LEACHATE DETECTION OR HYDRAULIC CONTROL: TWO DESIGN OPTIONS

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SUMMARY: Some technical advantages and disadvantages associated with different uses for a granular layer constructed beneath a landfill liner are examined. The importance of diffusion is discussed and it is shown that there is potential for significant contaminant impact on an underlying aquifer even if all leachate escaping through the primary liner is collected by the secondary leachate collection system.

1. INTRODUCTION

It is becoming increasingly more common to install a layer of highly permeable granular material beneath the primary liner in a landfill. However, this layer may be used in two quite different ways.

Most commonly, the layer is intended to allow detection and collection of leachate which escapes through the primary liner (see Figure 1). In this application, there will be an outward hydraulic gradient across the primary liner and the design involves minimizing the hydraulic head on the secondary (either natural or manmade) 'liner' by collecting as much leachate as possible from the secondary leachate collection system.

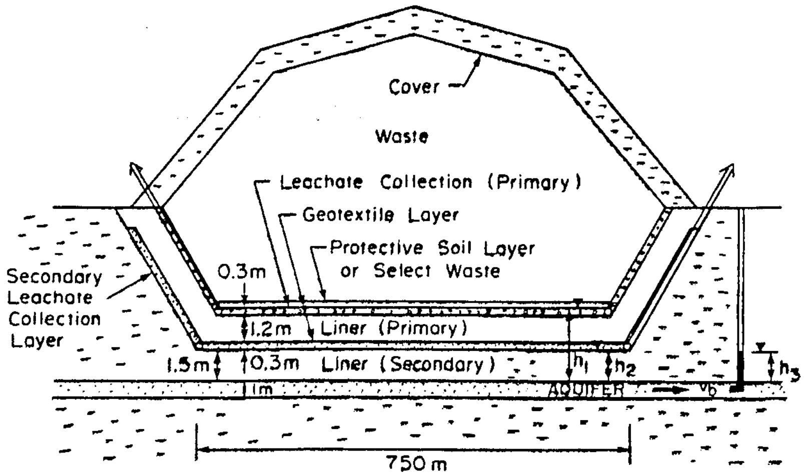

Fig. 1 Schematic showing a primary liner underlain by a leak detection secondary leachate collection system. Advective flow is downward through the primary liner.

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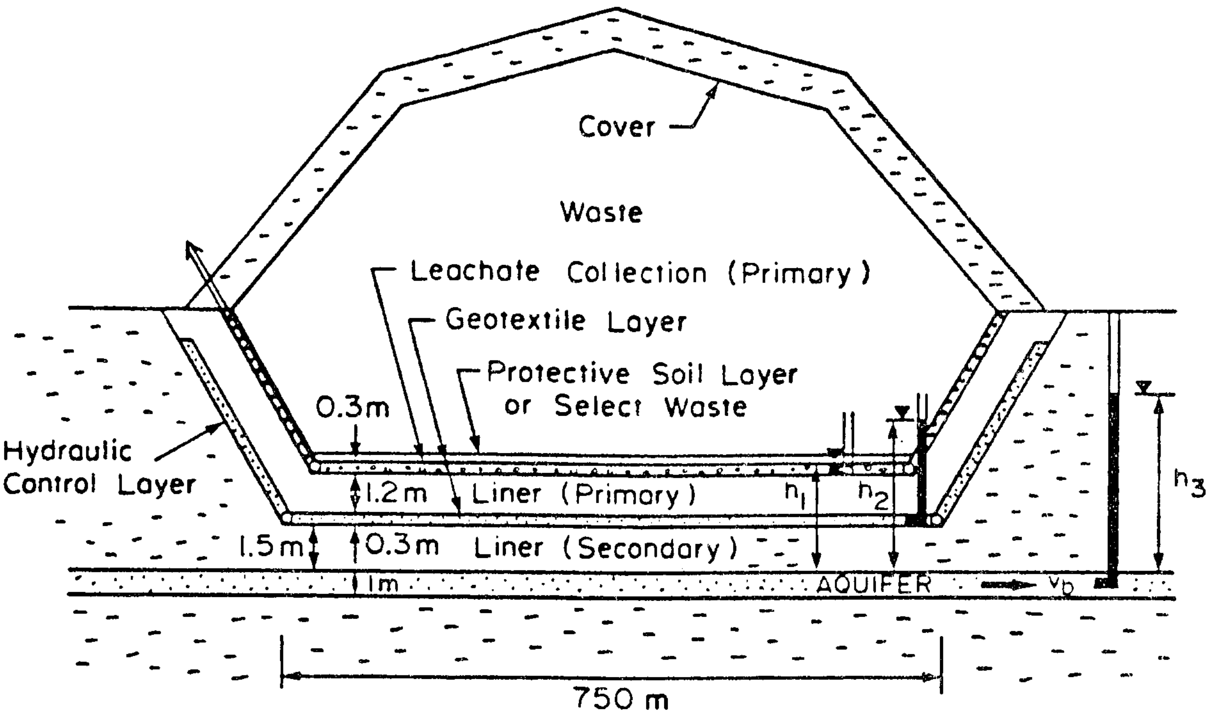

Fig. 2 Schematic showing a primary liner underlain by a hydraulic control layer. The landfill is designed as a hydraulic trap with advective flow into the landfill.

A second approach to using the granular layer is to maintain a hydraulic gradient across the primary liner and <u>into</u> the landfill; thereby creating an engineered 'hydraulic trap' in which the egress of leachate is inhibited by the inward flux of water from the hydraulic control layer, as shown in Figure 2.

The objective of this paper is to discuss some of the technical advantages and disadvantages of these two approaches.

2. ILLUSTRATIVE CASE

For the purposes of quantitatively illustrating a number of points, consideration will be given to the design of a hypothetical landfill with an average waste thickness of 15 m which is constructed above a natural sand aquifer as illustrated in Figures 1 and 2. For simplicity of illustration, it is assumed that the design consists of (from the waste down) a 0.3 m thick primary leachate collection system, a 1.2 m thick compacted clay liner, a 0.3 m thick granular layer (for secondary leachate collection or hydraulic control) and a 1.5 m thick secondary (natural) clay liner which is underlain by a 1 m thick granular aquifer. The landfill is assumed to be 750 m long in the direction of groundwater flow and it is assumed that the primary piping and slope on the leachate collection system is out of the plane being considered (i.e. the cross-section being examined is the critical cross-section). It is noted that some slope from the left to right of the cross-section is assumed, however this detail is not shown on the schematics.

Consideration will be given to the migration of chloride assuming an initial source value of 1500 mg/L and that the mass of chloride represents 0.2% of the total dry mass of the waste. The infiltration through the landfill cover is assumed to be 0.15 m/a. The diffusion coefficient and effective porosity for chloride through the compacted clay liner are assumed to be 0.019 m^2/a and 0.35 respectively. The corresponding values for the secondary clay liner are 0.015 m^2/a and 0.25 respectively.

Consideration is also given to the migration of dichloromethane assuming an initial source concentration of 1500 μg/L and a sorption parameter in the primary liner of $\rho K_d = 2$. As a first approximation, the diffusion coefficient for dichloromethane is taken to be the same as that of chloride and the mass of contaminant is assumed to be proportional to the initial concentration.

The hydraulic conductivity of the compacted liner is assumed to be 3×10^{-8} cm/s. Two values of hydraulic conductivity of the natural liner are considered, namely 10^{-7} cm/s and 10^{-8} cm/s.

Unless otherwise noted, the Darcy velocity in the aquifer is assumed to be 1 m/a (i.e. a gradient of 0.003 and hydraulic conductivity of 10^{-3} cm/s in the aquifer).

The leachate mound in the hydraulic control layer is assumed to be 0.3 m above the top of the compacted clay liner (i.e. h_1 = 3.3 m, measuring head relative to the top of the aquifer). The head in the secondary leachate collection/hydraulic control layer (h_2) and in the aquifer (h_3) will vary depending on the hydrogeologic conditions being considered.

All the analyses reported herein were performed using a finite layer contaminant transport model (Rowe & Booker, 1985, 1987, 1990) as implemented in computer program POLLUTE v5 (Rowe & Booker, 1990).

3. SECONDARY LEACHATE COLLECTION

3.1 Potentiometric surface in aquifer below secondary collection system

For situations where the water table and potentiometric surface in the underlying aquifer is well below the base of the landfill (eg. see Figure 1), the construction of a permeable drainage system, which is located beneath the compacted clay liner, serves two purposes. Firstly, the drainage layer functions as a secondary leachate collection system which can remove a portion of the leachate which escapes through the liner (and some escape is to be expected through any liner system where there are downward gradients). Secondly, this layer serves to reduce the hydraulic gradient through the underlying soil.

potentiometric surface beneath the aquifer which, for this case, is assumed to correspond to the head of $h_3 = 1.5$ m at the downgradient toe of the landfill. This ensures an adequate factor of safety against 'blowout' of the secondary liner and, if there is no mounding of leachate in the secondary collection layer (i.e. $h_2 = h_3 = 1.5$ m), creates a situation where there is no inward or outward flow through the secondary liner. Thus for this case there will be downward advective transport through the primary liner ($K = 3\times10^{-8}$ cm/s, $i = 1.25$) corresponding to a Darcy velocity of 0.012 m/a. For this scenario, all leachate should be collected and contaminant transport through the secondary liner is by the process of molecular diffusion.

The results of analyses performed for case 1 are summarized in Table 1. Although this case represents perfect secondary leachate collection (i.e. no advective escape through the secondary liner), it is evident that the process of molecular diffusion through the secondary liner results in significant impact in the aquifer.

The impacts evident for case 1 would be unacceptable. One means of reducing impact would be to place a geomembrane above the compacted clay liner to create a composite primary liner. The geomembrane may be expected to reduce the advective flow through the liner. Based on Giroud and Bonaparte (1990), for the situation examined here (i.e. operating primary leachate collection system), the escape of leachate by advective transport is likely to be of the order of 0.1 mm/a (or less) for a well constructed liner system (for so long as the liner system remains intact). Under these conditions, the primary transport mechanism is likely to be diffusion. Very little data has been published concerning the diffusion of contaminant through geomembranes. Diffusion coefficients (which would appear to represent the diffusive flux nD for a unit concentration gradient) of $2\text{-}4\times10^{-8}$ cm^2/s have been reported by Lord et al. (1988) and Hughes and Morteleone (1987). Based on a value of nD of 1×10^{-4} m^2/a (i.e. about 3×10^{-8} cm^2/s) and an advective flow of 0.0001 m/a in the primary composite liner, the impact was calculated for two cases (cases 2 and 3).

Case 2 assumes that the granular layer between the primary and secondary liner is a sand, and that a significant portion of the sand contains water held by capillarity. For this case, even though the advective transport is very small, there is significant potential for contaminant transport through the secondary leachate collection systems by diffusion. Assuming an effective value of nD of 0.001 m^2/a in the partially saturated sand, the contaminant impact on the aquifer is reduced by a little less than 50% for chloride and a little over 50% for dichloromethane. The concentrations of dichloromethane are still quite large and would be unacceptable based on Ontario's Reasonable Use Policy (MoE, 1986).

Relatively little research has been conducted concerning diffusion through a humid, moist granular layer such as the secondary leachate collection system. It may be anticipated that if an open granular stone was used (rather than sand) then the potential diffusion through water trapped in soil pores would be reduced. At present, the extent to which diffusion would be reduced has not been clearly established and more research is required. To illustrate the potential effect this could have, case 3 assumes that the diffusion through the secondary leachate collection system is reduced by two orders of magnitude from that in case 2. As is apparent from Table 1, this results in a substantial reduction in impact on the aquifer. It is apparent that the major role for the unsaturated secondary leachate collection system in this case is to act as a barrier to diffusion and that any significant failure of the geomembrane (which is restricting advective flow through the liner) would result in significant impact on the aquifer even if all the leachate was collected by the secondary leachate collection system.

From the foregoing, it is evident that diffusion is a major consideration in the design of systems such as that shown in Figure 1; this is particularly true if a geomembrane liner is used to minimize advective transport through the liner system. Considerable research has been conducted into the diffusion of contaminant in clayey barriers (eg. see Rowe et al., 1988; Barone et al., 1989), however much more

Table 1 Summary of Cases Examined

Case	Hydraulic Conductivity of Secondary Liner	Heads			Darcy Velocity			Peak Impact in Aquifer			
		h_1	h_2	h_3	v_{a_1}	v_{a_2}	v_b	Chloride Conc.	Chloride Time	Dichloromethane Conc.	Dichloromethane Time
	(cm/s)	(m)	(m)	(m)	(m/a)	(m/a)	(m/a)	(mg/L)	(a)	(μg/L)	(a)
1	10^{-7} or 10^{-8}	3.3	1.5	1.5	.012	0	1	>240	160	>70	550
2[a]	10^{-7} or 10^{-8}	3.3	1.5	1.5	.0001	0	1	125	230	30	880
3[b]	10^{-7} or 10^{-8}	3.3	1.5	1.5	.0001	0	1	10	310	<2	1150
4	10^{-8}	3.3	1.5	3.3	.012	-0.004	1	70	140	20	500
5	10^{-7}	3.3	3.95	4.2	-0.005	-.005	1	15	160	<5	580
6	10^{-8}	3.3	3.49	4.2	-0.0015	-0.0015	1	85	190	20	670
7	10^{-8}	3.3	4.2	4.2	-0.007	0	1	40	170	10	630
8	10^{-8}	3.3	5.2	4.2	-0.015	.002	1	10	170	3	580

Note: All concentrations greater than 5 have been rounded to the nearest 5 and all times rounded to the nearest decade.

2[a] nD in secondary leachate collection system 10^{-3} m^2/a.

2[b] nD in secondary leachate collection system 10^{-5} m^2/a.

v_{a_1} Vertical Darcy "velocity" (flux) through the primary liner (Positive down); composite primary liner involving a 2 mm thick HDPE geomembrane and 1.2 m clay.

v_{a_2} Vertical Darcy "velocity" (flux through the secondary liner (Powitive down); composite primary liner involving a 2 mm thick HDPE geomembrane and 1.2 m clay.

v_b Horizontal Darcy velocity (flux) in the aquifer.

GM

HCL

research is required into the diffusion of contaminants through geomembranes and through unsaturated granular (or geosynthetic) secondary leachate collection systems since this is likely to control impact for systems such as that shown in Figure 1.

3.2 Other considerations

The examples considered in the previous section assumed that the potentiometric surface in the aquifer coincided with the top of the secondary liner and hence there was no advective component of flow in the secondary liner (i.e. $v_{a_2} = 0$ for cases 1-3 in Table 1). In many cases it will not be practical to select the base contours of the landfill such that this condition is satisfied.

In some cases, the potentiometric surface in the aquifer will be below the base of the secondary leachate collection system (i.e. $h_2 > h_3$) and there will be some downward advective transport of contaminant which enters the secondary leachate collection system. Advective-diffusive transport through the soil beneath the secondary leachate collection system is an important consideration in the design of these facilities. If the hydraulic conductivity of the secondary liner is of the order of 10^{-7} cm/s, then a substantial proportion of the leachate may escape through the secondary liner rather than be collected by the secondary leachate collection system. This should be considered in the design of, and assessment of impact for, these facilities.

In some cases the potentiometric surface in the aquifer will be above the base of the secondary leachate collection system. Under these circumstances, it may be necessary to reduce heads in the aquifer during construction to ensure an adequate factor of safety against blowout. By pumping, one could ensure that the potentiometric surface is maintained at, or below, the base of the secondary leachate collection system. Potentially, this would involve pumping for hundreds of years. Alternatively, the potentiometric surface could be allowed to recover after construction. This would give rise to inward gradient into the secondary leachate collection system. The disadvantage of this is that the volume of fluid collected by the secondary collection system would not provide a good indication of the volume escaping through the primary liner since it would be difficult to distinguish the different components of flow to the layer. The advantage of inward flow to the secondary leachate collection system is that it would resist outward diffusion of contaminant. To illustrate the potential effect, case 4 is essentially the same as case 1 (i.e. no geomembrane) except that the potentiometric surface in the aquifer is assumed to correspond to the design level of leachate mounding in the landfill (i.e. $h_3 = h_1 = 3.3$ m, $h_2 = 1.5$ m). Assuming all other parameters are the same, the calculated impacts given in Table 1 are reduced by about a factor of three compared to case 1, even for a relatively small inflow of 4 mm/a (i.e. assuming a hydraulic conductivity of the secondary liner of 10^{-8} cm/s). Ironically, a higher hydraulic conductivity of the secondary liner would result in larger inflows and hence even smaller contaminant impact. However, it is important to recognize that the inflow is controlled by both the hydraulic conductivity of the secondary liner and the hydraulic capacity of the hydrogeologic system to provide water. For example, if the hydraulic conductivity of the secondary liner in the system examined here were 10^{-8} cm/s or higher, it may not be possible for the head h_3 in the aquifer to recover to the original value of $h_3 = 3.3$ m unless the aquifer is highly permeable or there is an adequate supply of water from a second deeper aquifer.

4. HYDRAULIC CONTROL

An alternative to using the granular layer beneath the primary liner as a secondary leachate collection system is to use it as a hydraulic control layer. For example, suppose that the potentiometric surface in the aquifer shown in Figure 2 is such that $h_3 > h_2 > h_1$. In this case, there is both a natural hydraulic trap (i.e. water flows from the natural soil into the hydraulic control layer) and an engineered hydraulic trap (i.e. water flows from the hydraulic control layer into the landfill). Where practical, this design has the following advantages. Firstly, since there is inward flow to the hydraulic control layer and a relatively impermeable clay liner, it may be possible to design the system such that the engineered hydraulic trap is entirely passive. That is, all water required to maintain an inward gradient is provided by the natural hydrogeologic system and no injection of water to the hydraulic control layer is required. Secondly, because of the two level hydraulic trap, there will be substantially greater attenuation of any contaminants that do migrate through the primary liner. Thirdly, since fluid can be injected and withdrawn from the hydraulic control layer, it is possible to control the concentration of contaminant in the layer (and hence the impact at the boundary) in the event of a major failure of either the liner or primary leachate collection system.

There are three factors that must be considered in the design of this engineered hydraulic trap. Firstly, the head in the hydraulic control layer must be controlled such that "blowout" of either liner does not occur during or after construction. Secondly, the volumes of water collected by the "hydraulic trap" must be manageable and the hydrogeologic system must have the capacity to provide the water required to maintain the hydraulic trap (if this is not the case, then the head in the aquifer will drop and the effectiveness of the trap may deteriorate with time). Thirdly, although there is a hydraulic trap, some outward diffusion of contaminants is to be expected in most cases. Contaminant migration analyses are required to assess what (if any) impact may occur under these conditions. If the impact at the site boundary is not acceptable then it can be reduced by pumping water through the hydraulic control layer (i.e. injecting fresh water at one end and extracting contaminated water at the other end). The volume of fluid to be pumped can be assessed by appropriate modelling. Models are available (eg. Rowe & Booker, 1988, 1990) which readily allow the designer to estimate potential impact as a function of the flow in the hydraulic control layer.

To illustrate the effect of a hydraulic control layer, cases 5, 6 and 7 each examine the case where the total head, h_1, on the landfill liner is 3.3 m (i.e. 0.3 m of leachate mounding on the liner - see Figure 2) and the total head in the aquifer is 4.2 m. This induces an inward gradient across the liner system. In each case, the primary liner is assumed to have a hydraulic conductivity of 3×10^{-8} cm/s. In cases 5 and 6, the secondary liner is assumed to have a hydraulic conductivity of 10^{-7} and 10^{-8} cm/s respectively and the hydraulic control layer is assumed to be operating as a natural hydraulic trap (i.e. no human introduction or removal water from the hydraulic control layer). Under these circumstances the head, h_2, in the hydraulic control layer is established by the hydraulic system and depends on the relative hydraulic conductivity of the primary and secondary liner.

As might be expected, the flows in the system with the higher permeability secondary liner (case 5) are larger than for the lower permeability secondary liner (case 6) and hence the resistance to outward flow is also greater. The greater the inward flow, the greater the resistance to outward diffusion and, consequently, the impact for case 5 is less than for case 6. It is interesting to note that the impact for case 5 with a clay primary liner system and hydraulic control is similar to that for the system with a very efficient secondary leachate collection system and a composite (geomembrane/ clay) primary liner.

Cases 7 and 8 examine the behaviour of an engineered hydraulic trap where water is introduced to increase the head in the hydraulic control layer to 4.2 m and 5.2 m respectively. In case 7, there is the maximum gradient across the primary liner without creating an outward gradient across the secondary liner. This reduces impact compared to the corresponding passive case (case 6) with a 10^{-8} cm/s secondary liner. Case 8 relies more heavily on the induced pressure in the hydraulic control layer resisting outward movement of contaminant through the primary liner at the cost of causing an outward advective gradient through the secondary liner.

5. DISCUSSION AND CONCLUSIONS

The role of advection for allowing the migration of contaminants from waste disposal facilities is well recognized. Both the conceptual design shown in Figures 1 and 2 minimize outward advective flow through the secondary liner and of the cases examined, only one (case 8) involves any outward advective movement through the secondary liner. However, there is still significant calculated contaminant impact on the aquifer for most of the cases examined. Based on regulations in the Province of Ontario (MoE, 1986), only three of the scenarios considered are even close to being acceptable (viz. cases 3, 5 and 8). In all cases, diffusion of contaminant is a major transport process.

The results of this preliminary study, which is based on available data, suggest that there can be significant diffusion of contaminant through a HDPE geomembrane. In fact, the major potential barrier to diffusive transport for the system shown in Figure 1 is the secondary leachate collection system. However, very little is known about the diffusion of contaminant through an unsaturated layer in a humid environment typical of that anticipated when this layer is located between two liners beneath a landfill. More research is required to determine relevant parameters however it is evident that diffusive transport through geomembranes and secondary leachate collection systems is an important consideration in the design of these facilities.

Diffusion is a slow process. Inspection of Table 1 shows that for the cases considered, the time prior to peak impact being reached in the underlying aquifer ranges from around 140 to 310 years for a conservative species such as chloride and from 500 to 1150 years for an organic species such as dichloromethane which experience retardation by the soil. For this 15 m thick landfill, the contaminant lifespan (i.e. the period of time during which there could be unacceptable impact if the engineering features did not function as designed) is in excess of 100 years. Thus careful consideration must be given to the amount of human intervention and the length of time the engineered systems are likely to last. Of the cases considered, case 5 which involves a hydraulic control layer and passive hydraulic trap requires the least intervention. The implications of contaminating lifespan and the design of hydraulic traps are discussed in more detail by Rowe (1991a,b).

The results presented herein suggest that it may be possible to design a landfill which, under operating conditions, will have negligible impact on groundwater quality. This design could involve the use of a granular layer which provides a "barrier" by being kept unsaturated or by being maintained at a hydraulic head greater than that on the base of the landfill. Preference for one system or another will depend on the hydrogeologic conditions and, in particular, on the potentiometric surface in any underlying aquifer. The processes involved in contaminant migration for hydraulic control systems are better understood than the processes of migration for systems that use the granular layer as a secondary leachate collection system.

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