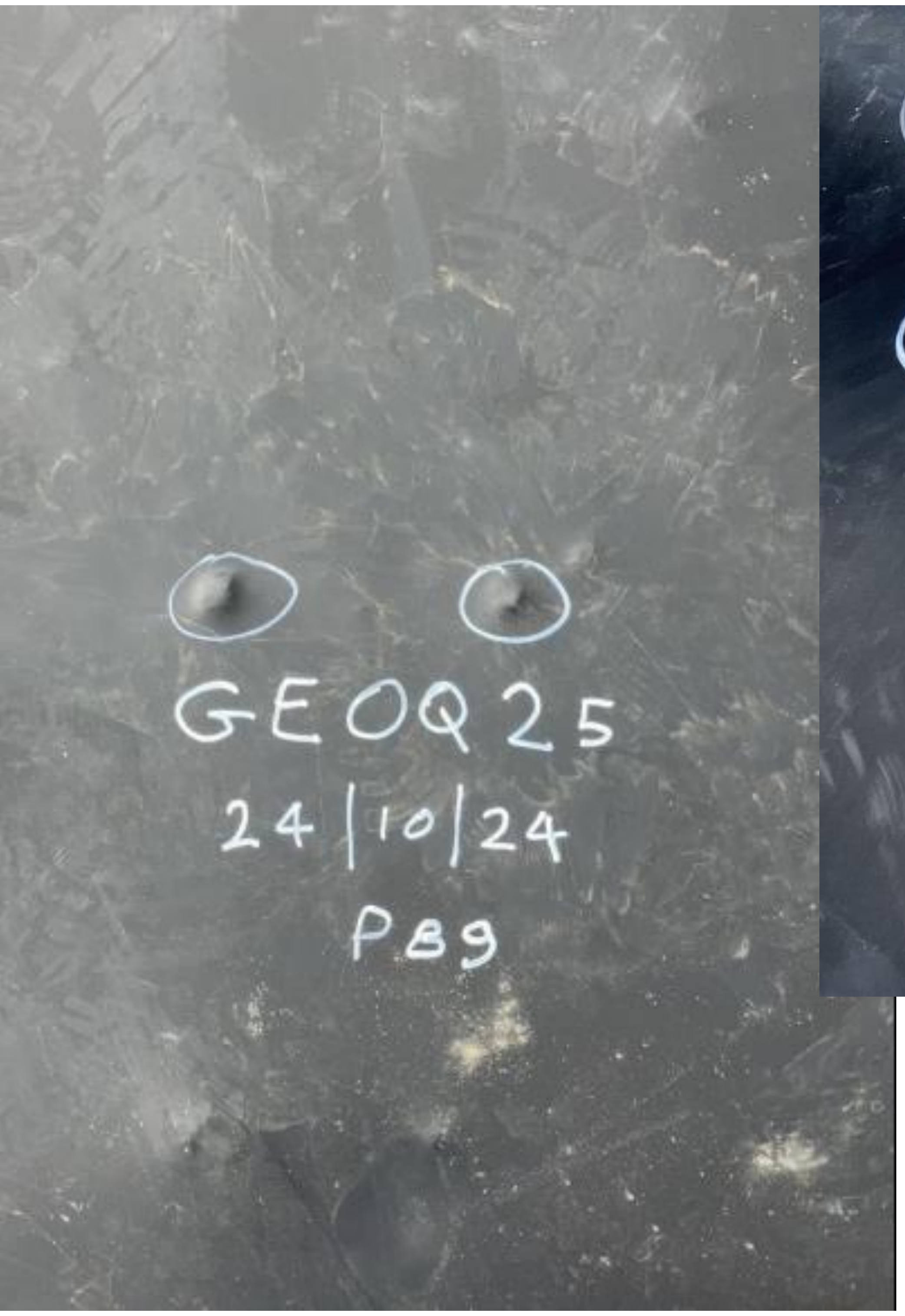
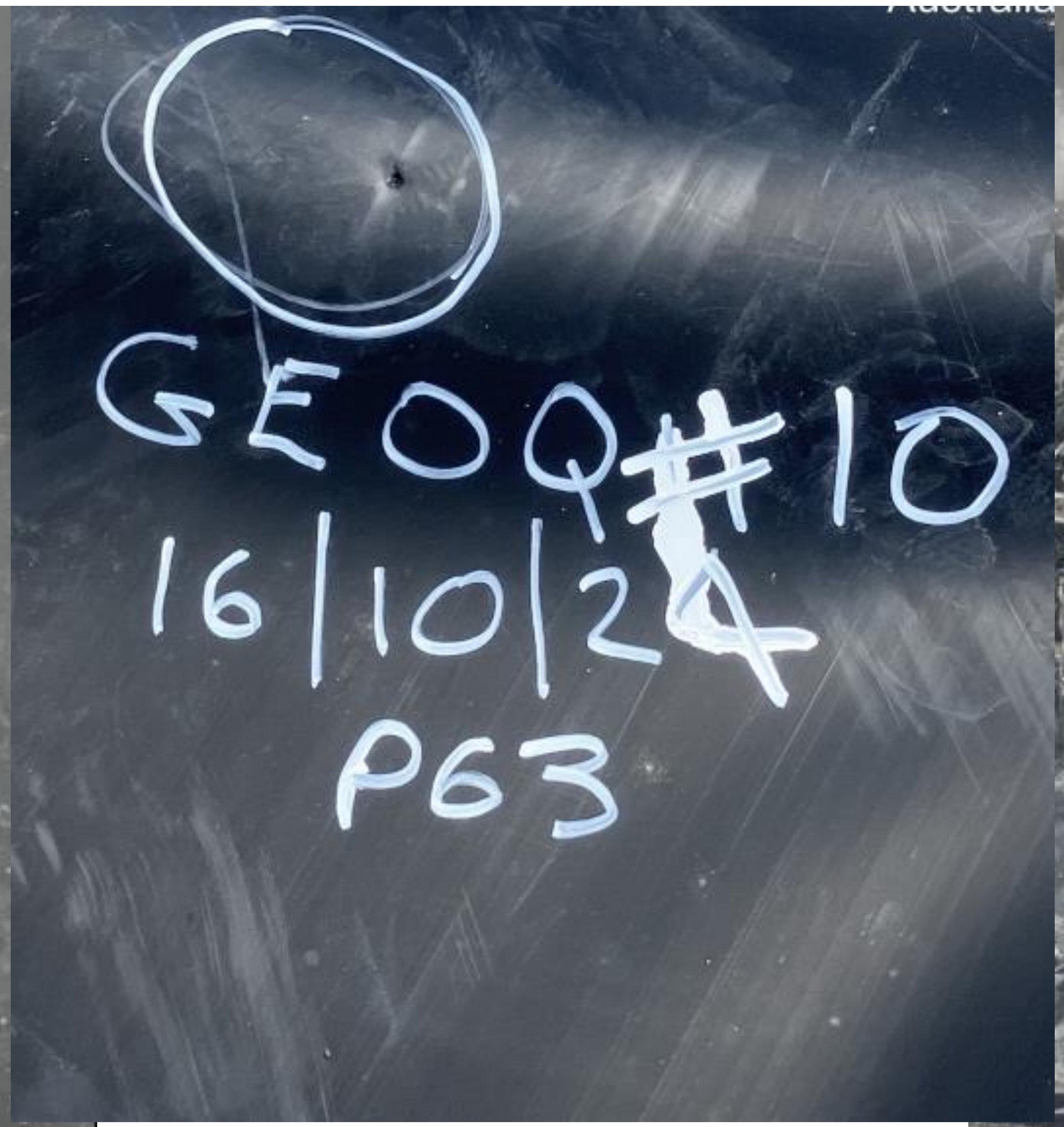


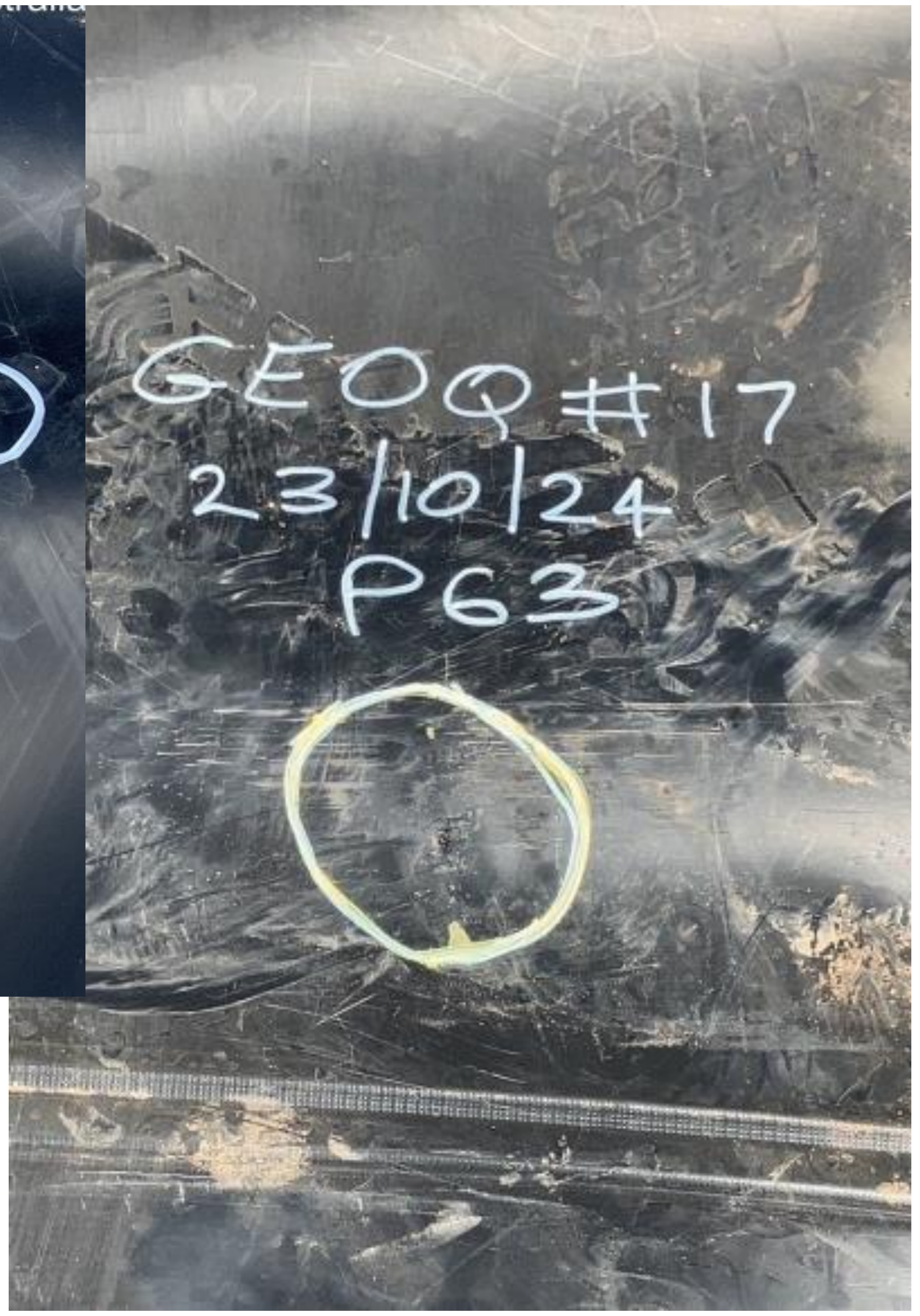
FIG. 4 Schematic of Arc Testing Method

LEAK LOCATION SERVICES, INC.

Examples of holes in exposed geomembrane testing







GeoQ. pers. comm. 2026

Fig. 8. One repair patch location with pinhole leak.

Gilson-Beck. 2019

Covered geomembrane ELL (dipole)

Covered geomembrane testing, picks up post cover layer installation damage

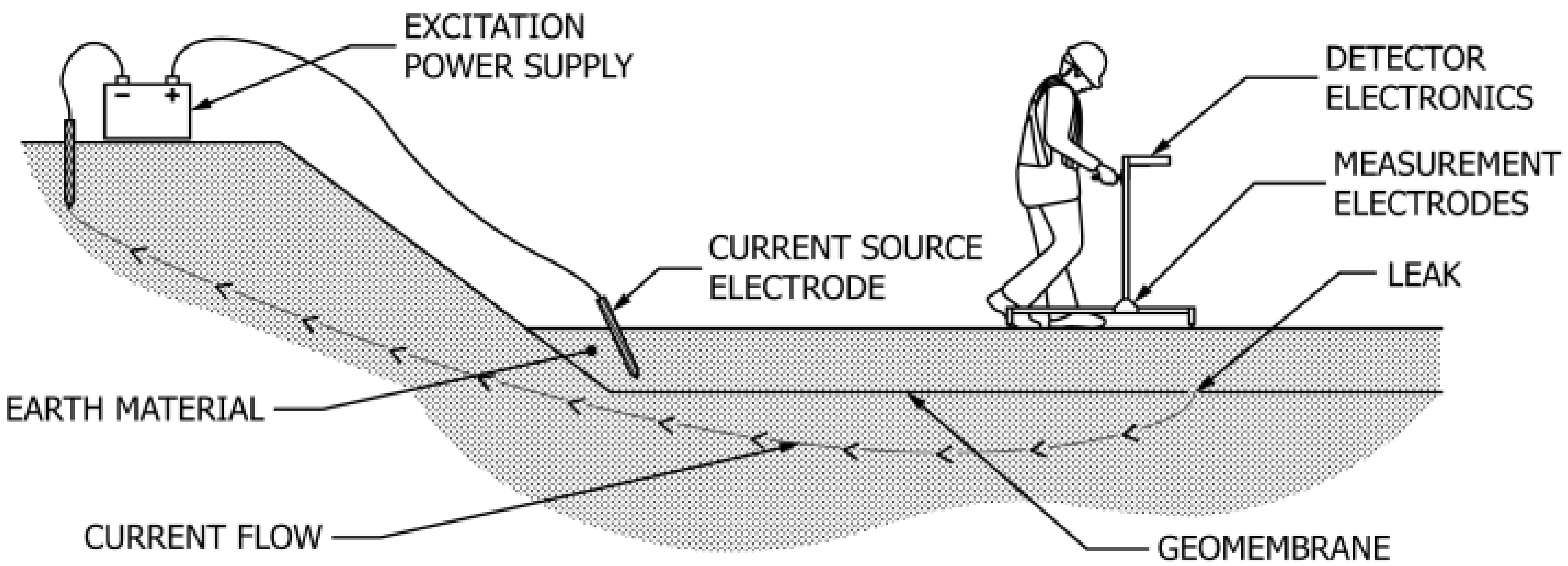


FIG. 9 Schematic of the Dipole Method on Earthen Material-Covered Geomembrane

TRI Australasia

Examples of holes under covered geomembrane testing

Fig. 5. Damage caused during cover material placement.

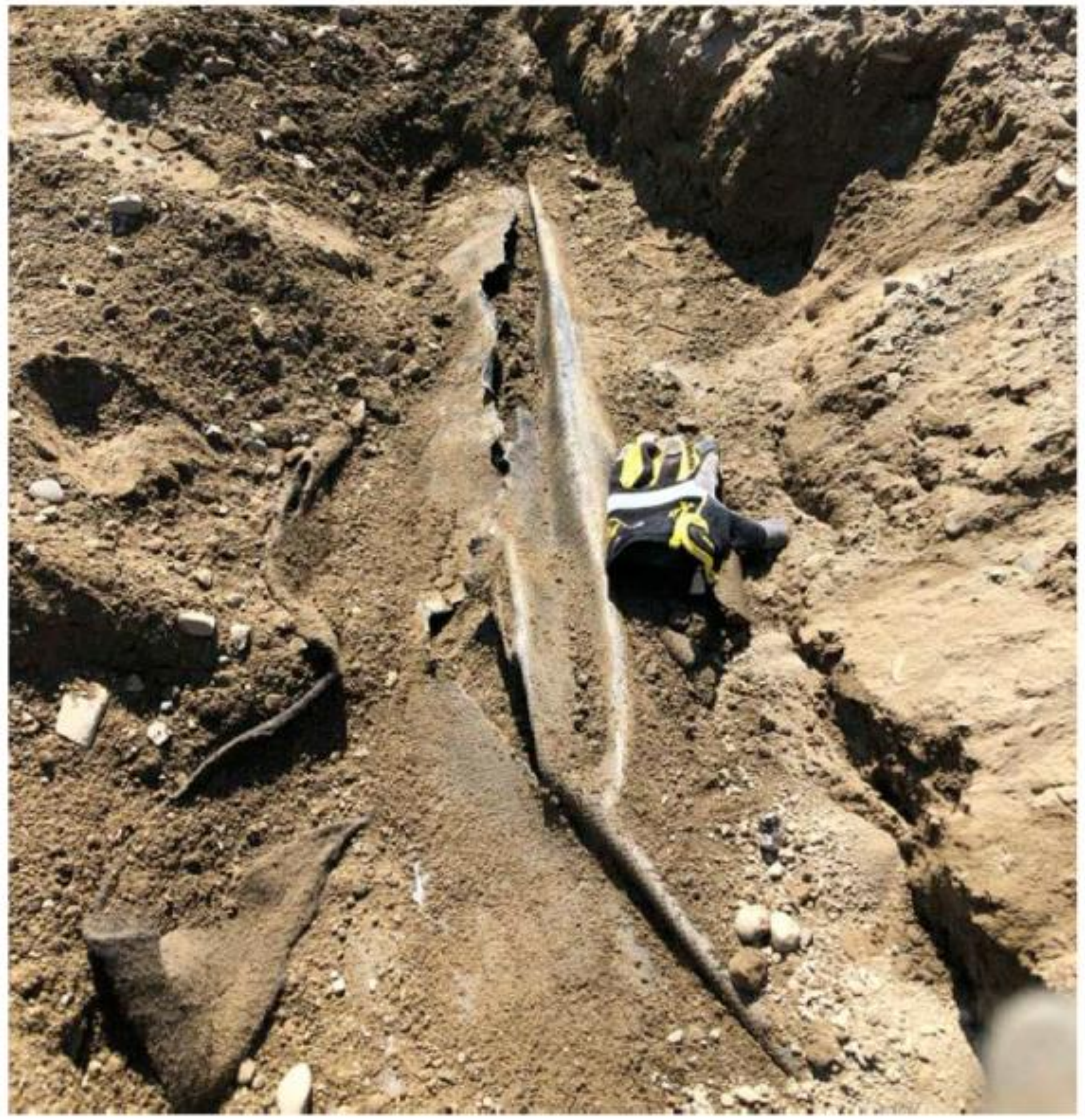


Fig. 6. Equipment damage caused during cover material placement.

Fig. 16. Wrinkle hit by dozer blade.

Gilson-Beck. 2019

Conclusions

New Zealand landfill design standards are effects based, so realistic leakage rates need to be used as inputs to groundwater models, for examination of possible impacts. Wrinkles in the geomembrane need to be considered in the calculations.

Good design is critical to limit the leak rate by keeping head build up on liner system low (good drainage), keeping the base area small, and limiting tension in the liner.

Managing installation is also critical for liner system performance, ensuring good contact, limiting wrinkles, testing welds, and providing good CQA supervision during all stages of construction.

Electrical Leak Location surveys need to be incorporated into landfill construction CQA practice to reduce leak rates.

With good design, and good CQA practice, acceptable leakage rates can be achieved to provide protection of the environment.

Questions?

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