A systems engineering approach to minimizing leachate leakage from landfills

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ABSTRACT: Leakage through composite base liners in landfills depends on the number and size of holes as has long been recognized. However it is not well recognized that other aspects of design, construction, and operations also can have a profound impact on leakage during both the operating life and contaminating lifespan of the landfill. This paper highlights the need to consider the landfill as a system when seeking to minimize leachate leakage through composite liners. In particular it demonstrates that calculations of leakage that do not consider the interactions between the different components of the system will significantly underestimate the leakage that will occur. On the positive side, it is also argued that by taking a systems approach with the objective of minimizing long-term contaminant impact, the leakage through the barrier system can be minimized for the operating life of the composite liner.

1 INTRODUCTION

The barrier system at the bottom of modern landfills typically incorporates a leachate collection system, a geotextile protection layer and a composite liner comprised of a geomembrane (GM) over either a geosynthetic clay liner (GCL) or compacted clay liner (CCL) on an attenuation layer (which typically has a hydraulic conductivity of less than 10^{-7} m/s). It is well recognized that even with good construction quality control and assurance (CQC/CQA) there will be some holes in the geomembrane and that leakage will occur through those holes with an assumption of 2.5 to 5 holes/ha being commonly used as a design value (Giroud and Bonaparte 2001). Leakage through composite base liners in landfills depends on the number and size of holes as has long been recognized. However it is not well recognized that other aspects of design, construction, and operations also can have a profound impact on leakage during both the operating life and contaminating lifespan of the landfill.

The objective of this paper is to highlight the need to consider the landfill as a system when seeking to minimize leachate leakage through composite liners. In particular, attention will be devoted to demonstrating that calculations of leakage that do not consider the interactions between the different components of the system will significantly underestimate the leakage that will occur.

2 A SYSTEMS ENGINEERING APPROACH

Rowe (2009a) discussed the need to adopt a systems engineering approach to the design and operation of municipal solid waste (MSW) landfills. It was argued that from an engineering perspective, the long-term performance of the modern MSW landfills will be governed by the performance of a system comprised of three primary subsystems: the barrier system below the waste, the landfill operations, and the landfill cover and gas collection system. That paper took a very broad approach to the issue of ensuring environmental protection. This paper aims to focus on the need to take a systems approach to calculate and minimize leakage through composite liners during their service life.

The thesis of this present paper is that any evaluation of leachate leakage must consider how the interaction between different components of the landfill system affects the leakage. In particular, factors such as the design of: (i) the landfill cover (which controls the influx of fluid), (ii) leachate collection system (which controls the leachate head on the liner and hence the driving force to cause leakage), and (iii) the choice of GCL or CCL as the clay component of the composite liner (which controls the effectiveness of the composite action) will impact on leakage through the composite liner. Likewise, factors associated with construction including: (iv) the number and size of unfixed holes, (v) the area of landfill with wrinkles (waves) and, in particular, the interconnected length of any wrinkles with a hole, (vi) and the nature of the surface of the foundation upon which a GCL is placed or the surface of a CCL upon which the GM is placed will have a significant effect on the magnitude of leakage through the liner. Finally, operational issues such as the (vii) nature of the waste, (viii) the waste placement sequence, (ix) recirculation of leachate or other moisture addition, and (x) and operation and maintenance of the leachate collections system can impact on leakage through a composite base liner. These various factors will be discussed in the following sections of the paper.

3 LEAKAGE CALCULATIONS

Traditionally leakage has been calculated, assuming the GM is in direct contact with the clay liner, with equations developed by Giroud and Bonaparte (1989), and subsequently the modified equations by Giroud (1997) are being most commonly used. These equations are appropriate to use where the GM is indeed constructed and covered with no significant wrinkling (e.g. Figure 1) as is reported to be the case in Germany. However, in most parts of the world, when a geomembrane is covered by the leachate collection system there will be interconnected wrinkles in the GM (Figure 2).

Figure 1. GM with essentially no wrinkles (in direct contact with the underlying clay liner); cloudy early November morning when ambient temperature 3°C.

Rowe (1998) presented an analytical solution for the case where a hole coincides with a wrinkle in the GM (Figure 3) assuming unobstructed lateral flow along the length, L, and across the width, 2b, of the wrinkle and lateral flow between the GM and the soil outside the wrinkle. This equation allows consideration of interactions between adjacent similar wrinkles assumed to be spaced at a distance 2x apart and the leakage, Q, is given by:

Figure 2. Interconnected wrinkles in a GM; midmorning when ambient temperature is 17°C (same location as shown in Figure 1)

$$Q = 2\,L\,k_s\,[b + \{1 - \exp(-\alpha\,(x-b))\}/\alpha]\,h_d / D \quad (1)$$

where L is the length of the wrinkle (m); 2b is the width of the wrinkle (m); $\alpha = [k_s/(D\theta)]^{0.5}$; k_s is the harmonic mean of the hydraulic conductivity of the clay liner, k, and the underlying attenuation layer (m/s); θ is the transmissivity of the GM-clay liner interface (m^2/s); h_d is the head loss across the composite liner (m); and D is the thickness of the clay liner and attenuation layer (m). Assuming no interaction with an adjacent wrinkle, the leakage, Q, is given by:

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

Rowe (2005) demonstrated that the observed leakage through composite primary liners (both with a CCL and GCL) in double liner landfills where leakage had been monitored is considerably (often by an order of magnitude or more) greater than what would be expected for the typical number of holes in GMs if the GM were in intimate contact with the underlying clay liner. However the observed leakage was explained by using Rowe’s Equation (Equation 2 above) and considering the holes being in, or closely adjacent to, wrinkles in the GM.

Equation 2 provides a convenient mean of calculating leakage for many practical situations where wrinkles are expected, and the assumption of direct contact is not appropriate.

4 SCENARIO USED FOR NUMERICAL EXAMPLES

For the purposes of numerically illustrating many of the points to be raised in this paper, consideration will be given to two specific examples of a composite liner.

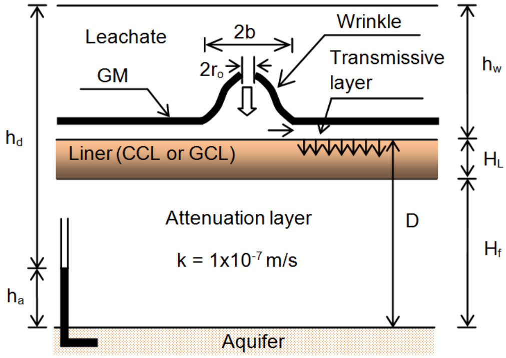

Figure 3. Schematic showing leakage through a wrinkle of length L and width 2b with a hole of radius r_o.

Case 1 examines a composite GM/GCL liner where the GCL is 0.007m thick (H_L=0.007m in Figure 3) and rests on an attenuation layer with a hydraulic conductivity of 10^{-7} m/s and thickness such that the distance between the top of the GCL and the top of the underlying aquifer is 3.75m (i.e D=3.75m in Figure 3; the minimum allowed under regulations in Ontario Canada). The base case hydraulic conductivity, k, of the GCL is taken to be 5x10^{-11} m/s, although other values will also be explored.

Case 2 examines a composite GM/CCL liner where a CCL of thickness H_L=0.6m rests on an attenuation layer with a hydraulic conductivity of 10^{-7} m/s and thickness such that the distance, D (Figure 3) between the top of the CCL and the top of the underlying aquifer is 3.75m (i.e. the same as for Case 1). The base case hydraulic conductivity, k, of the CCL is taken to be 1x10^{-9} m/s.

In both cases it is assumed that the poteniometric surface in the aquifer is 3.5m above the top of the aquifer (h_a=3.5m in Figure 3). For the base case the leachate head on top of the liner, h_w, is 0.3m (although other values will also be considered). The head difference, h_d, across the liner (Figure 3) is given by:

$$h_d = D - h_a + h_w = 0.25\text{m} + h_w \qquad (3)$$

and the gradient in the absence of the GM would be h_d/D. This gradient and the harmonic mean hydraulic conductivity of the liner and attenuation layer places a limit on the leakage that can occur (i.e the composite action of the liner is lost when the leakage through the composite liner is equal to that which would occur with no GM: leakage limit = $k_s h_d/D$). A second limit on the leakage is imposed by the sum of the flow through the landfill cover (which depends on climate and cover design) and the amount of fluid introduced to accelerate gas generation. For the purposes of the calculations presented in this paper it is assumed that this is sufficiently greater than the calculated leakage not to impose a limit.

The calculation of leakage assumes that a hole with a radius of 0.00564m (r_o=0.00564m, Figure 3) in the geomembrane coincided with one interconnected wrinkle of width 2b=0.2m and a length, L, of 125m/ha, although lengths ranging from 15m/ha to 6600m/ha will be examined. If there is no hole in, or near, an interconnected wrinkle the leakage will be much lower than calculated. If there is more than one hole in an interconnected wrinkle per hectare, the leakage could be greater than is calculated.

5 IMPLICATIONS OF CONSTRUCTION

It is well recognised that good CQC/CQA is necessary to minimize the number of holes in the GM. However, it is not so widely recognised that the leakage through the holes that remain after any leak detection survey will be highly dependant on (a) the wrinkles in the GM at the time it is covered by the leachate drainage layer and, especially where the clay liner is a CCL, (b) the nature of the surface of the clay liner upon which the GM is placed.

Take et al. (2007) described a means of documenting wrinkles present at a landfill site using high resolution low level photography. Chappel et al. (2010) used this technique to document the manner in which wrinkling of a GM develops during a day for a landfill located at 44°23' N 79°43' W on June 11, 2007. The ambient temperature ranged between a low of 19°C at 8:00 and a high of 26°C at 14:00 (2pm). They found that, for the specific conditions examined, wrinkles covered 3%, 21% and 7% of the entire area surveyed at 8:45, 12:25 and 17:15, respectively. The interconnectivity of wrinkles also varied substantially throughout the day with interconnected wrinkle feature greater than 2000 m long being observed at around noon and in the early afternoon. The shortest maximum interconnected wrinkle feature of 150 m/ha was measured at 8:45 while the longest such feature was 6600 m/ha at 13:45.

The probability that a hole will coincide with a wrinkle would increase substantially if the GM were covered with the leachate collection drainage layer after it has heated up due to solar radiation and the interconnected wrinkle length, L, can be quite substantial. This highlights the need to specify limits on the amount of wrinkling that is allowed at the time the GM is covered and to require that procedures be adopted (e.g. covering only in the early morning) to minimize wrinkles being “locked-in” to the liner system when it is covered.

The composite action of the GM/CCL away from a wrinkle is dependant on the transmissivity, θ, of the interface between the GM and CCL. Giroud and Bonaparte (1989) characterized two typical GM -

CCL contacts: "good" and "poor". Based on calculations for typical liner properties (k=10^{-9} m/s) these descriptors can be related to average transmissivities of the GM/CCL interface of $1.6\text{x}10^{-8}$ m^2/s and $1\text{x}10^{-7}$ m^2/s respectively (Rowe, 1998). Cartaud *et al.* (2005a,b) used laser rugosimetry to study the topography of the interface between 2mm thick HDPE GM and CCL and found that within a $1m^2$ area, the apertures could vary from direct contact to 10mm. Figures 4 and 5 show some of the defects that contribute to "poor" contact between a GM and CCL in that the irregularities and defects (such as desiccation cracks) provide a conduit for fluid to distribute beneath the GM.

Figure 4. Photograph of a clay liner just before placement of overlying GM. Note desiccation cracks.

Figure 5. Photograph of a poor surface of a clay liner.

Because the GCL can be placed flat on a well compacted, smooth and firm foundation and because the bentonite in the GCL can swell to reduce the effect of minor irregularities, the transmissivity of the GM/GCL interface can be expected to be much lower than for GM/CCL interface. Thus when a GM is placed over a GCL, there is greater potential for obtaining good contact with a low permeability layer than when placed over a CCL. Harpur *et al.* (1993) reported transmissivities of GM/GCL interfaces of between $1\text{-}2\text{x}10^{-12}$ m^2/s (at a normal stress of 70kPa) and $2\text{x}10^{-10}$ m^2/s (at 7kPa).

The effect of interconnected wrinkle length and interface transmissivity is illustrated in Figure 6 for composite liners involving a CCL (k=$1\text{x}10^{-9}$ m/s; θ= $1\text{x}10^{-7}$ m^2/s for "poor" contact and $1.6\text{x}10^{-8}$ m^2/s for "good" contact) and a GCL (k=$5\text{x}10^{-11}$ m/s; θ= $2\text{x}10^{-10}$ m^2/s for "poor" contact and $2\text{x}10^{-12}$ m^2/s for "good" contact). Noting that this is a logarithmic scale for leakage, it can be observed that for a given interconnected wrinkle length, composite liners with a GCL generally give substantially lower leakage than those with a CCL. This is largely a result of the much lower interface transmissivities with a GCL than CCL. This observation ceases to be valid if there is a very large interconnected wrinkle length (greater than 5000m/ha) and relatively poor contact at the GM/GCL interface. This might occur if there is both poor construction and low stress on the liner. However in the more likely case where there is good contact between the GM and GCL, the composite with a GCL is still better than that with a CCL. It can be observed from Figure 6 that the GM/CCL composite liner reach the leakage limit of 750 lphd, when the wrinkle length is about 600 m/ha and 1500m/ha for poor and good contact conditions, respectively. Reaching this limit implies that the GM is no longer effectively contributing to controlling leakage assuming a hydraulic conductivity of the CCL of 10^{-9} m/s.

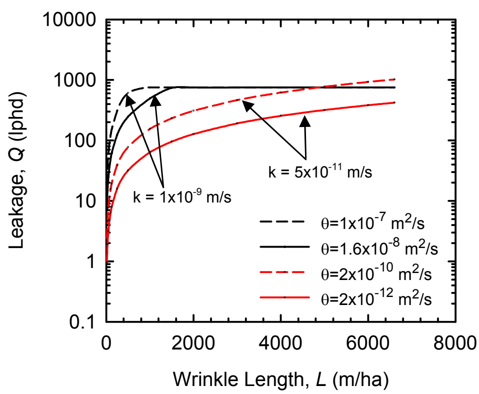

Figure 6. Leakage through a hole in an interconnected wrinkle of length L (in metres per hectare) for a single composite liner with (i) CCL with k=$1\text{x}10^{-9}$ m/s and "poor" contact away from wrinkles, θ=$1\text{x}10^{-7}$ m^2/s, (ii) CCL with k=$1\text{x}10^{-9}$ m/s and "good" contact away from wrinkles, θ=$1.6\text{x}10^{-8}$ m^2/s, (iii) GCL with k=$5\text{x}10^{-11}$ m/s and "poor" contact away from wrinkles, θ=$2\text{x}10^{-10}$ m^2/s, and (iv) GCL with k=$5\text{x}10^{-11}$ m/s and "good" contact away from wrinkles, θ=$2\text{x}10^{-12}$ m^2/s.

Assuming excellent construction supervision and covering in the cool of the very early morning such that the interconnected wrinkles are kept to only 15-30m/ha, then the leakage through composite liner with a GCL in good contact (θ= $2x10^{-12}$ m^2/s) is only 1-2 lphd. For the same liner systems but less attention to when the GM is covered, one can easily get the range of interconnected wrinkle length up to 2000 m/ha. Here the leakage through the composite liner ranges from 8 to 127 lphd for interconnected wrinkles between 125-2000 m/ha. With a hole in an interconnected wrinkle of length 6600m/ha (the largest observed by Chappel et al. (2010) near mid-day when ambient temperature was 26°C), the leakage increases to 420 lphd.

For higher transmissivity GM/GCL of the interface $\theta=2x10^{-10}$ m^2/s but excellent construction supervision ensuring that when the drainage layer is placed the buried largest interconnected wrinkles are only 15-30 m/ha, the leakage through the composite liner is 2-5 lphd or a little more than twice that with good contact. For the range of interconnected wrinkle length between 125-2000m/ha, the leakage through the composite liner ranges from about 20 to 310 lphd.

For a CCL and "good" contact away from the wrinkle and excellent construction supervision with interconnected wrinkles of only 15-30 m/ha, the leakage through composite liner is 7-15 lphd. For the range of interconnected wrinkle lengths between 125-2000 m/ha, the leakage through the composite liner ranges from about 60 to 750 lphd. In fact with a CCL, as described earlier, once the interconnected wrinkle length exceeds about 1500m/ha, the advantages of a composite liner are essentially lost and the leakage becomes asymptotic to that which would occur if there were no GM.

For a CCL and "poor" contact away from the wrinkle with interconnected wrinkles of 15-30 m/ha, the leakage through composite liner is 18-36 lphd. For the range of interconnected wrinkle length of 125-2000 m/ha, the leakage through the composite liner ranges from about 150 to 750 lphd with the advantages of a composite liner being essentially lost when the interconnected wrinkle length exceeded about 600m/ha.

For a CCL, a key construction related issue is the nature of the surface between the GM and GGL at the time the drainage layer is placed over the composite liner. This is not only related to the surface when the GM is placed (see Figs. 4 and 5) but also to desiccation cracking that can occur beneath the GM after it is placed and before the drainage layer is placed. Poor interface conditions and interconnected wrinkle length around 600 m/ha can result in significant leakage through the composite liner to the point that the composite action and the effect of the GM is largely gone.

For a GCL the key construction issues include: (a) ensuring a firm smooth surface, upon which the GCL is placed, (b) ensuring that the overlap is sufficient to maintain adequate overlap after any shrinkage of panels between the time the composite liner is constructed and the drainage layer is placed (this problem can be minimized by covering the composite liner quickly), (c) ensuring the GM and GCL are not torn during subsequent construction activities (e.g. placements of the drainage layer).

6 IMPLICATIONS OF CHANGES IN THE GCL HYDRAULIC CONDUCTIVITY

A typical GCL hydraulic conductively with respect to water is $5x10^{-11}$ m/s although is not uncommon to get as low as $2x10^{-11}$ m/s and higher values can result from interaction of the bentonite with either cations in the soil or leachate. To examine the effect of GCL hydraulic conductivity, the leakage was calculated for the case of good ($\theta=2x10^{-12}$ m^2/s) and poor ($\theta=2x10^{-10}$ m^2/s) interface transmissivity and an interconnected wrinkle with a hole of length 125m/ha for a range of hydraulic conductivities between $2x10^{-11}$ m/s and $2x10^{-8}$ m/s (see Rowe 1998 or Rowe et al. 2004) as shown in Figure 7. If the interface transmissivity does not change, a change in hydraulic conductivity from $2x10^{-11}$ m/s to $2x10^{-8}$ m/s resulted in an increase in leakage from about 4 to 34 lphd for good contact ($\theta=2x10^{-12}$ m^2/s) and an increase from about 12 to 60 lphd for poor contact ($\theta=2x10^{-10}$ m^2/s). Thus, provided that the interconnected wrinkle length remains modest (125m/ha or less), a significant increase in the hydraulic conductivity of the GCL has only a modest effect on leakage. This is because the primary roll of the GCL is to reduce the spread of leachate by reducing the transmissivity of the GM/GCL interface rather than due to the hydraulic conductivity of the GCL below the wetted area itself.

Although the results in Figure 7 are reassuring, they do assume the transmissivity does not change when the GCL hydraulic conductivity, k, changes. This represents a best case. It could be argued the transmissivity could also increase as the hydraulic conductivity increased. This case is examined in Figure 8 which shows that for a good initial interface ($\theta=2x10^{-12}$ m^2/s = 0.1k), the leakage increased from about 4 to 120 lphd due to an increase in both k and θ by 3 orders of magnitude. However for the increase in k and θ by about one order of magnitude, the leakage only increased from 4 to a still relatively low 23 lphd. Thus while interaction between the bentonite and leachate or cations in the soil may cause an increase in leakage, the leakage is still likely to be small provided that the interconnected wrinkle length is kept modest (125m/ha or less).

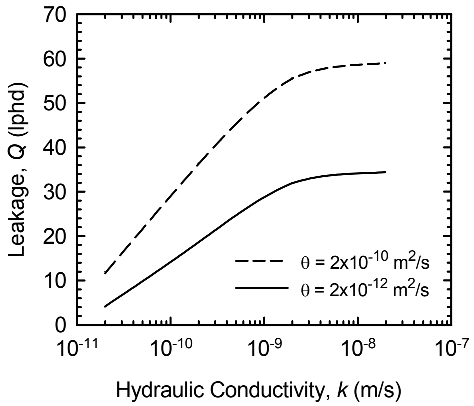

Figure 7. Leakage through composite liner (GM and GCL) as a function of GCL hydraulic conductivity for two constant interface conditions and a hole in a wrinkle with an interconnected length of 125m/ha.

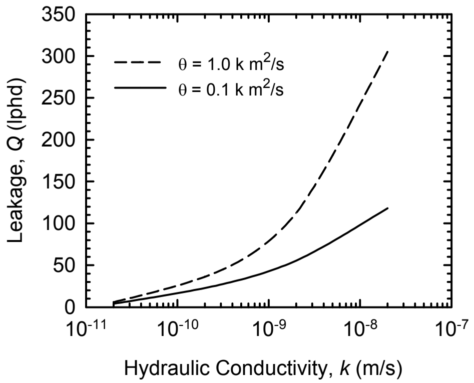

Figure 8. Leakage through a hole in a wrinkle with an interconnected length of 125m/ha for a composite liner (GM and GCL) as a function of GCL hydraulic conductivity, k, assuming that the interface transmissivity is (i) θ=1k, and (ii) θ=0.1k.

7 IMPLICATIONS OF LANDFILLING OPERATIONS

In the absence of a waste that generates heat due to either biological or exothermic chemical reactions, the landfill liner temperature would be very close to the ground temperature below the depth affected by seasonal changes (typically within a few degrees of annual average ambient temperature). In many parts of the world, this temperature is in the 10 to 25°C range. However, as discussed in more detail by Rowe (2009a), the nature of the waste that is disposed and operational factors such as the rate at which waste thickness increases and the addition of moisture (e.g. for a wet or "bioreactor" landfill) all affect the liner temperature. For "typical" MSW with a significant organic component and normal landfill operations, a liner temperature of the order of 30-40°C is common. For MSW with a significant organic component and enhanced moisture so that it operates as a bioreactor to maximize the rate of gas generation, the liner temperature is often in the 50-60°C range (Rowe and Islam 2009). In other cases landfill temperatures of 70-80°C (or, in a few cases even higher) have been encountered. These temperatures have significant implications for the service life of the liners (Rowe and Islam 2009). For the present paper, however, attention will be focused on the effect of the increase in the leakage through the composite liner during the service life of the GM.

The transport of fluids, such as leachate, through a clay liner depends on the hydraulic gradient, the structure of the clay, and the viscosity of the fluid. Assuming here that the change of temperature does not change the clay structure (e.g. does not cause desiccation cracking which is a key factor affecting the service life of the clay liner), there can still be a significant increase in hydraulic conductivity (Rowe 2005) and interface transmissivity due to an increase in temperature. Taking the hydraulic conductivity and interface transmissivity at 20°C as the base case since this corresponds to laboratory temperature at which these parameters are often established and hence are the parameters typically used in design calculations, Figures 9 and 10 show how the leakage through a hole in a wrinkle with an interconnected length of 125m/ha changes with changing temperature for composite liners involving a GCL and CCL respectively.

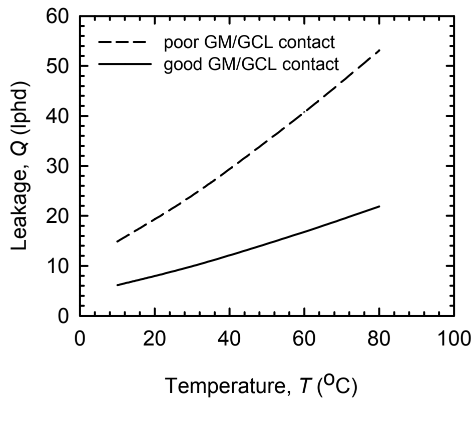

Figure 9. Effect of temperature on leakage through a hole in a 125m/ha wrinkle in a GM over a GCL for "good" and "poor" contact conditions (Base case parameters at 20°C: $k=5x10^{-11}$ m/s and "good" $\theta=2x10^{-12}$ m^2/s, "poor", $\theta=2x10^{-10}$ m^2/s)

For a composite liner with a GCL and "good" GM/GCL interface conditions (Figure 9), the leakage at 10-20°C is 6-8 lphd but this more than doubles to 17 lphd at 60°C and almost trebles to 22 lphd at 80°C. For "poor" interface conditions the corresponding values at 20, 35, 60 and 80 °C are 19, 27, 41 and 53 lphd.

For a composite liner with a CCL and "good" GM/GCL interface conditions (Figure 10), the leakage at 10-20°C is 47-62 lphd but this more than doubles to 130 lphd at 60°C and almost trebles to 170 lphd at 80°C. For "poor" interface conditions the leakage values at 20, 35, 60 and 80°C are 150, 210, 320 and 420 lphd.

It can be inferred from the forgoing that the leakage at a temperature of 35 and 60°C are likely to be 40% and 110% greater than that calculated using traditional parameters at 20°C and this should be considered in the landfill design and any contaminant transport modeling.

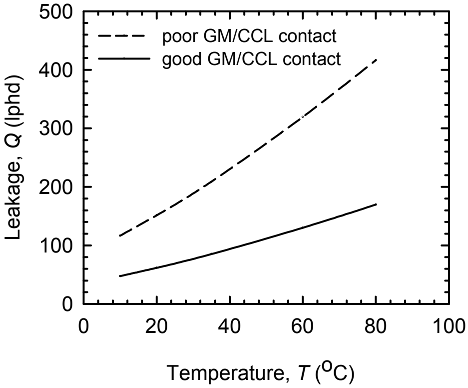

Figure 10. Effect of temperature on leakage through a hole in a 125m/ha wrinkle in a GM over a CCL for "good" and "poor" contact conditions (Base case parameters at 20°C: $k=1\times10^{-9}$ m/s and "good" $\theta=1.6\times10^{-8}$ m^2/s, "poor" $\theta=1 \times 10^{-7}$ m^2/s)

8 IMPLICATIONS OF LEACHATE COLLECTION SYSTEM OPERATION

Leakage is a function of the hydraulic gradient and hence the leachate head on the liner, although generally it is not a linear function of the leachate head on the liner except for the special case where the water table in the underlying soil is at the top of the clay liner. It is common to design landfills such that the design leachate head lies within the thickness of the drainage layer, with 0.3m being a commonly used design value.

It is a relatively simple matter to select a drainage material that will meet the criteria of keeping the head in the drainage layer based on the as delivered properties of the material. For example a sand with a specified hydraulic conductivity of 10^{-4} m/s (or higher) will meet these criteria for typical pipe spacing. However, as discussed in detail by Rowe (2009b), the hydraulic conductivity of drainage material does not remain constant but rather decreases with time due to biological, chemical and physical processes. Empirical evidence (Rowe 2005) and numerical modeling (Cooke and Rowe 2008) have indicated that sand meeting this criteria will clog and the leachate mound will exceed a 0.3m drainage layer thickness in 10 years or less (considerably less if the sand does not have a very uniform grading curve). Thus if sand is used for the drainage layer, consideration must be given to the implications of a increased leachate head on the liner, and hence increased leakage, potentially during the operating life and certainly during the contaminating lifespan of the landfill.

Figure 11 shows the effect of the leachate head, h_w, of between 0.1 and 5m on leakage for composite liners with both CCLs and GCLs as the clay component. For a GCL and good contact leakage was below 50 lphd for leachate heads less than 3m and hence remains modest (i.e. average Darcy flux of less than 0.002 m/a) provided that the interconnected wrinkle length is kept modest (125m/ha or less). For "poor" interface conditions this limit is reached at a head of about 1.2m. The leakage was below (usually well below) 200 lphd for all the cases examined with a GCL.

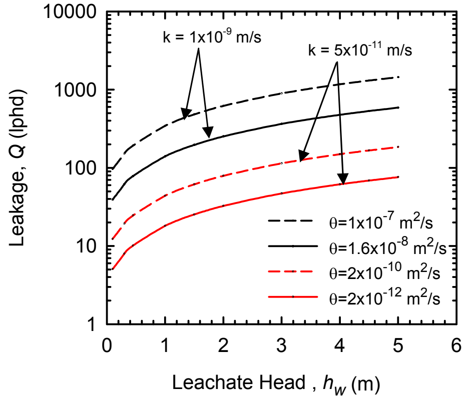

Figure 11. Effect of leachate head on leakage through a hole in a 125m/ha wrinkle in a GM over a (i) CCL ($k=1\times10^{-9}$ m/s) for "poor" ($\theta=1\times10^{-7}$ m^2/s) and "good" ($\theta=1.6\times10^{-8}$ m^2/s) contact conditions, and (ii) GCL ($k=5\times10^{-11}$ m/s) for "poor" ($\theta=2 \times 10^{-10}$ m^2/s) and "good" ($\theta=2\times10^{-12}$ m^2/s) contact conditions.

For a CCL even with good interface characteristics, leakage exceeds 50 lphd at a head of greater than 0.2m. At a design head of 0.3m the leakage through a hole in a 125m/ha GM wrinkle for a composite liner with good and poor contact is about 60 lphd and 150 lphd respectively and for a head of 0.45m to about 80 lphd and 190 lphd, respectively. Once the leakage exceeds about 200 lphd one is moving into the advection controlled transport zone and careful consideration must be given to the potential impact on groundwater. This point is reached for leachate head of about 1.5m and 0.5m for "good" and "poor" contact conditions with a CCL.

All the leakages quoted above would be substantially higher if the interconnected wrinkle length exceeded 125 m/ha and the impact of leachate mounding would be substantially increased. For a hole in a 500 m/ha wrinkle the values would be about 4 times the leakages quoted above.

Because of the risk of clogging, the use of sand is not recommended for leachate drainage layers. Coarse uniform gravel provides the best long-term performance of the drainage layer, serving to keep the head well below the nominal design value 0.3m for a considerable period of time (many decades to centuries, Rowe et al. 2004). However gravel can damage the underlying GM and, in particular, induce the tensile strains (Brachman and Gudina 2008a,b) that would results in stress cracks forming and ultimately, along with the reduction in stress crack resistance, control the service life of the GM. In contrast while sand is not a good drainage layer, together with a typical geotextile protection layer, it provides an excellent protection to the GM. Thus from a systems approach to providing long-term environmental protection, the best design detail would involve a sand protection layer (e.g. 0.15m) and an overlying gravel drainage layer. Even if this means increasing the design head to 0.45m or 0.5m above the liner, the leakages with modest wrinkling (less than about 125m/ha of maximum interconnected wrinkle length) was about 200 lphd or less with a CCL and 25 lphd or less for a GCL and would provide much better long term performance.

Although good design is critical to ensuring good long-term control of leachate heads on the liner, good management of the system is also critical. Leachate collection pipes can clog (Rowe et al. 2004; Rowe 2009b) if they are not cleaned. An important part of design is ensuring the leachate collection pipes can be inspected and cleaned and an important part of operations is actually cleaning them on a regular basis. Clog material can be readily removed by jetting while it remains as a soft biofilm, however it can become very hard to remove when it becomes calcified and hard.

9 CONCLUSIONS

The fact that leakage through composite base liners in landfills depends on the number and size of holes as has long been recognized. However it has not been well recognized that other aspects of design, construction, and operations also can have a profound impact on leakage during both the operating life and contaminating lifespan of the landfill. This paper has highlighted the need to consider the landfill as a system when seeking to minimize leachate leakage through composite liners. In particular it has demonstrated that calculations of leakage that do not consider the interactions between the different components of the system will significantly underestimate the leakage that will occur. Based on the results and discussion that have been presented, the following conclusions can be reached:

- Construction related issues such as (a) the quality of surface upon which the GM is placed (which affects the transmissivity of the GM/CCL interface) and its quality at the time the drainage layer is placed, and (b) the length of interconnected wrinkles/waves present when the drainage layer is placed over the GM both have a very significant effect on the leakage that can be expected through the composite liner.
- Due to the much lower interface transmissivities with a GCL than CCL, for a given interconnected wrinkle length, composite liners with a GCL give substantially lower leakage than those with a CCL, except in severe case for GM/GCL liner when the interconnected wrinkle length becomes more than 5000m/ha and there is a poor GM/GCL interface condition.
- For a CCL, poor interface conditions and interconnected wrinkle length around 600 m/ha cause significant leakage through the composite liner to the point that the composite action and the effect of the GM are largely lost.
- While interaction between the bentonite and leachate or cations in the soil may cause an increase in hydraulic conductivity, k, of the GCL and hence an increases in leakage, the leakage is still likely to be small provided: (a) the increase in k is only about an order of magnitude, (b) there is sufficient stress to ensure good interface conditions between GM and GCL, and (c) the interconnected wrinkle length is kept modest (e.g. 125m/ha or less).
- The increase in temperature of the liner due to biological and chemical reactions in the waste can result in a significant increase in leakage compared to that calculated using hydraulic conductivity and transmissivity measured at room temperature. The leakage at 60^{o}C is more than double that at 20 ^{o}C and that at 80^{o}C is almost three times that at 20 ^{o}C. Thus even apart from significant issues related to service life, waste management practices that cause high liner temperatures can significantly increase leakage

through the composite liner and this should be considered in the landfill design and any contaminant transport modeling.

- For a GCL and good contact at the GM/GCL interface, leakage was below 50 lphd for leachate heads less than 3m and hence remains modest (i.e. average Darcy flux of less than 0.002 m/a) provided that the interconnected wrinkle length is kept modest (125m/ha or less). For “poor” interface conditions this limit is reached at a head of about 1.2m. The leakage was below (usually well below) 200 lphd for all the cases examined with a GCL and an interconnected wrinkle length of 125m/ha or less.
- For a CCL even with good interface characteristics, leakage exceeds 50 lphd at a head of greater than 0.2m. At a design head of 0.3m the leakage through a hole in a 125m/ha GM wrinkle for a composite liner with good and poor contact was about 60 lphd and 150 lphd respectively and for a head of 0.45m to about 80 lphd and 190 lphd respectively. Once the leakage exceeds about 200 lphd one is moving into the advection controlled transport zone and careful consideration must be given to the potential impact on groundwater. This point is reached for leachate head of about 1.5m and 0.5m for “good” and “poor” contact conditions with a CCL and modest wrinkling (maximum length <125 m/ha).
- Adopting a systems approach to providing long-term environmental protection, a design involving a sand protection layer (e.g. 0.15m) and an overlying uniform coarse gravel drainage layer will provide the best long-term performance of the barrier system. Even if this means increasing the design head to 0.45m or 0.5m above the liner, the leakage with modest wrinkling (less than about 125m/ha of maximum interconnected wrinkle length) was about 200 lphd or less with a CCL and 25 lphd or less for a composite liner with a GCL.
- Leachate collection pipes can clog if they are not cleaned. To minimize leakage through the composite liner, an important part of landfill design is ensuring the leachate collection pipes can be inspected and cleaned and an important part of operations is actually cleaning them on a regular basis.

By taking a systems approach, the design, construction and operations can be managed so that the leakage through the barrier system can be minimized for the operating life of the composite liner and thus the long-term contaminant impact can be minimized.

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