ROLE OF GCLs IN CONTROLLING LEAKAGE THROUGH COMPOSITE LINERS

It has been demonstrated, both theoretically and through field measurements (e.g., TR-316), that leakage through composite liners which include a GCL will typically be less than leakage through composite liners with a compacted clay liner. The traditional method for calculating leakage through a composite liner using Giroud's equations (TR-258) assumes direct contact with the geomembrane – however, this is not always consistent with field observations, mostly due to geomembrane wrinkles.

In the attached keynote paper from the 3rd International Symposium on Geosynthetic Clay Liners, equations for calculating leakage through a composite liner with geomembrane wrinkles are presented. The equations look at wrinkle width, interconnected length, and area. Leakage rates observed in the field are consistent with calculated estimates for landfills in North America with interconnected wrinkle lengths between 160 ft/acre (120 m/ha).and 800 ft/acre (600 m/ha).

The author recommends that more emphasis be placed on controlling wrinkles, especially if there are low stresses on the liner and/or potential for significant increase in the hydraulic conductivity of GCL with time (due to clay-leachate interaction). To minimize leakage, it is recommended that interconnected wrinkle lengths be limited to less than 660 ft/acre (500 m/ha), and ideally less than 165 ft/acre (125 m/ha). Wrinkling can be controlled by covering the geomembrane either early in the morning or late in the evening.

TR-269
01/11

Role of GCL's in controlling leakage through composite liners

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ABSTRACT
It is demonstrated both theoretically and empirically that the leakage through composite liners involving a GCL will typically be less than that for a composite liner involving a compacted clay liner. Examining data related to observed leakage through primary composite liners in double lined landfills in North America, it is inferred that the interconnected wrinkle lengths with a hole after waste placement were typically less than 1300 m/ha and most commonly likely in the range from 120 to 600 m/ha, with values less than 100 m/ha being possible with good attention to the conditions when the GM is covered. The paper explores the implications of GCL hydraulic conductivity, interface transmissivity, GCL-leachate interaction and hydrogeological conditions on leakage through composite liners. It is demonstrated that the length of interconnected wrinkle that will give rise to a given leakage is highly dependent on the liner configuration and hydrogeological conditions. It is also shown that the significance of the effect of wrinkles on leakage is also highly dependent on the potential for interaction between the leachate and GCL. This is likely to be especially important for GCLs in primary liners in double lined landfills. It is suggested that while it already is required in some jurisdictions, more emphasis should be placed on controlling wrinkles in most construction specifications or regulations.

1. INTRODUCTION

Rowe (2009) provided a general discussion of the need to adopt a systems engineering approach to the design, construction and operation of municipal solid waste (MSW) landfills. Without getting into great detail, that paper examined the entire landfill system. Rowe and Hosney (2010) followed this by taking a more focussed systems approach to minimize leakage through composite bottom liners. They examined factors affecting leakage through single composite liners involving both compacted clay liners (CCLs) and geosynthetic clay liners (GCLs). The specific factors discussed were: (i) the design of the landfill cover, (ii) the design of the leachate collection system, (iii) the choice of GCL or CCL as the clay component of a single composite liner, (iv) the number and size of unfixed holes, (v) the area of landfill with interconnected wrinkles (waves), (vi) the nature of the surface upon which the GM is placed, (vii) nature of the waste, (viii) the waste placement sequence, (ix) recirculation of leachate or other moisture addition, and (x) the operation and maintenance of the leachate collections system.

The present paper builds on that of Rowe and Hosney (2010) with the objective of: (a) discussing the accuracy of a simple equation for calculating leakage compared to more sophisticated numerical analyses, (b) highlighting the differences in leakage between primary composite liners in double lined systems where the clay component is either a 0.9 thick CCL or 0.007 m thick GCL and comparing the results with those observed by Bonaparte et al. (2002), (c) discussing the effect of modest leakage rates on the transport of a typical volatile organic compound found in MSW leachate through a single composite liner system, (d) illustrating the effect of the presence or absence of an attenuation layer and the hydrogeological conditions on leakage through composite liners with a GCL, (e) comparing the potential effects of GCL-leachate compatibility on leakage through primary composite liners in double lined systems and single composite liners.

2. CALCULATING LEAKAGE THROUGH COMPOSITE LINERS

It has long been recognized that a geomembrane (GM) installed as part of liner system generally cannot be installed without some holes (2.5 to 5 holes per hectare being most commonly assumed, Rowe et al. 2004). Composite liners provide a means of minimizing the leakage and various approaches have been proposed for calculating the leakage through holes in GMs forming part of a composite liner. An early, and still widely used, approach is that proposed by Giroud and Bonaparte (1989) and subsequently modified by Giroud (1997) for calculating the leakage through a GM in direct contact with the clay liner. This approach and the related equations are appropriate for use when the GM is constructed and covered with no significant wrinkling as is reported to be the case in Germany. Under these circumstances, the leakage through typical numbers and sizes of holes are very small. However, Rowe (2005) demonstrated that the leakage actually observed at landfills where leakage has been reported for composite liners in double lined landfill systems is generally orders of magnitude larger than what could be expected based on a reasonable number and size of holes in landfills where there was appropriate construction quality control and assurance (CQC/CQA). Rowe postulated that this was likely due to the fact that in most parts of the world (Germany being a notable exception) there are interconnected wrinkles in the GM when it is covered by the leachate collection system. However while a simple equation had existed for calculating leakage through interconnected wrinkles since 1998 (Rowe 1998), in 2005 there was no data regarding the potential length of interconnected wrinkles or the factors affecting these wrinkles that could inform the calculation of leakage through interconnected wrinkles.

2.1 Winkles (waves)

A technique for documenting wrinkles present at a landfill site using high resolution low level photography was published by Take et al. (2007). This technique has subsequently been used to document how wrinkling of a GM develops as a function of exposure conditions. For example, Chappel et al. (2010) demonstrated how the interconnected wrinkle length varied during a day for a landfill located in Canada (44°23' N 79°43' W) on a day (June 11, 2007) when the ambient temperature ranged between a low of 19°C at 08:00 (8am) and a high of 26°C at 14:00 (2pm). For the specific conditions they examined, wrinkles covered 3%, 21% and 7% of the entire area surveyed at 8:45, 12:25 and 17:15, respectively. The length of interconnected wrinkles, L, varied substantially throughout the day. The shortest maximum interconnected wrinkle length was 150 m/ha at 8:45 while the longest interconnected wrinkle length was 6600 m/ha at 13:45.

It can be expected that the probability that a hole will coincide with a wrinkle increases with increasing percentage area of the GM with winkles when the leachate collection drainage layer is placed. It follows that the length of interconnected wrinkle that becomes “locked-in” to the liner system when it is covered can be controlled by controlling, inter alia, the time of day and conditions when the drainage layer is placed over the composite liner. However, the example given above involved significant wrinkling under relatively mild conditions and the interconnected wrinkle length was 150 m/ha or greater as early as 8:45 and late as 17:15. Thus controlling wrinkles will require special attention.

2.2 Interface transmissivity

Away from a wrinkle, the composite action of the GM/CCL or GM/GCL is dependant on the transmissivity, θ, of the interface between the GM and clay liner. Giroud and Bonaparte (1989) characterized typical GM - CCL contacts as “good” and “poor”. Rowe and Hosney (2010) presented photographs of some defects that contribute to “poor” contact between a GM and CCL, such as desiccation cracks that provide a conduit for fluid to distribute beneath the GM. Cartaud et al. (2005) studied the topography of the interface between 2 mm thick HDPE GM and a CCL and found that within a 1 m^2 area, the apertures between the GM and CCL could vary from direct contact to as much as 10 mm. Based on calculations for typical liner properties, Rowe (1998) related these descriptors to average transmissivities of the GM/CCL interface and these values are used in the calculations described herein.

Since a GCL can be placed flat on a smooth, well compacted foundation and since the bentonite in the GCL can swell to reduce the effect of minor irregularities, one might expect that the transmissivity of the GM/GCL interface will be much lower than that for the GM/CCL interface. Harpur et al. (1993) experimentally examined the transmissivities of GM/GCL interfaces for different GCLs at normal stresses of 7 and 70 kPa. Recognising that, except early in the active period, the stress on the liner will typically exceed 70 kPa and putting aside for the moment the possible effect of GCL-leachate interaction (which is discussed later), based on the data from Harpur et al. (1993), a reasonable value for GM/GCL transmissivity θ is considered to be 1×10^{-11} m^2/s with upper and lower bounds of 2×10^{-10} m^2/s and 2×10^{-12} m^2/s.

2.3 Rowe (1998) equation for calculation leakage through a wrinkle with a hole

Rowe (1998) presented an analytical solution for the case where a hole coincides with a wrinkle in the GM (Figure 1) assuming (a) unobstructed lateral flow along an interconnected length (L) and width (2b) of the wrinkle, and (b) lateral flow between the GM and the clay liner outside the wrinkle. Although the full form of this equation allows consideration of interactions between adjacent similar wrinkles, for the purposes of the present discussion is suffices to consider the leakage, Q, when there is no interaction between wrinkles (which gives the highest calculated leakage):

$$Q = 2\,L\,[k_s\,b + (k_s\,D\,\theta)^{0.5}]\,h_d\,/\,D \qquad [1]$$

where L is the length of the wrinkle (m); 2b is the width of the wrinkle (m); k_s is the harmonic mean of the hydraulic conductivity of the clay liner, k_L, and the underlying attenuation layer (if present), k_f, (m/s); θ is the transmissivity of the GM-clay liner interface (m^2/s) ($D/k_s = H_L/k_L + H_f/k_f$); h_d is the head loss across the composite liner (m) ($h_d = h_w + H_L + H_f - h_a$ in Figure 1); and D is the thickness of the clay liner and attenuation layer (m) ($D = H_L + H_f$ in Figure 1). Equation 1 involves some approximations but is much more convenient that a full numerical analysis that would otherwise be required. El-Zein and Rowe (2008) compared leakages obtained from Eq. 1 with those from a rigorous numerical analysis and found that for GCLs with $k_L = 5 \times 10^{-11}$ m/s it was accurate to better than 10% and for GCLs with $k_L = 2 \times 10^{-10}$ m/s it was within 20%. Given the uncertainty regarding L, k_L and θ in any design calculation, Eq. 1 is considered to be sufficiently accurate for most practical purposes.

2.4 Cases examined

Three cases are examined as illustrated schematically in Figure 2. Cases 1 and 2 involve a primary composite liner as part of a double liner system. The clay liner was a CCL ($H_L = 0.9$ m: Figure 2a) and GCL ($H_L = 0.007$ m: Figure 2b) for Cases 1 and 2 respectively. In both cases the pressure head was taken as zero at the bottom of the clay liner ($h_a = 0$) since the leak detection system was assumed to be free draining. Case 3 involved a composite liner with GCL (H_L=0.007 m) on a 3.75 m thick attenuation layer ($k_f = 1 \times 10^{-7}$ m/s) underlain by aquifer with variable location of potentiometric surface (h_a = 1.75 m and 3.5 m). In all cases there is assumed to be a wrinkle with a 1 cm^2 hole (r_o = 0.00564 m) with an interconnected length L and width 2b=0.2 m. Unless otherwise noted, "good contact" is assumed for the GM/CCL interface and a transmissivity $\theta = 1 \times 10^{-11}$ m^2/s is adopted for the GM/GCL interface.

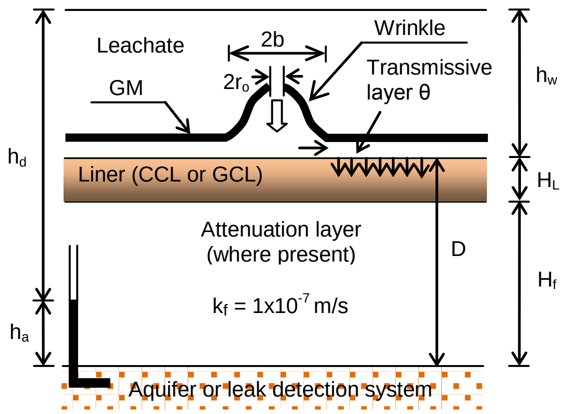

Figure 1. Schematic showing leakage through a wrinkle of length L and width 2b with a hole of radius r_o (adapted from Rowe 1998).

3. COMPARISION OF OBSERVED AND CALCULATED LEAKAGE

3.1 Observed leakage

Table 1 summarizes the mean, standard deviation (SD) and maximum average monthly leakage in the leak detection system (LDS) for composite liners with a CCL and GCL clay liner component based on data reported by Bonaparte et al. (2002). The interpretation of leakage rates for GM/CCL systems requires some consideration of the potential effect of fluid collected that may be due to consolidation water from the CCL. However for typical clay liners consolidation is relatively quick and most of the flow reported is considered to be due to leakage (see Rowe 2005 for a more extensive discussion). Compared to a GM/CCL composite liner, a GM/GCL composite reduces leakage typically by factors ranging from one to two orders of magnitude. This provides empirical evidence for superior performance of GCLs compared to CCLs in composite liners. However there is also theoretical support for this finding as discussed in the following subsection.

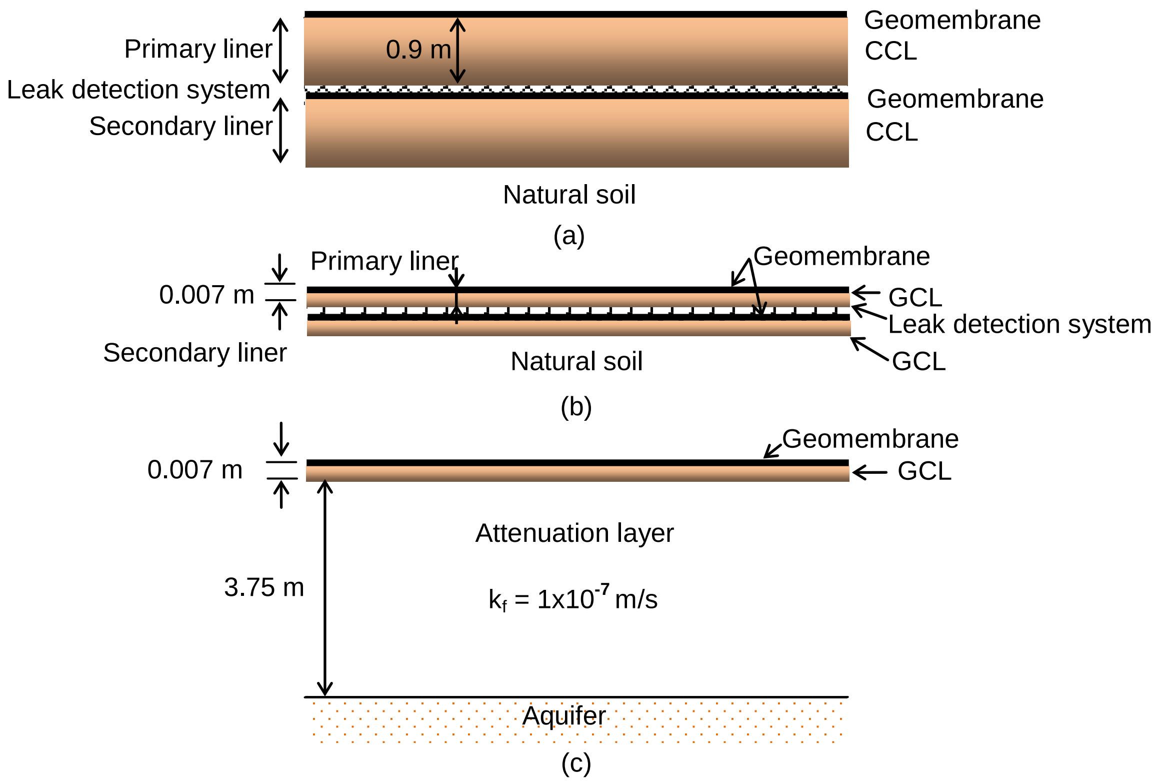

Figure 2. Schematic showing liners considered: (a) Primary composite liner with CCL, H_L=0.9 m, (b) Primary composite liner with GCL, H_L=0.007 m, (c) Single composite liner with GCL (H_L=0.007 m) on a 3.75 m thick attenuation layer underlain by aquifer with variable location of potentiometric surface (h_a = 1.75 m and 3.5 m).

3.2 Comparison of observed and calculated leakage

Using Eq. 1, the leakage was calculated for a range of assumed interconnected wrinkle lengths, L, for composite primary liners with both CCL and GCL clay components (Figure 3) and the results are compared with the observed values as given in Table 1. Table 2 summarizes the calculated length of interconnected wrinkle required to explain the observed flows for different combinations of parameters (lengths, L, greater than 60 are rounded to nearest 10 m/ha). For a CCL with a typically specified hydraulic conductivity (k_L =1x10^{-9} m/s), the maximum peak flow (1240 lphd) can be explained with a leachate head of 0.4 m and interconnected wrinkle length of 1290 m/ha. This peak flow occurs in the active period at a specific landfill and likely corresponds to a specific heavy rainfall event where leachate built up in the drainage layer before removal. The maximum average monthly flow (260 lphd) can be explained for the same conditions as the peak flow by a interconnected wrinkle length L=270 m/ha but in fact probably does not correspond to the same leachate head as the peak flow and so this represents a lower bound for the likely interconnected wrinkle length needed to explain this flow. If the leachate head were 0.05m then for the same liner L =370 m/ha would explain the maximum average monthly flow while if allowance is made for some consolidation of the liner and a decrease in k_L to $5x10^{-10}$ m/s (as has been observed; Rowe 2005), then a length L =600 m/ha is required to explain the maximum average leakage.

Table 1. Mean and standard deviations of flow in leak detection system (LDS) for landfill cells with a primary composite liner. Numbers have been rounded.
(Based on data from Bonaparte et al. 2002; adapted from Rowe 2005)

			Average Monthly Flows (lphd)			Peak Monthly Flows (lphd)		
Clay Liner	Stage	# of Cells	Mean*	SD**	Maximum	Mean*	SD**	Maximum
CCL	Active	11	90	90	260	250	370	1240
	Closure	3	50	50	220	60	90	250
	Active	22	1.5	2.7	11	9	16	54
GCL	Closure	5	0.6	0.9	2	4	5	10

* Mean and ** Standard deviation of reported average and peak average monthly flows; Maximum value in active phase for liner systems with geonet LDS.

Table 2. Calculated interconnected wrinkle length needed to explain observed leakage (Table 1) through primary composite liners for different assumed conditions (liner hydraulic conductivity, k_L; interface transmissivity, θ; leachate head, hw).

Liner	k_L (m/s)	θ (m^2/s)	h_w (m)	Length, L, of interconnected wrinkle (m/ha) needed to give				Observed (lphd)	
				Closure mean	Active mean	Maximum	Peak	Mean (Max.)	Peak
CCL	$1x10^{-10}$	$3.2x10^{-9}$	0.05	500	910	-	-		
CCL	$5x10^{-10}$	$1.2x10^{-8}$	0.05	120	210	600	-	50-90	
CCL	$1x10^{-9}$	$1.6x10^{-8}$	0.05	70	130	370	-	(260)	
CCL	$1x10^{-9}$	$1x10^{-7}$	0.05	29	52	150	-		
CCL	$5x10^{-10}$	$1.2x10^{-8}$	0.4	80	150	440	-		1240
CCL	$1x10^{-9}$	$1.6x10^{-8}$	0.4	51	90	270	1290		
GCL	$5x10^{-11}$	$2x10^{-12}$	0.05	75	180	1340	6600		
GCL	$5x10^{-11}$	$1x10^{-11}$	0.05	60	160	1140	5600	0.6-1.5	
GCL	$2x10^{-10}$	$1x10^{-11}$	0.05	18	46	330	1620	(11)	
GCL	$2x10^{-10}$	$1x10^{-10}$	0.05	13	34	250	1210		
GCL	$2x10^{-10}$	$2x10^{-10}$	0.05	12	29	210	1040		
GCL	$5x10^{-11}$	$2x10^{-12}$	0.4	11	26	190	920		54
GCL	$5x10^{-11}$	$1x10^{-11}$	0.4	9	22	160	780		

The mean average monthly leakage over a number of landfills in the active (90 lphd) and (post) closure (50 lphd) can be explained by interconnected wrinkle lengths of between 120 and 210 m/ha for k_L = $5x10^{-10}$ m/s and 500 and 900 m/ha allowing for further consolidation (especially in the post closure period) to give k_L = $1x10^{-10}$ m/s (Rowe et al. 2004; Rowe 2005).

For a GCL with a typically specified hydraulic conductivity k_L = $5x10^{-11}$ m/s, the maximum peak flow (54 lphd) can be explained with a leachate head of 0.4 m and interconnected wrinkle length of 780 m/ha.

For the same head, the maximum average monthly flow (11 lphd) can be explained an interconnected wrinkle length of about 160 m/ha but in fact probably does not correspond to the same leachate head as the peak flow and so this represents a lower bound on the likely interconnected wrinkle length needed to explain this flow. If the leachate head were 0.05 m then for the same liner L=1140 m/ha would explain the maximum average monthly flow. For h_w=0.05 m, the mean average monthly leakage over a number of landfills in the active (1.5 lphd) and post-closure (0.6 lphd) period can be explained by interconnected wrinkle lengths of between 60 and 180 m/ha.

While one can not establish any definitive interconnected wrinkle length to explain the observed leakages, the analysis given above suggested that for the primary composite liners for which data was reported by Bonaparte et al. (2002) as summarized in Table 1, the interconnected wrinkle lengths with a hole after waste placement were typically less than 1300 m/ha and most commonly likely in the range from 120 to 600 m/ha, with values less than 100 m/ha being possible with good attention to the conditions when the GM is covered. These values are generally within the range observed for landfills in North America assuming that the GM is not covered when a large proportion of the landfill is wrinkled (i.e. it is covered when less than 5% of the area is wrinkled).

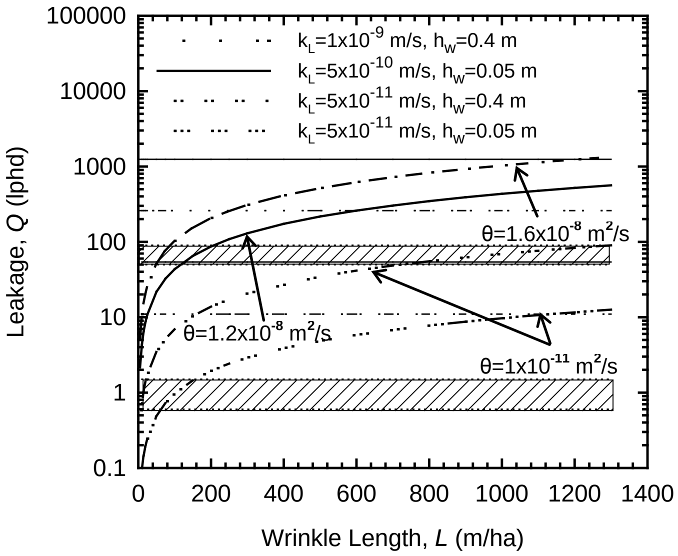

Figure 3. Calculated and observed leakage for primary composite liners with CCL and GCL showing the effect of leachate head and interconnected wrinkle length.

CCL (Figure 2a): (i) k_L= $1x10^{-9}$ m/s, h_w=0.4 m, θ = $1.6x10^{-8}$ m^2/s (good contact); (ii) k_L=$5x10^{-10}$ m/s, h_w=0.05m, θ = $1.2x10^{-8}$ m^2/s (good contact); GCL (Figure 2b): (iii) k_L=$5x10^{-11}$ m/s, h_w=0.4m, θ = $1x10^{-11}$ m^2/s; (iv) k_L=$5x10^{-11}$ m/s, h_w=0.05 m, θ = $1x10^{-11}$ m^2/s. The upper shaded region is defined by the mean value of the observed average monthly flows in the active (90 lphd) and post-closure (50 lphd) period for GM/CCL primary liners. The lower shaded region shows corresponding typical field leakage rates (1.5-0.6 lphd) for GM/GCL primary liners. Upper and lower solid lines are the maximum peak flows of 1240 lphd and 54 lphd for GM/CCL and GM/GCL, respectively. Upper and lower dashed lines are the maximum average monthly flows of 260 lphd and 11 lphd for GM/CCL and GM/GCL, respectively.

4. FACTORS AFFECTING LEAKAGE THROUGH COMPOSITE LINERS

For leakages of less than about 6 lphd (corresponding to a Darcy flux of 0.0002 m/a), diffusion will be the dominate transport mechanism for volatile organic compounds (e.g. DCM, benzene etc) that can diffuse through the geomembrane and the effect of leakage is small. For leakages greater than 275 lphd (corresponding to a Darcy flux of 0.01 m/a) leakage will dominate over diffusion. Between these limits both transport mechanisms can be important. For example, El-Zein and Rowe (2008) examined pure diffusion and diffusive-advective transport of dichloromethane (DCM) through a composite liner similar to that shown in Figure 2c. For the specific case that they examined, the diffusion of DCM though an intact GM and the liner system gave a peak impact in the aquifer of 2.1 µg/L after 75 years. For a leakage of 6 lphd the peak impact (2.2 µg/L) that was only 5% higher than for pure diffusion, indicating that diffusion was the dominate transport mechanism. As the leakage increased to 24, 48 and 80 lphd the peak impact increased by 24%, 52% and 114% to 2.6, 3.2 and 4.5 µg/L. Thus leakages less than 6 lphd are likely to cause negligible impact as a result of the leakage itself for most common practical cases (and this covers most of the cases reported in Table 1). Even for the greatest observed leakage reported in Table 1 (54 lphd), for the case examined by El-Zein and Rowe (2008), the increase in impact would be modest (about 1 µg/L).

4.1 Liner configuration and hydrogeological conditions

The leakage through a composite liner will depend on the liner configuration and hydrogeological conditions as illustrated in Figure 4. For a typically specified k_L=5x10^{-11} m/s (θ=1x10^{-11} m^2/s) the leakage through a single composite liner configuration shown in Figure 2c (H_f=3.75m) is greater than that for a primary composite liner (Figure 2b, H_f=0, h_a=0) and is quite sensitive to the assumption regarding the level of the potentiometric surface in the underlying aquifer (h_a) since this controls the head difference h_d across the liner and hence the hydraulic gradient across the liner (recognizing that for an unsaturated attenuation layer beneath the GCL, matric suctions beneath the GCL will increase the gradient across the GCL compared to that in a primary liner). For a typical as specified GCL with k_L=5x10^{-11} m/s (θ = 1x10^{-11} m^2/s) in a primary liner, the leakage was in the diffusion controlled range (Q<6 lphd) for interconnected wrinkle lengths, L, up to about 100 m/ha, below 54 lphd for L< 1000 m/ha, and did not go into the advection controlled range (Q>275 lphd) until ≈5300 m/ha. Whereas for the single composite liner (Figure 2c and the same k_L and θ) these leakages are reached for L of 75, 650 and 3600 m/ha for h_a=3.5m, 20, 150 and 860 m/ha for h_a=1.75m, and 10, 90 and 490 m/ha for h_a=0m. Thus the significance of a given wrinkle network and length of interconnected wrinkle will depend on the liner configuration and hydrogeological conditions. As illustrated in the next subsection it also depends on the hydraulic conductivity of the GCL.

4.2 Clay-leachate interaction

Figure 5 again shows that for a typical as specified case with k_L=5x10^{-11} m/s (θ=1x10^{-11} m^2/s), the leakage was about 6, 54 and 275 lphd for L of about 100, 1000 and 5300 m/ha respectively. Thus with reasonable care, it should not be difficult to ensure interconnected wrinkle lengths, L, that will result in small leakages for this case. However if there is significant interaction with leachate leading to k_L=2x10^{-10} m/s (θ = 2x10^{-10} m^2/s) the leakage was only in the diffusion controlled range for interconnected wrinkle lengths of L of 20 m/ha or less. The leakage was below 54 lphd only for L< 200m/ha and goes into the advection controlled range at ≈ 1000 m/ha. Thus the interconnected wrinkle length becomes much more significant if there is likely to be a significant increase in k_L due to clay-leachate interaction.

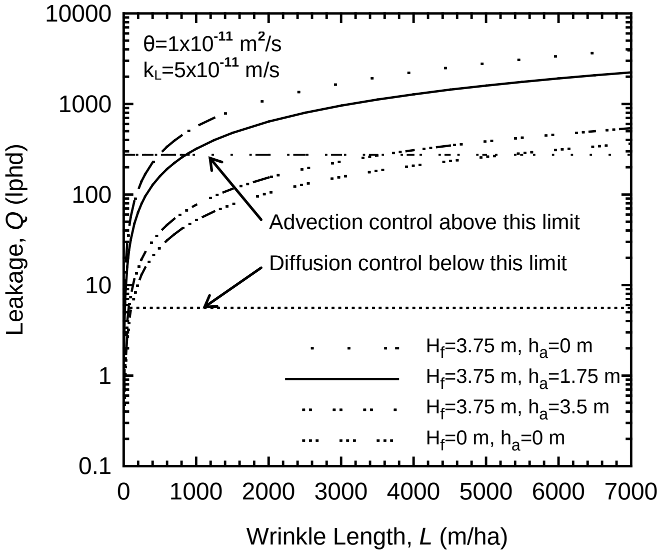

Figure 4. The effect of hydrogeological conditions on leakage. Variation in leakage with interconnected wrinkle length for a GCL as part of a primary composite liner (h_w=0.3m).

To explore the effect of GCL-leachate interaction further, Figures 6 and 7 show the calculated leakage as a function of GCL hydraulic conductivity for a primary composite liner (Figure 2b, h_w=0.3m, h_a=0) and single composite liner (Figure 2c, h_w=0.3m, h_a=3.5m) respectively. Results are shown assuming (a) transmissivity does not change with clay leachate interaction ($\theta=1\times10^{-11}$ m^2/s) and (b) that the transmissivity increases in direct proportion to the increase in k_L (θ=0.2 k_L) for two wrinkle lengths (L= 125 and 500 m/ha).

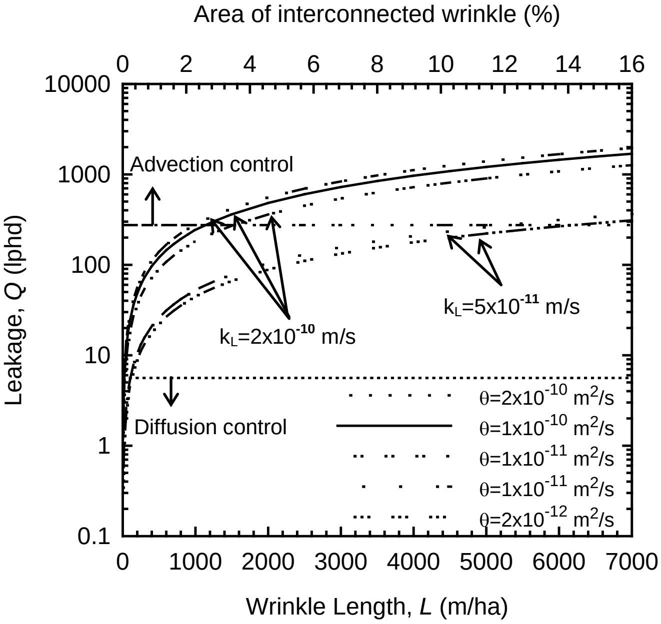

Figure. 5. Variation in leakage with interconnected wrinkle length for a GCL as part of a primary composite liner (Figure 2b, h_w=0.3m, h_a=0m) for different combination of GCL hydraulic conductivity and interface transmissivity.

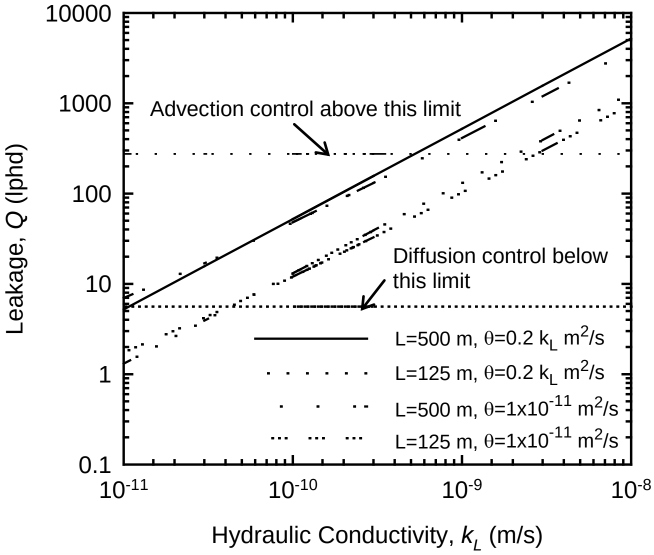

Figure 6. Variation in leakage with GCL hydraulic conductivity (leachate head h_w=0.3m) for primary composite liner (Figure 2b).

For a primary composite liner (Figure 6) the assumption regarding interface transmissivity, while having some effect, is secondary to the effects of k_L and L. For L=500 m/ha, leakage exceeds 50 lphd for k_L > $1x10^{-10}$ m/s and moves into the advection dominated range (Q >275 lphd) for k_L> $5x10^{-10}$ m/s. With strict control on wrinkle length when the liner is covered such that L<125 m/ha, leakage exceeds 50 lphd for $4x10^{-10}$ m/s and moves into the advection dominated range (Q >275 lphd) for k_L> $2x10^{-9}$ m/s. Thus controlling wrinkle length assumes increasing importance with increasing potential for a significant increase in k_L due to interaction with leachate. This is likely to be especially important for GCL in double liner systems where there is limited capacity to hydrate before coming into contact with leachate.

For a single composite liner (Figure 7) the leakages for low GCL k_L are higher than for the double composite liner, however this situation changes as k_L of the GCL increases (e.g. due to interaction with leachate) and the attenuation layer places a control on the leakage. Also the assumption regarding interface transmissivity assumes somewhat greater significance for this case than for the primary liner.

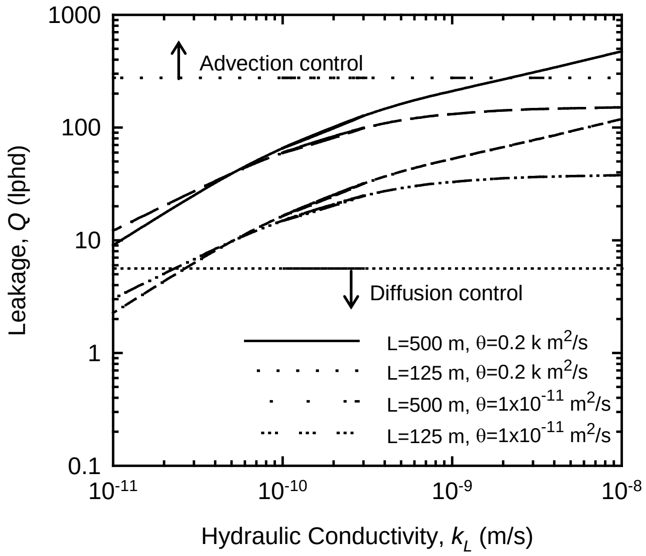

Figure 7. Variation in leakage with GCL hydraulic conductivity (leachate head h_w=0.3m) for (i) single composite liner (Figure 2c, h_a=3.5m).

5. CONCLUSIONS

The simple one-line equation proposed by Rowe (1998) for calculating leakage through a wrinkle with a hole provides estimates of leakage though primary composite which are consistent with those observed in landfills in North America for interconnected wrinkle lengths typically less than 1300 m/ha and most commonly likely in the range from 120 to 600 m/ha, with values less than 100 m/ha being possible with good attention to the conditions when the GM is covered. These values are generally with in the range observed for landfills in North America assuming that the GM is not covered when a large proportion of the landfill is wrinkled. Both theoretical calculations and empirical observations suggest that a composite liner with a GCL will generally perform better than a composite liner with a CCL. It is suggested that leakages less than 6 lphd are likely to cause negligible impact as a result of the leakage itself for most common practical cases involving a GCL as part of a composite liner (and this covers most of the cases observed where leakage has been monitored). However the length of interconnected wrinkle that will give rise to leakages of less than 6 lphd will depend on the liner configuration and hydrogeological conditions and could range between 10 and 100 m/ha for the cases examined. To control leakage to less than about 50 lphd, the interconnected wrinkles with a hole must be less than about 90-1000 m/ha depending on the configuration examined. The significance of the effect of wrinkles on leakage also depends on the potential for interaction between the leachate and GCL. For a 0.3m design head and assuming strict control on wrinkle length when a primary composite liner is covered such that it is less than 125 m/ha, leakage, Q, exceeds 50 lphd for a hydraulic conductivity of the liner, k_L, greater than 4×10^{-10} m/s and moves into the advection dominated range (Q >275 lphd) for $k_L > 2 \times 10^{-9}$ m/s. Thus controlling wrinkle length assumes increasing importance with increasing potential for a significant increase in k_L due to interaction with leachate. This is likely to be especially important for GCL in double liner systems where there is limited capacity to hydrate before coming into contact with leachate. The available evidence would suggest that in landfill applications where there has been good construction quality control and assurance and where data is available, the leakages through composite liners with a GCL are low and they have been performing well despite some wrinkling in the geomembrane when covered. However the results presented herein suggest that more attention should be addressed to the control of wrinkling especially if there are (a) low stresses on the liner and/or (b) potential for significant increase in the hydraulic conductivity of the GCL with time (e.g. due to clay-leachate interaction). While more research is required to confirm the findings, based on exiting evidence it would appear highly desirable to control the wrinkling when a geomembrane is covered such that the length of interconnected wrinkles is less than 500m/ha and ideally less than 125 m/ha. While this is required in some jurisdictions (e.g. Germany where wrinkles are not permitted at time of covering of the liner) more emphasis needs to be placed on this issue in construction specifications or regulations in most countries.

ACKNOWLEDGEMENTS

Funding for the research infrastructure and research was provided by the Canada Foundation for Innovation, the Ontario Innovation Trust (OIT-MRI) the Natural Sciences and Engineering Research Council of Canada and the Ontario Ministry of the Environment. The author gratefully acknowledges the value of discussions with his colleagues at the Geongineering Centre at Queen's-RMC and industrial partners (Terrafix Geosynthetics Inc., Solmax International Inc., AMEC Earth and Environmental, AECOM, Golder Associates, and the CTT Group), however the opinions stated here in are solely those of the author. Mr. M.S. Hosney assisted with the preparation of the figures.

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