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Effect of vadose zone on the steady-state leakage rates from landfill barrier systems

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ABSTRACT

Leakage rates are evaluated for a landfill barrier system having a compacted clay liner (CCL) underlain by a vadose zone of variable thickness. A numerical unsaturated flow model SEEP/W is used to simulate the moisture flow regime and steady-state leakage rates for the cases of unsaturated zones with different soil types and thicknesses. The results of the simulations demonstrate that harmonic mean hydraulic conductivity of coarse textured vadose zones is 3–4 orders of magnitude less than saturated hydraulic conductivity; whereas, the difference is only one order of magnitude for fine textured vadose zones. For both coarse and fine textured vadose zones, the effective hydraulic conductivity of the barrier system and the leakage rate to an underlying aquifer increases with increasing thickness of the vadose zone and ultimately reaches an asymptotic value for a coarse textured vadose zone thickness of about 10 m and a fine textured vadose zone thickness of about 5 m. Therefore, the fine and coarse textured vadose zones thicker than about 5 m and 10 m, respectively, act as an effective part of the barrier systems examined. Although the thickness of vadose zone affects the effective hydraulic conductivity of the overall barrier system, the results demonstrated that the hydraulic conductivity of the CCL is the dominant factor controlling the steady-state leakage rates through barrier systems having single low permeability clay layers.

1. Introduction

Leachate leakage from the landfill barrier systems is among the most important factors affecting surface and groundwater contamination (Bouzza and Van Impe, 1998; Rowe et al., 2004). In many parts of the world composite liners involving a geomembrane and either geosynthetic clay liner or compacted clay liner (CCL) are used, and there has been considerable recent research addressing factors affecting leakage through these liners (Rowe and Orsini, 2003; Rowe, 2005; Cartaud et al., 2005a,b; Barroso et al., 2006; Bergado et al., 2006; Dickinson and Brachman, 2006; Touze-Foltz et al., 2006). For some cases, single low permeability clay liners have also proven effective in controlling leakage (advective transport) to negligible levels (Rowe et al., 2004). In the absence of a geomembrane and with a well functioning leachate collection system that controls the head to the design value (typically 0.3 m or less; Rowe, 2005), the CCL and any natural aquitards control the leakage through the landfill barrier systems and hence the transport of contaminants into the underlying aquifer (Kaczmarek et al., 1997). Thus, the design of landfill barrier systems requires effective modelling of the system with appropriate model parameters in order to assess the potential impact of a proposed barrier system. Most landfill models calculate leakage from the barrier system to an underlying aquifer based on Darcy's law. Consequently, the selection of the appropriate hydraulic conductivity values for the CCLs and the underlying vadose zones is of great importance.

In the unsaturated soils of the vadose zone, the hydraulic conductivity is a function of pore-water pressure (Green and Corey, 1971; Freudlund and Raharjdo, 1993). Despite the fact that the hydraulic conductivity in the vadose zone can change by several orders of magnitude in response to a small change in the water content, most modelling approaches (e.g., HELP) calculate leakage rates using a single uniform hydraulic conductivity value for the CCL, without considering the dependence of hydraulic conductivity on moisture content in the underlying vadose zone. The layer type and the sequence of the layers determine the percolation through the overall barrier system. Furthermore conventional approaches (e.g., U.S. EPA HELP – Schroeder et al., 1994a,b) that neglect the effect of the vadose zone also neglect the effects of suction in the unsaturated soil beneath the CCL on the leakage through the CCL. Therefore, leakage rates below barrier systems are considerably underestimated. To take account of this fact in assessing the leakage rates, it is necessary to use an unsaturated flow model.

The objective of this paper is to evaluate steady-state leakage rates into an aquifer from a landfill barrier system having a CCL underlain by a vadose zone of varying thickness using a modelling approach that considers the unsaturated behaviour of the vadose zone. For this purpose, SEEP/W, a finite element general seepage analysis program that can model both saturated and unsaturated

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flow within porous materials (GEO-SLOPE, 2002), was used. SEEP/W considers the functional dependence of hydraulic conductivity on water content. The vadose zone is modelled to be composed of either coarse textured or fine textured soil. The effects on leakage rates of uniform saturated hydraulic conductivity values and unsaturated soil hydraulic conductivity functions, texture and thickness of vadose zone, and hydraulic conductivity of CCL were assessed.

In the present analysis, the focus was on the case of a single low conductivity CCL underlain by a vadose zone. With respect to leakage rates, this case represents a more conservative situation compared to the case of composite liner, involving a geomembrane and a compacted clay liner (CCL), underlain by a vadose zone, since the geomembrane would further reduce the overall leakage rates through the CCL. As long as the flux through the CCL is not increased significantly (i.e., several orders of magnitude), the underlying vadose zone would not be fully saturated and its barrier function would not be impaired. Therefore, the findings of this work are also expected to be conservative for the case of composite liners.

2. Methodology

The landfill barrier system examined is comprised of 0.3-m-thick gravel leachate collection (LCS) layer, a 0.6-m-thick CCL, and a vadose zone of variable thickness. Coarse textured vadose zones are represented by sandy soils, and fine textured vadose zones are represented by silty soils. Leachate flow through such a landfill barrier system is modelled using unsaturated flow model SEEP/W. Simulations are performed assuming steady-state conditions, which yield more conservative results with respect to leakage rates than transient analyses since the maximum flux is reached at steady-state.

To describe the landfill barrier system in the numerical unsaturated flow model SEEP/W, two specified head boundary conditions are defined. As the top boundary, 0.3-m-pressure head is prescribed, with 0.3 m corresponding to the typical design leachate head. Zero pressure head is defined at the bottom boundary to represent the groundwater table at the bottom of the barrier system. The mesh adopted in SEEP/W used an element thickness of 2.5 cm. The 60-cm-thick CCL has 24 nodes. The number of nodes in the vadose zone (VZ) varies with thickness of the vadose zone (i.e., 1-m-thick VZ has 40 nodes, 5-m-thick VZ has 200 nodes, 10-m-thick VZ has 400 nodes, etc.). Finer meshes were also used to check mesh refinement but no significant improvement in model results was obtained.

SEEP/W estimates the hydraulic conductivity function from a soil-water characteristic function by using the Green and Corey (1971) procedure. When the hydraulic conductivity is defined for negative pore-water pressure regions, it is possible to analyze both unsaturated and saturated flow problems (GEO-SLOPE, 2002). Simulations are performed both using soil hydraulic conductivity functions and uniform saturated hydraulic conductivity values. Uniform sand, sand, and fine sand hydraulic conductivity functions and uniform silt, silt, and silt tailings hydraulic conductivity functions are chosen to represent coarse and fine textured soils, respectively. The saturated hydraulic conductivity values of uniform sand, sand and fine sand were taken to be 1×10^{-4} m/s, 5×10^{-5} m/s, and 4×10^{-6} m/s, respectively. The saturated hydraulic conductivity values for uniform silt, silt and silt tailings were taken to be 1×10^{-8} m/s, 2.5×10^{-7} m/s, and 5.8×10^{-8} m/s, respectively. The hydraulic conductivity versus pressure curves of these functions are given in Fig. 1, and the corresponding Green and Corey empirical parameters are given in the Appendix. To evaluate the effect of the hydraulic conductivity of CCL on the performance of the overall landfill barrier system, barrier systems having a CCL with a hydraulic conductivity value of 1×10^{-9} m/s as commonly specified and one order of magnitude lower (of 1×10^{-10} m/s), typical of what may be actually achieved when waste is in place (Rowe et al., 2004; Rowe, 2005), are simulated. Since the CCL has a constant source of fluid above it, experiences consolidation under the weight of the waste, and is fine grained, it remains essentially saturated throughout its thickness for all cases examined. The cases examined using the SEEP/W model are given in Table 1. To validate SEEP/W results, steady-state leakage rates into the aquifer were also hand calculated using the effective hydraulic conductivity of the overall barrier system, following Darcy's Law.

The simulations using hydraulic conductivity functions to represent unsaturated flow conditions yielded spatially varying hydraulic conductivity values depending on the prevailing level of variation in moisture content across the vadose zone. To determine the most representative hydraulic conductivity value for the entire vadose zone for use in a hand calculation, the harmonic mean was used (Freeze and Cherry, 1979). The harmonic mean hydraulic conductivity of the overall barrier system was calculated from:

$$\bar{k} = \frac{D_{\mathrm{VZ}} + D_{\mathrm{CCL}}}{\left(\frac{D_{\mathrm{VZ}}}{k_{\mathrm{VZh}}}\right) + \left(\frac{D_{\mathrm{CCL}}}{k_{\mathrm{CCL}}}\right)} \tag{1}$$

where $\bar{k}$ is the effective (combined harmonic mean) hydraulic conductivity of the vadose zone and CCL; D_{VZ} is the thickness of the vadose zone underlying the CCL; D_{CCL} is the thickness of the CCL; $\bar{k}_{VZh}$ is the harmonic mean hydraulic conductivity of the vadose zone; and k_{CCL} is the hydraulic conductivity of the CCL. The value of $\bar{k}_{VZh}$ was calculated using the hydraulic conductivity values corresponding to each of the nodes (elements) across the vadose zone as

$$\bar{k}_{\mathrm{VZh}} = \frac{n}{\frac{1}{k_1} + \frac{1}{k_2} + \cdots + \frac{1}{k_n}} = \frac{n}{\sum_{i=1}^{n} \frac{1}{k_i}} \tag{2}$$

where k_i is the hydraulic conductivity value corresponding to the finite element node i, and n is the number of nodes, or number of hydraulic conductivity values. Note that in Eq. (2) a uniform element thickness of 2.5 cm was used following the mesh size adopted in SEEP/W. The k_{VZh} value calculated from Eq. (2) is used in Eq. (1) to calculate $\bar{k}$. In Eq. (1), the thicknesses of CCL and vadose zone were taken into account separately, as this would have an impact on the value $\bar{k}$, which was used as a representative hydraulic conductivity value for the overall barrier system.

Steady-state leakage rates into the aquifer were also hand calculated following the Darcy's Law:

$$q_{\mathrm{SS}} = i \times \bar{k} \tag{3}$$

where

$$i = \frac{z_{\mathrm{T}} + h}{z_{\mathrm{T}}} \tag{4}$$

and q_{SS} is the steady-state leakage rate through the CCL and the vadose zone into the aquifer; i is the hydraulic gradient across the CCL and vadose zone; z_{T} is the combined thickness of the CCL and vadose zone; and h is the pressure head on the top of the CCL.

3. Results and discussion

3.1. SEEP/W model results for design conditions

The barrier system was simulated by SEEP/W for both coarse textured and fine textured vadose zones. A typical design leachate head of 0.3 m is selected for simulations (Rowe, 2005). For conditions where the leachate head above the CCL increases significantly beyond the typical design value of 0.3 m due to clogging of the drainage layer, a coarse gravel drainage layer was selected because

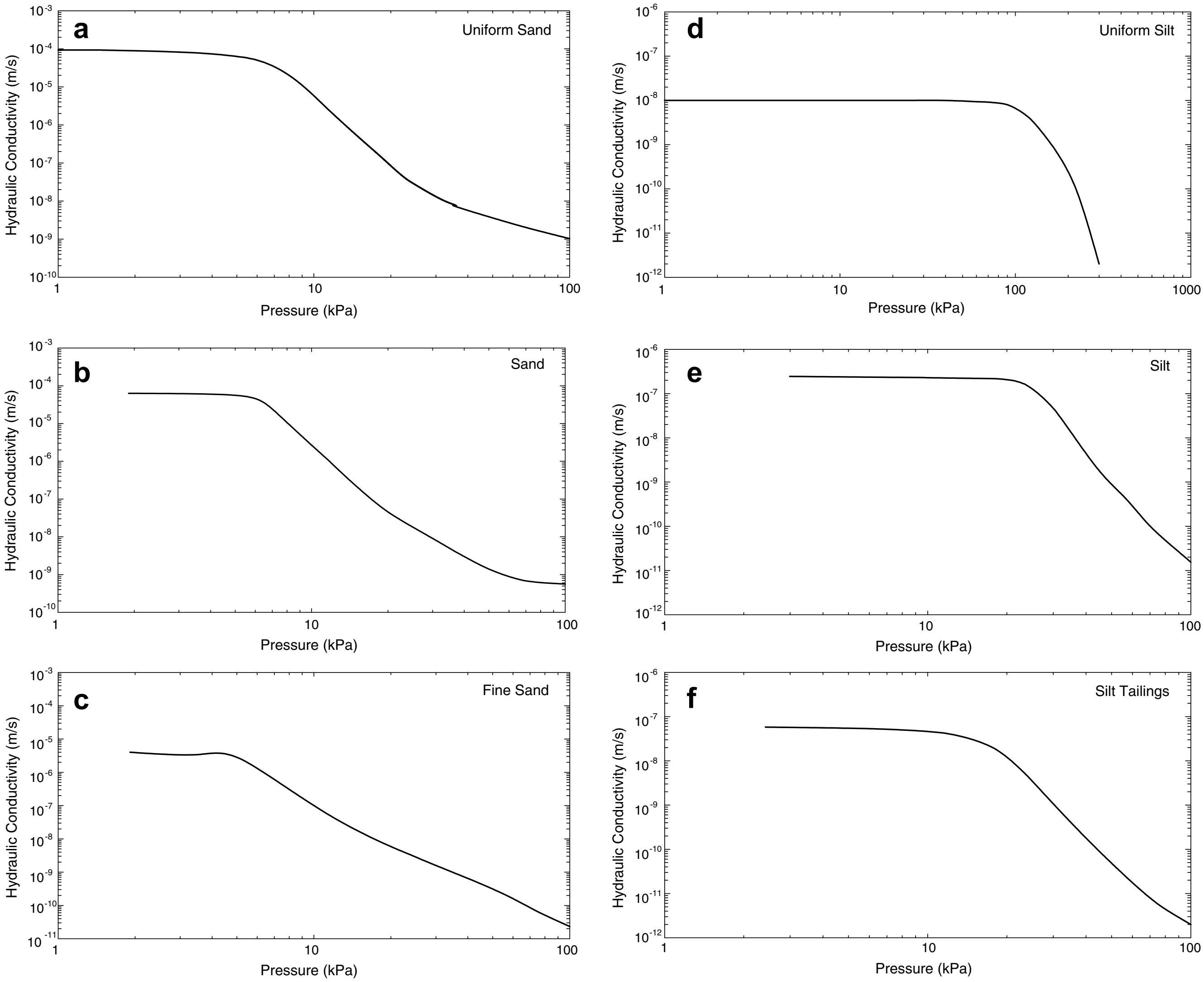


Fig. 1. Hydraulic conductivity functions for (a) uniform sand (b) sand, (c) fine sand, (d) uniform silt, (e) silt, and (f) silt tailings, simulated using SEEP/W.

Table 1
Landfill barrier system configuration in SEEP/W model

Barrier system design	Compacted clay liner (CCL)		Vadose zone (VZ)	
	k_{sat}[a] (m/s)	Thickness (m)	k_{sat}[a] (m/s)	Thickness (m)
CCL only	1×10^{-9}	0.6	–	–
CCL and (underlain by) vadose zone[b]	1×10^{-9}	0.6	1×10^{-4} or 1×10^{-8}	1, 5 or 10
CCL and uniform sand (US) vadose zone	1×10^{-9}	0.6	1×10^{-4}	1, 5 or 10
CCL and sand (S) vadose	1×10^{-9}	0.6	5×10^{-5}	1, 5 or 10
CCL and fine sand (FS) vadose zone	1×10^{-9}	0.6	4×10^{-6}	1, 5 or 10
CCL and uniform silt (USi) vadose zone	1×10^{-9}	0.6	1×10^{-8}	1, 5 or 10
CCL and silt (Si) vadose zone	1×10^{-9}	0.6	2.5×10^{-7}	1, 5 or 10
CCL and silt tailings (SiT) vadose zone	1×10^{-9}	0.6	5.8×10^{-8}	1, 5 or 10
CCL and sand (S) vadose zone	1×10^{-10}	0.6	5×10^{-5}	5 or 10
CCL and silt (Si) vadose zone	1×10^{-10}	0.6	2.5×10^{-7}	5 or 10

[a] Saturated hydraulic conductivity.
[b] Uniform saturated hydraulic conductivity values for coarse (1×10^{-4} m/s) and fine (1×10^{-8} m/s) textured soils are used.

of its excellent long-term performance (Rowe, 2005; Ont. Reg. 232/98, 2007) and hence, a drastic increase in the leachate leakage rate through the CCL should not be expected. Since there is a significant hydraulic conductivity contrast between the CCL and the vadose zone, unsaturated moisture flow conditions will prevail in the vadose even under relatively high leachate head conditions above the CCL.

3.1.1. Barrier system: compacted clay liner underlain by coarse textured vadose zones

The simulations performed using unsaturated soil hydraulic conductivity functions gave hydraulic conductivities in the coarse textured vadose zone ranging from a low of 7×10^{-9} m/s at the top of the vadose zone, just beneath the CCL, to a maximum of 9×10^{-5} m/s at the bottom of the vadose zone just above the water table (Fig. 2). Such a variation occurs because the unsaturated hydraulic conductivity is a function of pore-water pressure and hence as the suction decreases with distance below the clay liner, there is an increase in hydraulic conductivity with depth reaching the maximum near the water table.

As the thickness of the vadose zone increased, the portion of the vadose zone having low hydraulic conductivity values also increased; therefore, the effective harmonic mean hydraulic conduc-

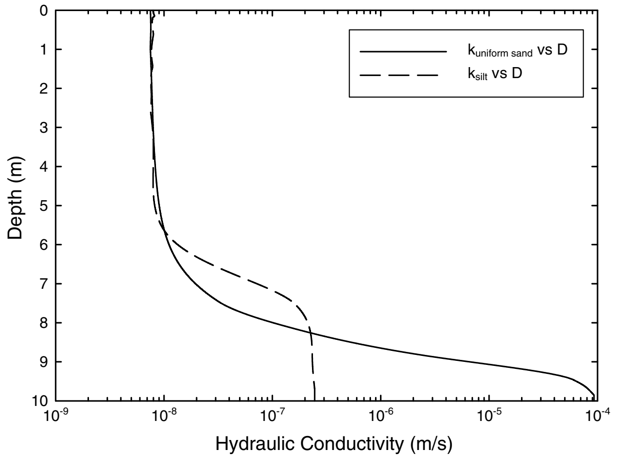


Fig. 2. Hydraulic conductivity change with depth for uniform sand (US) and silt (Si).

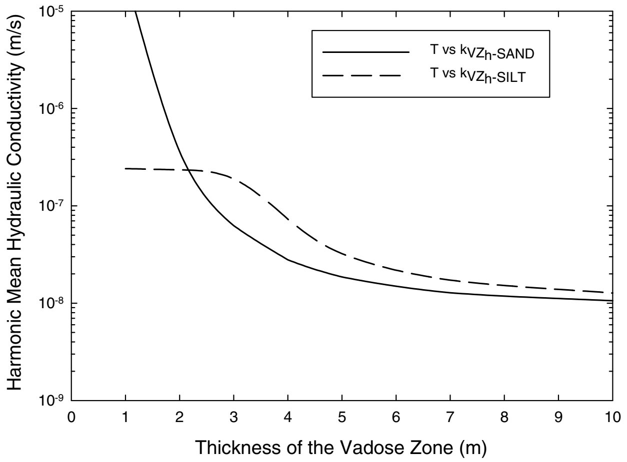


Fig. 3. Change in the harmonic mean hydraulic conductivity of the vadose zone with varying sandy (S) and silty (Si) vadose zone thickness.

tivity of the vadose zone decreased. The decrease in the effective hydraulic conductivity approached an asymptotic value as the vadose zone thickness approached 10 m (Fig. 3). Although the harmonic mean hydraulic conductivity of the vadose zone decreased when the thickness of the vadose zone increased, the overall effective hydraulic conductivity of the combined CCL and unsaturated sandy soil system increased (Table 2) because of the increased thickness of higher hydraulic conductivity material (the vadose zone) relative to the thickness of low hydraulic conductivity material (the CCL). The increased effective hydraulic conductivity of the overall barrier system resulted in a gradual increase in the steady-state leachate leakage rates into the aquifer (Table 2) although for increases in thicknesses beyond 5 m the increase in leakage is relatively small. The increase of leakage rates between 1 m and 3 m, 3 m and 5 m, 5 m and 7 m, and 7 m and 10 m are 90%, 12%, 1.5%, and 2%, respectively. Thus, it can be inferred that, like the effective hydraulic conductivity, the leakage rates approach an asymptotic value as the vadose zone thickness approaches 10 m (Fig. 4). Steady-state leakage rates obtained from SEEP/W runs were verified with the hand-calculated leakage rates. It is shown that model results are in agreement with the hand-calculated steady-state leakage rates (Table 2).

The leakages calculated taking account of the vadose zone (Table 2) are all substantially higher (by a factor of 2–5) than what would be calculated (1.5×10^{-9} m/s) neglecting the vadose zone and assuming zero suction at bottom of the CCL. This highlights the fact that simplistic calculations that neglect the vadose zone can be significantly unconservative. This applies to the cases exam-

Table 2
Harmonic mean hydraulic conductivity values of the coarse textured vadose zones, effective hydraulic conductivity values of the overall barrier system and steady-state leakage rates

Soil type[a]	Thickness of vadose zone (m)	$\bar{k}_{VZh}$[b] (m/s)	$\bar{\bar{k}}$[c] (m/s)	q_{hc}[d] (m/s)	q_{mc}[e] (m/s)
US	1	3.48×10^{-5}	2.67×10^{-9}	3.17×10^{-9}	3.17×10^{-9}
US	5	2.37×10^{-8}	6.91×10^{-9}	7.26×10^{-9}	7.26×10^{-9}
US	10	1.20×10^{-8}	7.40×10^{-9}	7.61×10^{-9}	7.58×10^{-9}
S	1	2.35×10^{-5}	2.67×10^{-9}	3.17×10^{-9}	3.17×10^{-9}
S	5	1.86×10^{-8}	6.45×10^{-9}	6.79×10^{-9}	6.79×10^{-9}
S	10	1.06×10^{-8}	6.87×10^{-9}	7.04×10^{-9}	7.07×10^{-9}
FS	1	9.17×10^{-7}	2.66×10^{-9}	3.16×10^{-9}	3.16×10^{-9}
FS	5	8.91×10^{-9}	4.82×10^{-9}	5.07×10^{-9}	5.07×10^{-9}
FS	10	6.86×10^{-9}	5.15×10^{-9}	5.30×10^{-9}	5.30×10^{-9}

Note: leakage calculated neglecting the vadose zone and assuming zero suction at bottom of the CCL is 1.5×10^{-9} m/s).

[a] US: uniform sand, S: sand, FS: fine sand.

[b] Harmonic mean of vadose zone hydraulic conductivities.

[c] Harmonic mean of vadose zone and compacted clay liner hydraulic conductivities.

[d] Steady-state leakage rate as a result of hand calculations.

[e] SEEP/W calculated steady-state leakage rates.

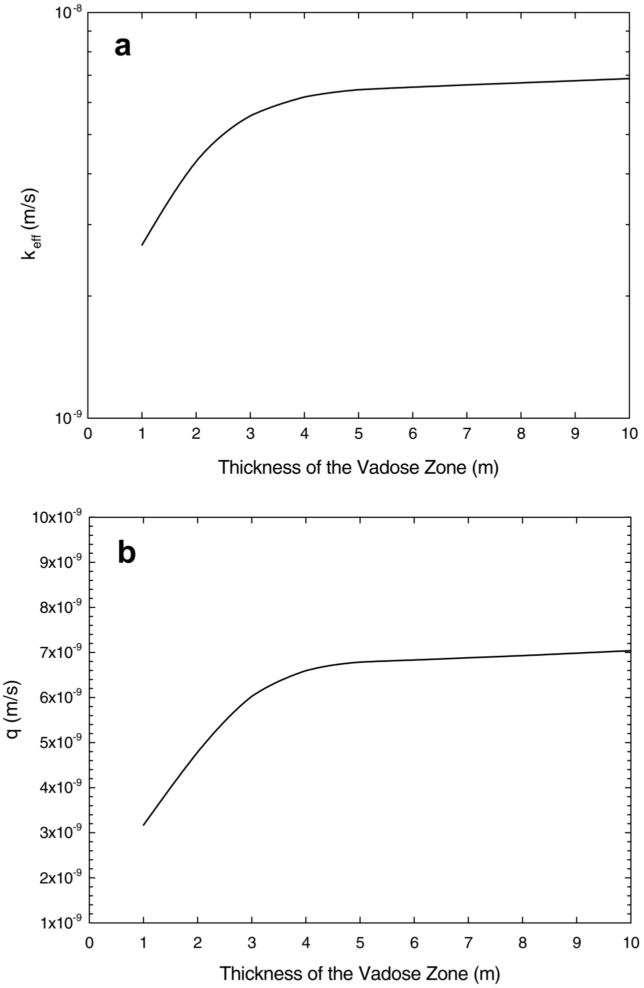


Fig. 4. Change in (a) the effective hydraulic conductivity of the overall barrier system and (b) the steady-state leakage rates with varying sandy (S) vadose zone thickness.

ined here as well as to cases where there is a composite liner involving a geomembrane above a clay liner over a vadose zone.

When the barrier system is simulated using uniform saturated hydraulic conductivities for the vadose zone, steady-state leakage rates (denoted by q_{kuni}) are about 2.5–3.5 times greater than the leakage rates simulated using soil hydraulic conductivity functions (denoted by q_{kfxn}) as the vadose thickness approaches 10 m (Fig. 5). Thus the use of uniform saturated hydraulic conductivity to calculate the steady-state leakage rates results in a substantial overestimation of the leakage with the error becoming significant as the thickness exceeds about 3 m. Consequently when there is a coarse textured vadose zone thicker than about 3 m underlying a CCL, it is desirable to consider unsaturated conditions and the use of soil hydraulic conductivity functions when calculating leakage through the barrier system.

3.1.2. Barrier system: Compacted clay liner underlain by fine texture vadose zones

The hydraulic conductivity profile of the fine textured vadose zones is not greatly affected by the pore-water pressure change within the vadose zone. The hydraulic conductivity of the uniform silt is essentially constant up to 100 kPa (Fig. 1d) and only shows a significant change for suctions in excess of 100 kPa. Thus for vadose zones less than 10 m thick where the suction does not reach 100 kPa, there is no change in hydraulic conductivity and the saturated hydraulic conductivity value is applicable.

For vadose zones of silt or silt tailings, there is nearly an order of magnitude difference in hydraulic conductivity between the bottom of the CCL and the top of water table, whereas the same difference was about four order of magnitudes for uniform sand (Fig. 2). However, the harmonic mean hydraulic conductivity of the fine textured vadose zone does not show a substantial difference with varying vadose zone thickness. It decreased by only half order of magnitude when the thickness is changed from 1 m to 5 m, and approaches an asymptotic value for vadose zones thicker than about 5 m (Fig. 3).

Similar to the coarse textured vadose zones, the effective hydraulic conductivity (which considers the combination of CCL and harmonic mean vadose zone hydraulic conductivities – Eq. (2)) of the barrier system increased with increasing thickness of the fine textured vadose zone (Fig. 6a) and approached a constant value at a thickness of about 5 m. The increased effective hydraulic conductivity of the overall barrier system resulted in a gradual increase in the steady-state leakage rates into the aquifer, which reached a constant value at a vadose zone thickness of about 5 m (Fig. 6b). Hand-calculated steady-state leakage rates also agree with the SEEP/W model results for fine textured vadose zones (Table 3).

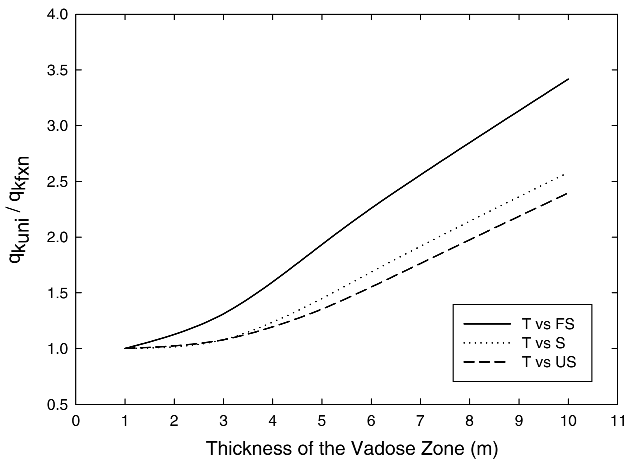
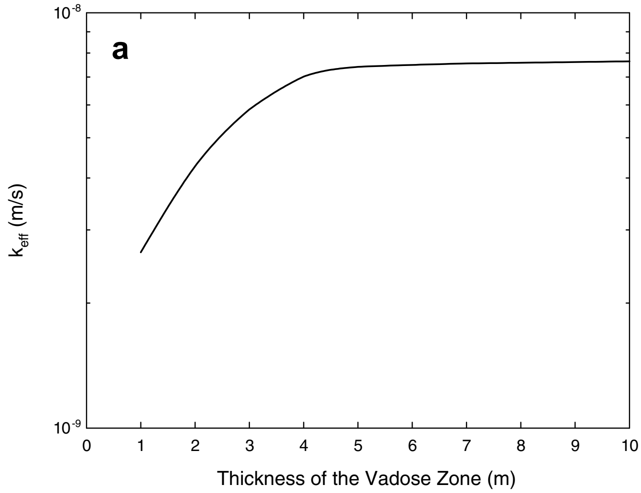


Fig. 5. Normalized steady-state leakage rates with varying coarse textured vadose zone thickness.



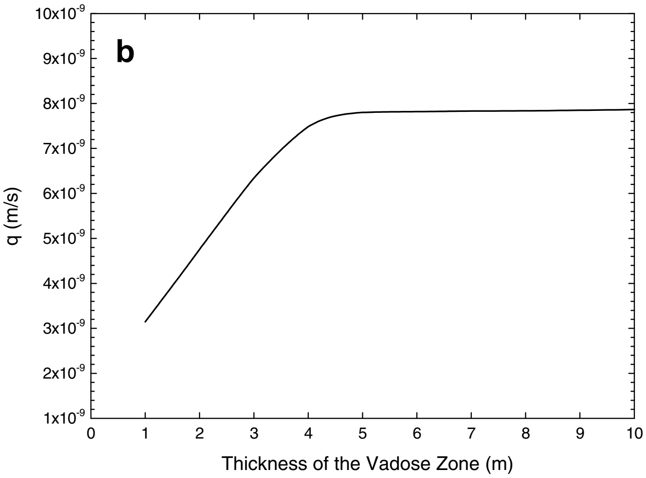


Fig. 6. Change in (a) the effective hydraulic conductivity of the overall barrier system and (b) the steady-state leakage rates with varying silty (Si) vadose zone thickness.

Table 3
Harmonic mean hydraulic conductivity values of the fine textured vadose zones, effective hydraulic conductivity values of the overall barrier system and steady-state leakage rates

Soil type[a]	Thickness of vadose zone (m)	$\bar{k}_{\mathrm{VZh}}$[b] (m/s)	$\bar{\bar{k}}$[c] (m/s)	q_{hc}[d] (m/s)	q_{mc}[e] (m/s)
Si	1	2.41×10^{-7}	2.65×10^{-9}	3.15×10^{-9}	3.15×10^{-9}
Si	5	3.22×10^{-8}	7.41×10^{-9}	7.80×10^{-9}	7.80×10^{-9}
Si	10	1.27×10^{-8}	7.64×10^{-9}	7.86×10^{-9}	7.86×10^{-9}
SiT	1	5.46×10^{-8}	2.59×10^{-9}	3.07×10^{-9}	3.07×10^{-9}
SiT	5	1.04×10^{-8}	5.18×10^{-9}	5.45×10^{-9}	5.45×10^{-9}
SiT	10	7.13×10^{-9}	5.29×10^{-9}	5.45×10^{-9}	5.45×10^{-9}
USi	1	1.00×10^{-8}	2.29×10^{-9}	2.71×10^{-9}	2.71×10^{-9}
USi	5	1.00×10^{-8}	5.09×10^{-9}	5.36×10^{-9}	5.36×10^{-9}
USi	10	1.00×10^{-8}	6.81×10^{-9}	6.82×10^{-9}	6.85×10^{-9}

Note: Leakage calculated neglecting the vadose zone and assuming zero suction at bottom of the CCL is 1.5×10^{-9} m/s.

[a] Si: silt, SiT: silt tailings, USi: uniform silt.

[b] Harmonic mean of vadose zone hydraulic conductivities.

[c] Harmonic mean of vadose zone and compacted clay liner hydraulic conductivities.

[d] Steady-state leakage rate as a result of hand calculations.

[e] SEEP/W calculated steady-state leakage rates.

When the barrier system is simulated using uniform saturated hydraulic conductivities, the steady-state leakage rates (denoted by q_{kuni}) are the same as the leakage rates simulated using soil

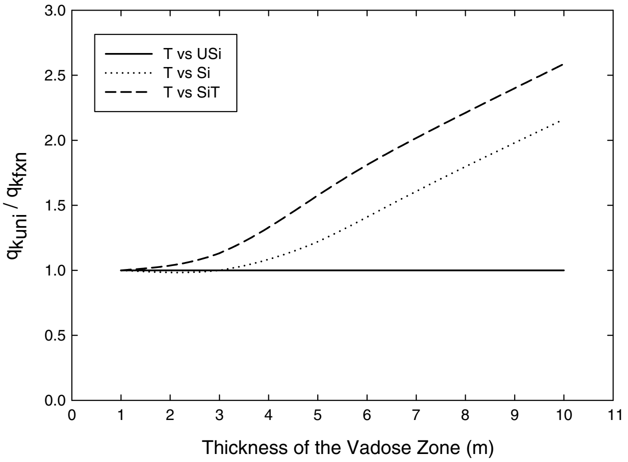


Fig. 7. Normalized steady-state leakage rates with varying fine textured vadose zone thickness.

hydraulic conductivity functions of silt and silt tailings (denoted by q_{kfxn}) for vadose zones with thickness less than 5 m (see Fig. 7). Vadose zones composed of silt and silt tailings and thicker than 5 m gave steady-state leakage rates that are 1.5–2.5 times greater than those obtained by using unsaturated soil hydraulic conductivity functions. As previously stated, the hydraulic conductivity of uniform silt is relatively constant with pore-water pressure and, therefore, the steady-state leakage rates in uniform silts are not affected by pore-water pressure for vadose zones with thickness up to 10 m (Fig. 7). The results show that fine textured vadose zones can be modelled reasonably using uniform saturated hydraulic conductivity values for vadose zones less than 4 m thick and up to 10 m if the silt is very uniform.

3.1.3. Effect of compacted clay liner hydraulic conductivity

The effect of CCL hydraulic conductivity on the overall performance of the barrier system was also evaluated using a saturated hydraulic conductivity of 1×10^{-10} m/s for the CCL. For both coarse textured and fine textured vadose zones, one order of magnitude decrease in the hydraulic conductivity of CCL resulted in almost the same (one) order of magnitude decrease in the effective hydraulic conductivity of the overall barrier system and steady-state leakage rates into the aquifer (Table 4). An order of magnitude increase in the vadose zone thickness, on the other hand, resulted in half order of magnitude increase in the steady-state leakage rate, and the effective hydraulic conductivity (Tables 2 and 3). Therefore, the effect of CCL hydraulic conductivity is dominant over the vadose zone thickness and it should be considered as the controlling factor for leakage into the aquifer.

3.1.4. Diffusion in the vadose zone

Increasing thickness of the soil layer between the top of the liner and the underlying receptor aquifer will substantially reduce diffusive mass transport to the aquifer (Rowe, 2007). However the effectiveness of the vadose zone as a diffusion barrier will, to some extent, depend on the water content and the nature of the contaminant. Non-volatile contaminants will readily diffuse through water but not air. Thus an unsaturated soil provides a better diffusion barrier than a saturated soil since they can only diffuse through the water phase. Equations for estimating the diffusion coefficient for unsaturated soils are given by Rowe et al. (2004). Volatile contaminants (VOCs) such as dichloromethane (DCM), 1,2 dichloroethane (DCA), trichloroethene (trichloroethylene, TCE), benzene, toluene, ethylbenzene, m&p-xylene and o-xylene will diffuse orders of magnitude faster in a dry soil than they will through a saturated soil. In an unsaturated soil, they will diffuse in both the gaseous and dissolved phases, but diffusion will be predominantly through the gas-filled pores if the water content is low enough to have a significant number of continuous gas-filled pores. This issue is addressed in more detail by Rowe et al. (2004).

4. Conclusions

Failure to consider the presence of an unsaturated zone beneath a CCL and the assumption of zero suction at the base of the CCL can result in substantial underestimation of the leakage through the clay liner. This consideration should be given to the effect of the vadose zone on the leakage through the CCL.

Unsaturated soil hydraulic conductivity is a function of water content and, hence, it increases with increasing water content towards the water table. Because the thickness of soil with low moisture content, and hence low hydraulic conductivity, increases with increasing vadose zone thickness, the harmonic mean hydraulic conductivity values of the vadose zone decrease with increasing thickness of the vadose zone. When the barrier system is simulated using unsaturated soil hydraulic conductivity functions, the resulting harmonic mean hydraulic conductivity values of the coarse textured vadose zones are 3 – 4 orders of magnitude less than the uniform saturated hydraulic conductivity values. For fine textured vadose zones, however, the difference is only one order of magnitude.

For both coarse and fine textured vadose zones, the effective hydraulic conductivity of the overall barrier system increases with increasing thickness of the vadose zone. The increased effective hydraulic conductivity values result in a gradual increase in the steady-state leakage rates into the aquifer. Steady-state leakage rates in the fine and coarse textured vadose zones reach an asymptotic value at about 5 m and 10 m thickness, respectively, for the cases examined herein. The coarse textured vadose zones thicker than 10 m and fine textured vadose zones thicker than 5 m start to act as a part of the barrier system. A 5 to 10-m-thick vadose zone can be not only an effective advective barrier, but also be an effective diffusive barrier. For inorganic contaminants, as the thicknesses of CCL and vadose increase, the diffusive mass flux and thus concentrations of contaminants diffusing through the barrier tend

Table 4
The effect of compacted clay liner hydraulic conductivity on the effective hydraulic conductivity and steady-state leakage rates into the aquifer

	Coarse textured VZ				Fine textured VZ			
T_{VZ}[a] (m)	5	10	5	10	5	10	5	10
k_{CCL}[b] (m/s)	1×10^{-9}	1×10^{-9}	1×10^{-10}	1×10^{-10}	1×10^{-9}	1×10^{-9}	1×10^{-10}	1×10^{-10}
q[c] (m/s)	6.79×10^{-9}	7.09×10^{-9}	8.88×10^{-10}	1.08×10^{-9}	7.80×10^{-9}	7.86×10^{-9}	9.20×10^{-10}	9.83×10^{-10}
$\bar{\bar{k}}$[d] (m/s)	6.45×10^{-9}	6.87×10^{-9}	8.51×10^{-10}	1.04×10^{-9}	7.41×10^{-9}	7.64×10^{-9}	8.70×10^{-10}	9.61×10^{-10}

Note: Leakage calculated neglecting the vadose zone and assuming zero suction at bottom of the CCL is 1.5×10^{-9} m/s and 1.5×10^{-10} m/s for k_{CCL} of 1×10^{-9} m/s and 1×10^{-10} m/s, respectively.

[a] Thickness of vadose zone.

[b] Hydraulic conductivity of compacted clay liner.

[c] Steady-state leakage rate into the aquifer.

[d] Effective hydraulic conductivity.

to decrease due to the decrease in concentration gradients. The vadose zone may not be as effective a diffusion barrier for VOCs, as discussed by Rowe et al. (2004) and Rowe (2007).

Modelling the barrier systems using uniform saturated hydraulic conductivity values resulted in a substantial overestimation of the leakage (by up to a factor of about 3.5) with the error becoming significant as the thickness exceeds about 3 m. Consequently when there is a coarse textured vadose zone thicker than about 3 m underlying a CCL, it is desirable to consider unsaturated conditions and the use of soil hydraulic conductivity functions when calculating leakage through the barrier system. Silty fine textured vadose zones can be modelled reasonably using uniform saturated hydraulic conductivity values for vadose zones less than 4 m thick, and up to 10 m thickness, if the silt is very uniform.

One order of magnitude decrease in the hydraulic conductivity of the CCL resulted in the same order of magnitude decrease in the steady-state leakage rate; whereas, the same order of magnitude increase in the vadose zone thickness only resulted in half order of magnitude increase in the steady-state leakage rate. While the vadose zone thickness affects the effective hydraulic conductivity of the overall barrier system, and in turn the steady-state leakage rates, the CCL hydraulic conductivity was the primary factor controlling the steady-state leakage rates through the barrier system.

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Appendix

Green and Corey (1971) equation to estimate hydraulic conductivity values for various soils is given in Eq. (A1) (GEO-SLOPE International Ltd., 2002).

$$k(\theta)_i = \frac{k_s}{k_{sc}} \times \frac{30T^2}{\mu g \eta} \times \frac{\xi^p}{n^2} \times \sum_{j=1}^{m} \left[(2j + 1 - 2i)h_i^{-2}\right] \tag{A1}$$

where $k(\theta)_i$ is the calculated hydraulic conductivity for a specified water content or negative pore-water pressure (cm/min), k_s/k_{sc} is the matching factor (the ratio of measured saturated hydraulic conductivity to the calculated saturated hydraulic conductivity), T is the surface tension of water (dyn/cm), μ is the density of water (g/cm^3), g is the gravitational constant (cm s^{-1}), η is the viscosity of water (g/cm s^{-1}), ξ is the water saturated porosity, n is the total number of pore classes, θ is the water content (cm^3/cm^3), p is a parameter that accounts for the interaction of pore classes (taken as either 2.0, 1.3, or 1.0), h is negative pore-water pressure head for a given class of water-filled pores, and i is the last water content class on the wet end (i = 1 identifies pore class corresponding to the lowest water content and i = m identifies pore class corresponding to the saturated water content).

First the hydraulic conductivity at zero pressure value is calculated by Eq. (A2).

$$k_{sc} = \sum_{j=1}^{m} \left[(2j + 1 - 2i)h_i^{-2}\right] \tag{A2}$$

Table A.1
Green and Corey parameters required to solve the hydraulic conductivity equation

Soil type	k_{sat}[a] (m/s)	ϕ[b]	Air entry value (kPa)
Uniform sand	1.0×10^{-4}	0.35	3
Sand	5.4×10^{-5}	0.39	6
Fine sand	4.3×10^{-6}	0.35	4
Silt	2.5×10^{-7}	0.38	20
Uniform silt	1.0×10^{-8}	0.50	80
Silt tailings	5.8×10^{-8}	0.30	10

[a] Saturated hydraulic conductivity.
[b] Porosity.

When the user specifies the k_s value, the entire conductivity function is moved up or down by a constant ratio of k_s/k_{sc}. SEEP/W also assumes that the value of $\frac{30T^2}{\mu g \eta} \times \frac{\xi^p}{n^2}$ is constant (i.e., 1.0) for a particular function when determining the shape of the hydraulic conductivity function (GEO-SLOPE International Ltd., 2002). The Green and Corey parameters required to solve the equation are given in Table A.1.

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