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Evaluating the effect of clay layer on the performance of composite liner having geomembrane defects

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ABSTRACT: This paper presents the effect of clay liner on the minimization of the leakage and contaminant transport through a landfill bottom liner, mainly due to defects in geomembrane, as well as a brief review on the methods to evaluate the leakage flow rate through geomembrane defects in previous researches. Based on the two-dimensional axially symmetrical numerical analyses, equivalent hydraulic conductivity of a geomembrane is proposed in order to quantify the leakage flow through defects in comparison with the flow due to the hydraulic conductivity of geomembrane itself. Further, the performances of three typical bottom liner systems in Japan are analytically investigated in aspects of the contaminant concentration and mass flux. The results show that a composite liner with a clay liner performs excellently in reducing both leakage rate and released contaminant mass flux.

1 INTRODUCTION

Geomembrane sheets are widely used for the purpose of leachate containment in solid waste landfills. However, defects in the geomembrane occur during the construction and operation of landfills (Giroud & Bonaparte 1989), and the leakage flow through defects could result in the contamination of the geoenvironment and groundwater. Several analytical and experimental studies have developed the methods to predict the leakage rate and contaminant transport through a landfill bottom liner having geomembrane defects (Giroud & Bonaparte 1989, Giroud et al. 1989, 1992, 1998, Foose et al. 1996, 2001, Giroud 1997, Rowe 1998, Katsumi et al. 2001). Although these proposed methods have been used mainly in the design of bottom liners, they also imply that the environmental risk assessment should consider the leakage flow due to defects in geomembrane. Generally, the geomembrane sheet is regarded as an impermeable material or a material of a constant hydraulic conductivity lower than 10^{-10} cm/s in the environmental impact analysis. However, the leakage rate through defects in the geomembrane was noticed to be significantly affected mainly by factors not concerning the geomembrane itself, such as the permeability of underlying layer, cross section of liner system and leachate head above the geomembrane. Therefore, the environmental assessment may result in the underestimation of the leakage rate without evaluating the hydraulic conductivity of geomembrane appropriately.

In this study, the appropriate parameter setting to represent the hydraulic conductivity of geomembrane having defects is discussed based on the simplified concept of equivalent hydraulic conductivity. Two-dimensional axially symmetric numerical analyses were conducted to quantify the leakage rate through a bottom liner system. Further, performances of three typical bottom liner systems in Japan were analytically evaluated in aspects of the released contaminant concentration and mass flux. Based on these results, the importance of clay liner overlaid by a geomembrane sheet was emphasized in terms of the minimization in leakage and chemical transport through a composite liner having geomembrane defects.

2 BACKGROUND

Defects in geomembrane were caused by defects in geomembrane seams, puncturing by stones, tensile failure due to excessive stresses, and fatigue by cyclic loading or creep. Giroud & Bonaparte (1989) investigated the defect size and frequency in geomembrane liners, and concluded that 1 defect per 10 m seam length was present without quality assurance. Even if quality assurance was conducted, 1 defect per 300 m seam length was observed. Calabria & Peggs (1997) reported the defect frequency in the seam of HDPE geomembrane landfill cover, and concluded that it was significantly dependent on the operator's skill, ranging from 1 defect per 85 m seam length to 1 defect per 1200 m seam length. However, the shapes and frequencies of defects vary in each landfill considerably. In many previous researches regarding the calculation of leakage rate through defects in the geomembrane, the defect was assumed to be a circular hole of 1 – 10 mm diameter with its frequency of 1 – 10 defects/ha.

Although many empirical and theoretical equations for predicting the leakage rate through defects in geomembrane have been developed, the most commonly used equations were proposed by Giroud et al. (1992). Giroud (1997) summarized the developed equations in aspects of the shapes of defects, liquid head on the liner, and the interface between the geomembrane

Table 1. Equations for calculating the leakage rate in composite liners (Giroud 1997)

Shapes of geomembrane defect (size)	Liquid head on the top of the liner: $h < t_s$	Liquid head on the top of the liner: $h > t_s$
Circular (diameter: d) Square($b \times b$)	$Q = C_{q0} a^{0.1} h^{0.9} k_S^{0.74}$	$Q = C_{q0}\left[1+0.1(h/t_S)^{0.95}\right] a^{0.1} h^{0.9} k_S^{0.74}$
Rectangular (length: $B \times b$)	$Q = C_{q0} b^{0.2} h^{0.9} k_S^{0.74} + C_{q\infty}(B-b) b^{0.1} h^{0.45} k_S^{0.87}$	$Q = C_{q0}\left[1+0.1(h/t_S)^{0.95}\right] b^{0.2} h^{0.9} k_S^{0.74}$ $+ C_{q\infty}\left[1+0.1(h/t_S)^{0.95}\right](B-b) b^{0.1} h^{0.45} k_S^{0.87}$
Infinite length(width: b)	$Q^* = C_{q\infty} b^{0.1} h^{0.45} k_S^{0.87}$	$Q^* = C_{q\infty}\left[1+0.1(h/t_S)^{0.95}\right] b^{0.1} h^{0.45} k_S^{0.87}$

h: liquid head on the top of the liner, t_s: thickness of underlying soil, a: defect area, k_S: hydraulic conductivity of underlying soil, Q: leakage rate through a defect, Q^*: leakage rate per unit-length of defect, C_{q0}, $C_{q\infty}$: contact quality factor between the geomembrane and underlying layer (good or bad); $C_{q0good} = 0.21$, $C_{q0bad} = 1.15$, $C_{q\infty good} = 0.52$, $C_{q\infty bad} = 1.22$.

and underlying layers, as shown in Table 1. Also, Giroud et al. (1998) proposed new equations that give a leakage rate considering the permeability of the layers contacting to the geomembrane.

Rowe (1998) developed an analytical equation for leakage rate through circular defects in composite liners including the lateral interface flow between the geomembrane and soil liner. Rowe (1998) also proposed another method to calculate the leakage through holes on the wrinkle.

Foose et al. (1997) and Katsumi et al. (2001) calculated the contaminant transport through defects in geomembrane using a finite-difference numerical model, and proposed simplified equations for estimating the mass of inorganic and organic contaminants released.

3 ANALYSIS OF LEAKAGE RATE

3.1 *Method*

The finite element method was used to calculate the leakage rate through defects in a bottom liner. This analysis solves the typical governing equation for saturated flow through porous media

$$\frac{\partial}{\partial x_i}\left(K_{ij}\frac{\partial h}{\partial x_j}\right) - q = S_S\frac{\partial h}{\partial t} \tag{1}$$

where K_{ij} = hydraulic conductivity tensor; h = total head drop across the bottom liner; q = flow rate of sinks and sources; S_S = specific storage.

Leakage through a circular defect was modeled as an axially symmetric system as shown in Figure 1. The bottom boundary was regarded as a freely draining boundary. Head loss that occurs in the layer above the geomembrane and through the defect was found to be negligible. The underlying layer was assumed to be saturated and homogeneous. The interface between the geomembrane and underlying layer was assumed to be negligible based on the experimental results by Walton et al. (1997) that a bottom liner has perfect contact between the fine sand layer and geomembrane subjected to the overburden pressure. The numerical analysis results considering the flow through the interface between the geomembrane and soil layer were presented by Foose et al. (2001).

In this analysis, leakage rates were calculated for different hydraulic conductivities of underlying layer, k_u (1.0×10^{-0}–1.0×10^{-7} cm/s), thicknesses of geomembrane, t_g (1–5 mm), thicnesses of underlying layer, t_u (0.3–10 m), and diameters of a circular defect (2–12 mm).

3.2 *Results and discussions*

As shown in the theoretical estimation of the flow rate from a circular defect (e.g. Giroud et al. 1992), the calculated results showed that leakage rates were significantly dependent on the hydraulic conductivity of underlying layer and diameter of a circular defect. However, thicknesses of geomembrane and undelying layer did not cause the significant change in calculated leakage rates. Figure 2 shows the leakage rate as a function of $k_u \times d$ for different h_T values (h_T = 30 cm, 300 cm). Relatively good linearity in the relationship between the leakage rate and $k_u \times d$ was observed over a wide rage of $k_u \times d$. This empirical linear relationship can be expressed as follows;

$$Q = 2.62\, k_u \times d \times h_T \tag{2}$$

Equation (2) has the similar form to Forchheimer's equation (Giroud et al. 1994), because both equations give the leakage rate through a circular defect in a composite liner having perfect contact between the geomembrane and underlying layer in the case that the diameter of defect is much smaller than the thickness of the underlying layer. In addition, Figure 3 shows the leakage rate according to Equation (2) in comparison with that based on the equations by Giroud (1997) shown in Table 1, in order to verify the reasonability of Equation (2). Leakage rate by Equation (2) has the similarity with that by Giroud (1997) for the larger $k_u \times d$ value, however, the leakage rate by Equation (2) is about one order of magnitude smaller in the case that $k_u \times d$ is lower than about 10^{-6} cm^2/s. The reason for this underestimation is considered to be that Equation (2) does not take the interface flow between geomembrane and underlying layer into account, and this interface flow is more dominant when the permeability of underlying layer is low.

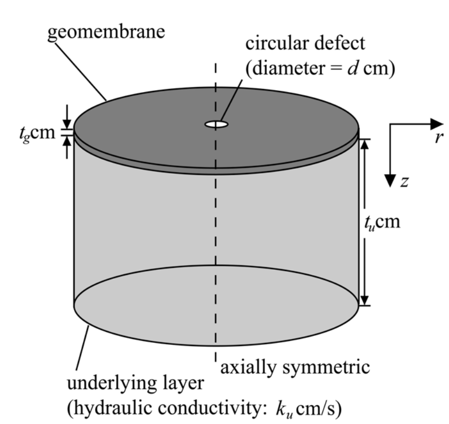

Figure 1. Model for the flow through defects in geomembrane.

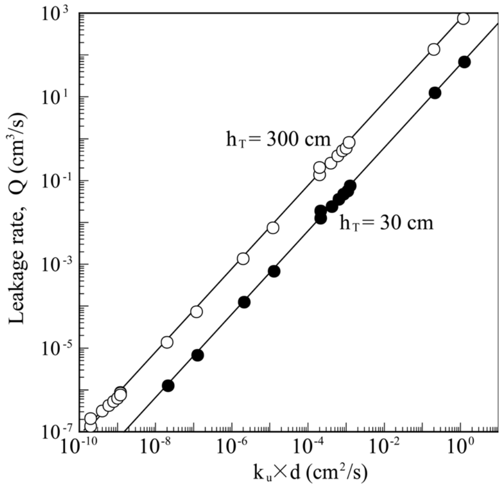

Figure 2. Leakage rate as a function of $k_u \times d$.

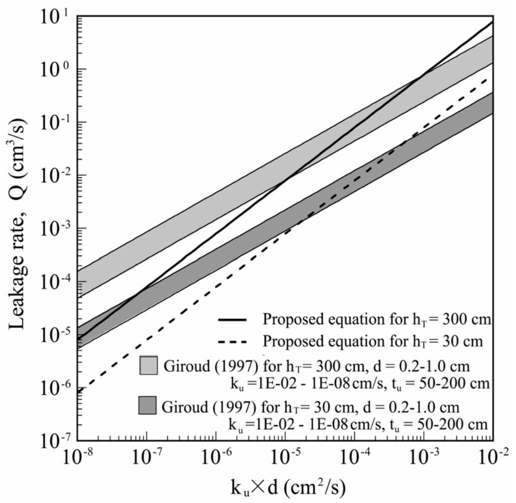

Figure 3. Calculation results compared with the equation proposed by Giroud (1997).

3.3 *Equivalent hydraulic conductivity of the geomembrane*

Equivalent hydraulic conductivity of the geomembrane, k_{eq}, was proposed based on Equation (2). k_{eq} gives the equivalent flow rate to the geomembrane sheet as a permeable material, based on the assumption that the geomembrane sheet should be subjected to the leakage through defects with some frequency in field. k_{eq} was determined by the following equation based on the Darcy's law.

$$Q_d = 2.62 k_u \times d \times h_T \times f \tag{3}$$

$$Q_g = \left(t_u/k_u + t_g/k_g\right)^{-1} h_T \tag{4}$$

$$Q_{eq} = Q_d + Q_g = \left(t_u/k_u + t_g/k_{eq}\right)^{-1} h_T \tag{5}$$

where Q_d = leakage rate per unit area through defects; f = defect frequency; Q_g = leakage rate per unit area due to the permeability of geomembrane itself; k_g = hydraulic conductivity of geomembrane; Q_{eq} = equivalent flow rate per unit area including the leakage through defects; k_{eq} = equivalent hydraulic conductivity of geomembrane. It is considered that k_{eq} means the effective hydraulic conductivity including the leakage due to both defects in geomembrane and permeability of itself. The authors have evaluated the appropriate structure of vertical barrier in a coastal landfill site, considering the leakage through defects in impermeable sheet using this method (Kamon et al. in press).

Figure 4 shows k_{eq} curves calculated for a HDPE sheet (t_g = 2 mm, k_g = 2.5×10^{-13} cm/s) with different defect frequencies, defect diameters and hydraulic conductivities of the underlying layer (t_u = 50cm). h_T was assumed to be 100 cm. The results show that k_{eq} is almost equal to k_g in the case of $k_u = 10^{-7}$ cm/s, regardless of the defect diameter and frequency. This means that the leakage rate through defects is negligible when the low permeable layer such as a clay liner is overlaid by the geomembrane, even if it has defects with a high frequency. However, when the geomembrane is installed on the layer of relatively high permeability (e.g. $k_u = 10^{-3}$ cm/s), k_{eq} increases significantly with a higher defect frequency. From these calculated results, it can be concluded that the construction of clay liner is more effective than the careful quality assurance in the geomembrane installation from a viewpoint of leakage reduction through a landfill bottom liner.

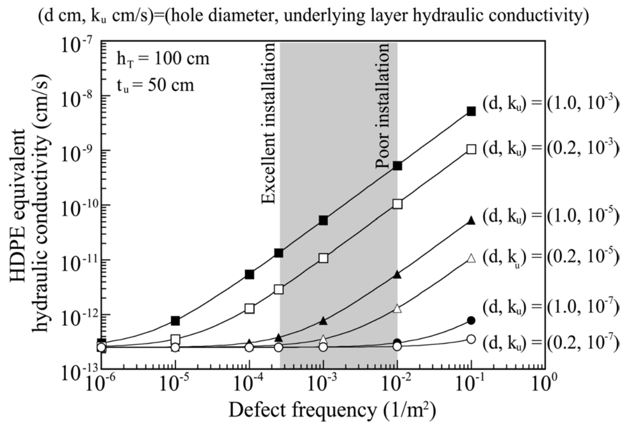

Figure 4. Calculated equivalent hydraulic conductivity.

4 ANALYSIS OF CHEMICAL TRANSPORT

4.1 *Method*

Three composite liners were analyzed to assess chemical transport through a defect in geomembrane. Figure 4 shows the cross sections for these composite liners typically applied to the municipal solid waste landfill bottom liner in Japan. The finite element advection-dispersion chemical transport model DTransu–2D·EL (Nishigaki et al. 1995) was used to analyze the concentration and mass flux of a contaminant released through a composite liner. This analysis solves the governing equation for saturated fluid-density dependent groundwater flow with mass transport:

$$R\rho\frac{\partial c}{\partial t} = \frac{\partial}{\partial x_i}\left(\rho D_{ij}\frac{\partial c}{\partial x_j}\right) - \frac{\partial}{\partial x_i}\left(\rho v_i c\right) \tag{6}$$

$$D_{ij} = \alpha_T \|V\| \delta_{ij} + \left(\alpha_T + \alpha_L\right)\frac{V_i V_j}{\|V\|} + D_{me}\delta_{ij} \tag{7}$$

where R = retardation factor; ρ = density of water; c = chemical concentration; D_{ij} = dispersion coefficient tensor; v_i = pore velocity; α_T = transversal dispersivity; α_L = longitudial dispersivity; $\|V\|$ = pore velocity norm; V_i: pore velocity vector; δ_{ij} = Cronecker's delta; D_{me} = effective diffusivity. Table 2 shows the values of these parameters, hydraulic conductivity (k) and effective porosity (n_e) for each material used in the numerical analysis.

These landfill liners were also modeled as an axially symmetric system as shown in Section 3. Chemical transport was analyzed under the total head distribution and saturated water flow condition based on the two-dimensional axially symmetric model described in Section 3. Leachate above the geomembrane was assumed to contain the solute inorganic contaminant of 1 mg/L. Diffusive chemical transport through the geomembrane was considered to be negligible.

4.2 *Results and discussions*

Table 3 shows the leakage rate through a defect and chemical re-

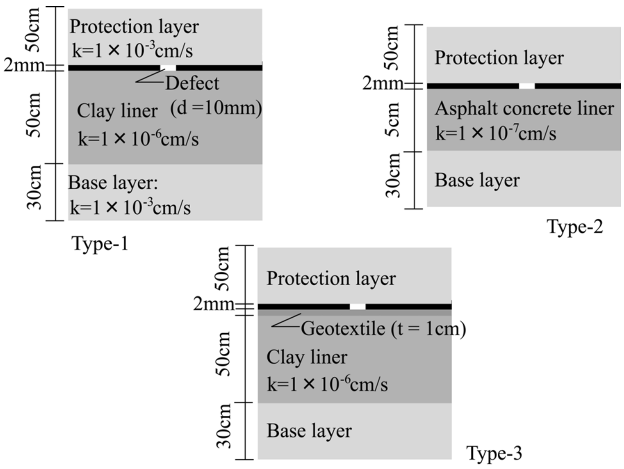

Figure 5. Cross section of three landfill bottom liners.

Table 2. Parameters used in the numerical analysis

Parameters	unit	Protection/ base layer	Geotextile	Clay liner	Asphalt concrete
k	cm/s	1.0×10^{-3}	1.0×10^{-3}	1.0×10^{-6}	1.0×10^{-7}
n_e	–	0.44 / 0.40	0.44	0.60	0.10
α_L	cm	10	10	10	10
α_T	cm	1	1	1	1
D_{me}	cm^2/s	1.0×10^{-5}	1.0×10^{-5}	1.0×10^{-5}	1.0×10^{-5}
R	–	1	1	2	1

n_e: effective porosity

Table 3. Calculated results of leakage rate and chemical release flux

Type of liner	h_T (cm)	Leakage rate (cm^3/day/defect)	Chemical release flux* ($mg/year/m^2$)
Type–1 (1)	300	5.1×10^{1}	1.5×10^{0}
(2)	50	8.4×10^{0}	4.8×10^{-2}
Type–2 (1)	300	5.4×10^{0}	5.0×10^{-1}
(2)	50	8.9×10^{-1}	3.1×10^{-2}
Type–3	300	1.6×10^{4}	4.0×10^{2}

*10 years after at the bottom of liner

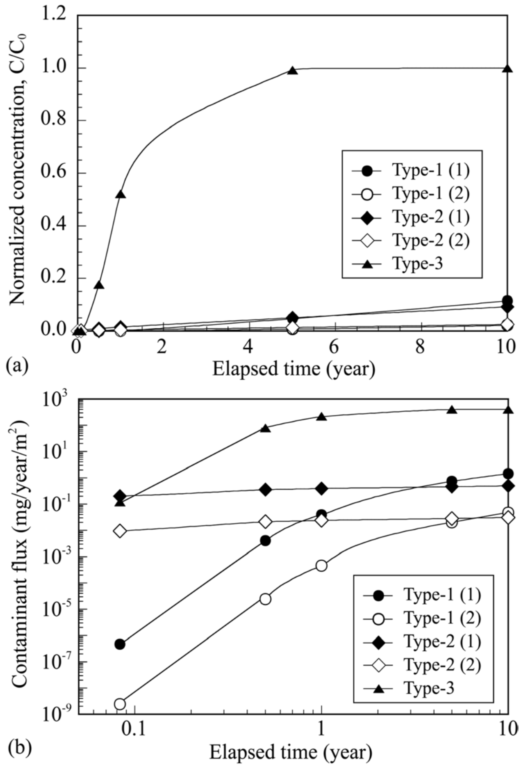

Figure 6. Chemical transport through a composite liner: (a) average normalized concentration; (b) Mass flux at the bottom of liner.

lease flux after 10 years at the bottom of liner. As shown in Equation (2), the leakage rate is dependent on the hydraulic conductivitity of underlying layer. Although some landfill bottom liners in Japan have a geotextile layer overlaid by a geomembrane to prevent the puncturing defect, the liner with a geotextile layer (Type-3) can be subject to significantly larger leakage rate when the geomembrane defects occur.

Figure 6 show the average contaminant concentration and mass flux in the circular area within 1 m away from a defect. As shown in Table 3, significantly higher concentration and larger mass flux of contaminants from Type-3 liner are observed, because the permeable geotextile under a geomembrane contribute to the larger leakage rate. In contrast, Type-1 and Type-2 liner can reduce the contaminant release coupled with the leakage through defects, reaching only under 5% in normalized concentration in the case of $h_T = 50$ cm. Particularly, Type-1 liner system with a clay liner reduces the initial mass flux, because the clay material usually has a larger porosity and chemical transport retardation effect. In Type-2 liner system, which has a relatively thin (5 cm) low-permeable asphalt-concrete layer, the leakage flow concentrated at a defect in geomembrane result in the directly chemical transportation to the bottom of liner.

5 CONCLUSIONS

The effect of clay liner on the performance of composite liner is analytically evaluated in terms of the leakage rate and chemical transport. As a simplified method to evaluate the effect of leakage through defects in geomembrane in the environmental impact assessment, equivalent hydraulic conductivity of the geomembrane, which gives the effective hydraulic conductivity including the leakage due to both defects in geomembrane and permeability of itself, is proposed. The results based on this proposed method show that the amount of leakage flow through defects is almost negligible in the case that a low hydraulic conductivity layer (< 10^{-6} cm/s) is overlaid by the geomembrane sheet. Further, chemical transport through landfill bottom liners typically applied to the MSW landfill in Japan is analyzed using the finite element advection-dispersion chemical transport model. The results show that a clay liner in the liner system can contribute to the significant reduction of chemical transport, particularly in the initial mass flux of contaminant released.

From these discussions, the importance of clay liner overlaid by a geomembrane on the performance of minimization of chemical leakage is emphasized.

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