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EVALUATION OF PERFORMANCE OF CHINESE STANDARD MUNICIPAL SOLID WASTE LANDFILL BOTTOM LINER SYSTEMS

Y. J. Du[1], S. Y. Liu[2] and S. Hayashi[3]

ABSTRACT: It is reported that nearly 80 % of the Chinese municipal solid waste (MSW) landfills were open-dump without strict landfill bottom liners. A serious environmental pollution has been exposed to landfill impacts. To solve this problem, Chinese Government prescribed standard MSW landfill bottom liners. However, very limited research has been conducted to evaluate the performance of the standard MSW landfill bottom liners prescribed Chinese Government. In this paper, it was assumed that the two standard Chinese landfill liners were applied in assumed field scenario, in which an aquifer was below the landfill. With the one-dimensional advection-diffusion-dispersion theory of contaminant transport, the impacts of the landfills on the aquifer were assessed. The performance of the two types of Chinese MSW landfill bottom liner systems was evaluated based on: 1) the leakage rate through the liners which were applied in assumed landfills; 2) the peak concentration of the target contaminant in an aquifer overlain by the assumed landfills, and 3) the maximum total mass per unit area of the target contaminant discharged into the aquifer. The performance of the German standard MSW landfill bottom liner system was evaluated and compared with that of Chinese ones. The calculated leakage rate, peak concentration and the maximum total mass per unit area in the aquifer of the target contaminant show that the performance of the Chinese standard landfill liner Type 2 is practically the same as that of the German standard landfill liner, while the Chinese standard liner Type 1 is less effective, with regarding the mitigation of the impact of landfills.

Keywords: Clay liner, contaminant, landfill, leakage, performance, sorption

INTRODUCTION

Recently in China, the amount of municipal solid waste (MSW) is increasing at about 10%. The annual amount of MSW produced in the urban areas is about 190 million tons (World Bank Report 2005). Among these wastes, 70% is disposed to landfills, 20% is composted and 10% is incinerated. Averagely, about 80% of the landfills is open-dump without any strict bottom liner systems, which has caused serious environmental pollution, especially the pollution of the ground water by the organic contaminants contained in the solid wastes (World Bank Report 2005). To solve this problem, Chinese Government prescribed standard MSW landfill bottom liners (Technical Code for Municipal Solid Waste Sanitary Landfill 2004). Some modern landfills are being built in municipals like Beijing, Shanghai, and Shengzhen (World Bank report 2005). Currently in China, researches on the shear strength and the compression properties of the solid wastes are of concern (Zhang and Chen 2005), while research on the effectiveness of the Chinese standard landfill liners in mitigating landfill impacts on underlying aquifer has not been received sufficient attention. As a result, an uncertainty exists when the Chinese MSW landfill bottom liners are used in practice.

The main purpose of this study is to evaluate the performance of the Chinese standard MSW landfill liner systems in terms of mitigating contaminant migrated from landfills. Firstly, the shortcomings of the Chinese standard MSW landfill bottom liner systems against the German standard MSW landfill bottom liner systems were discussed. Secondly, the performance of the two types of Chinese standard landfill liner systems was evaluated based on the leakage rate, concentration, and the total mass per unit area of the target contaminant under assumed hydrogeology conditions. The effectiveness of the German standard MSW landfill bottom liner system was also evaluated and compared with that of Chinese ones.

[1] IALT life Member, Institute of Geotechnical Engineering, Southeast University, Nanjing 210096, CHINA
[2] IALT Member, Institute of Geotechnical Engineering, Southeast University, Nanjing 210096, CHINA
[3] IALT life Member, Institute of Lowland Technology, Saga University, Saga 840-8502, JAPAN
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DESCRIPTION OF CHINESE STANDARD LANDFILL LINER SYSTEMS

Figure 1 show the minimum design requirement on two types of Chinese standard MSW landfill bottom liner system, Type 1 and Type 2. In Type 1, a natural clay deposit with a thickness larger than 2 m and hydraulic conductivity less than 10^{-9} m/s is used as a containment barrier. In Type 2, a composite liner system consisting a geomembrane liner and compacted clay liner (CCL) is used. The thicknesses of the geomembrane liner and CCL are greater than 1.5 mm and 1m, respectively. The hydraulic conductivity of the CCL is less than 10^{-9} m/s. The German standard MSW landfill bottom liner system (see Fig. 1) (EEA 2000) consists of a geomembrane liner and a CCL with thickness greater than 2.5 mm and 0.75 m, respectively. The hydraulic conductivity of the CCL is required to be less than 5×10^{-10} m/s. As compared with the German standard landfill bottom liner system, the Chinese standard landfill liner systems have following shortcomings:

1) In both Type 1 and Type 2, the hydraulic conductivity of the drainage layer in the leachate collection and removal system (LCRS) is required to be higher than 10^{-7}m/s, which is three orders of magnitude lower than that of the German one, 10^{-4} m/s. Du et al. (2007) conducted an analysis of the maximum leachate head (y_{max}) for both Chinese standard landfill liner system and German standard landfill liner system using the method proposed by Giroud (1992). The maximum leachate head refers to the maximum vertical distance from the leachate phreatic surface (due to the inflow into the drain layer) to the landfill liner (Rowe et al. 1995). The result shows that the calculated maximum leachate head in landfill for the case of Chinese standard landfill liner system would be 2 orders of magnitude greater than that for the German one.

2) The method for calculating y_{ma} is not discussed. However, for the German standard landfill liner system, a Hydrologic Evaluation of Landfill Performance (HELP) model is suggested for the calculation of y_{max} in landfill (GRL 1993).

3) The grain size of the gravels around the leachate collection pipes is not required, while it is required as 16 mm~32 mm by the German standard (EEA 2000). Rowe et al. (2000) and Rowe (2005) indicated with the presence of high organic matters contained in the wastes disposed to landfills and with the aid of anaerobic bacteria, small grain sized drain materials would easily be clogged due to the biochemical reactions. The clog could considerably reduce the original hydraulic conductivity (10^{-3}~10^{-4} m/s) of drain layer even to 10^{-7}

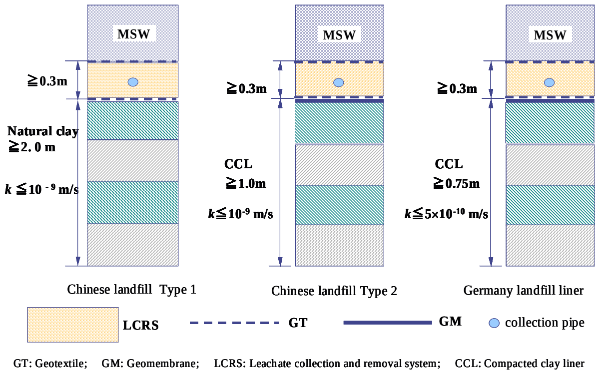

Fig. 1 A schematic illustration showing Chinese MSW standard landfill bottom liner systems and German MSW standard landfill bottom liner system

~10^{-8} m/s, and thereby could cause the build-up of a leachate mound in landfills.

ANALYSIS OF PERFORMANCE OF CHINESE LANDFILL LINER SYSTEMS

Leakage Rate at Liners Bottom

In this study, three performance criteria were adopted to evaluate the effectiveness of the Chinese standard landfill liners: 1) the leakage rate of landfill leachate through the liners, 2) the concentration of a target contaminant in an aquifer overlain by assumed landfills. The standard landfill liners were applied in the landfills. 3) the total mass of the target contaminant per unit area discharged into the aquifer overlain by assumed landfills. It was assumed that the clay liners were saturated and the water level at the clay liner bottom is the same as the liner base. For the Chinese standard landfill line Type 1, the downward Darcy velocity v_a is calculated based on the Darcy's law:

$$v_a = k_s i \tag{1}$$

where k_s = the hydraulic conductivity of the clay liner; i = the hydraulic gradient on the liner Type- l ($i = \Delta h/L$, in which Δh = the head difference on Type 1 liner; and L = the thickness of liner Type 1). It was assumed that the leachate head on liner Type 1 was 0.5 m, L = 2.0 m, and $k_s = 10^{-9}$ m/s. Therefore, Δh was calculated as 1.5m, and v_a was calculated as 1.5×10^{-9} m/s. The leachate volume per unit time through the liner (or leakage rate, Q) was calculated based on:

$$Q = v_a \times W \times L \tag{2}$$

in which W = the length of the landfill in which the Chinese standard landfill liner Type 1 is applied, and L = the length of the landfill.

For the Chinese standard landfill liner Type 2 and the German standard landfill liner, the leakage rate (Q_0) through a geomembrane defect with circular shape was calculated using the method proposed by Giroud et al. (1992):

$$Q_0 = C_{qo} \cdot i_{avg} \cdot a^{0.1} \cdot h_w{}^{0.9} \cdot k_s{}^{0.74} \tag{3}$$

where C_{q0} = the dimensionless coefficient (0.21 for good contact and 1.15 for poor contact condition), a = the area of the geomembrane hole, h_w = the leachate head on top of geomembrane, k_s = the hydraulic conductivity of CCL, and i_{avg} = the average hydraulic gradient in the CCL that is located under the wetted area around a geomembrane defect hole, which can be expressed as:

$$i_{avg} = 1 + \frac{h_w}{2H_s \ln(R/R_0)} \tag{4}$$

where H_s = the thickness of the CCL, R_0 = the radius of a defect hole, and R = the radius of the wetted area around a defect hole, as expressed as:

$$R = C_R \cdot a^{0.05} \cdot h_w{}^{0.45} \cdot k_s{}^{-0.13} \tag{5}$$

where C_R = the dimensionless coefficient (0.26 for good contact and 0.61 for poor contact condition). A good contact condition corresponds to a geomembrane installed, with as few wrinkles as possible, on top of the low permeability compacted clay liner that has a smooth surface (Giroud 1997). A poor contact condition corresponds to a geomembrane that has been installed with a certain number of wrinkles, and/or placed on a CCL that does not appear smooth (Giroud 1997). Equations 5-7 have been slightly modified by Giroud (1997), but were used in this study.

In this study, it was assumed that the landfills have a width of 100 m and length of 100 m. The landfill leachate head was assumed to be 0.5 m. For the geomembrane defects, it was arbitrarily assumed that the geomembrane defect frequency (f) was 20 holes/ha and the defect area was 28 mm^2. The assumed value of f was in the range of the value adopted by Rowe (1998) for analysis of leakage rate through geosynthetic clay liner, but is higher than the value recommended by Giroud and Bonaparte (1989) for calculations conducted to size the components of the landfill liners. The assumed defect area was slightly higher than the value adopted by Rowe (1998) but lower than the value recommended by Giroud and Bonaparte (1989). The leakage rates (Q) through the Chinese standard liner Type 2 and Germany standard liner, which have the geomembrane defect f, were then calculated as:

Table 1 Parameters for calculation of leakage rate

Parameter	MSW landfill liner type		
	CN 1	CN 2	Germany
H_s (m)	2.0	1.0	0.75
k_s (m/s)	10^{-9}	10^{-9}	5×10^{-10}
h_w (m)	0.5	0.5	0.5
C_{q0}	--	0.21*, 1.15**	0.21*, 1.15**
C_R	--	0.26*, 0.61**	0.26*, 0.61**
a (m^2)	--	2.8×10^{-5}	2.8×10^{-5}
f (hole/ha)	--	20	20
W (m)	100	100	100
L (m)	100	100	100

Note: CN 1: Chinese standard landfill Type 1; CN 2: Chinese standard landfill Type 2; * good contact condition; ** poor contact condition. H_s = thickness of clay liner, k_s = hydraulic conductivity of clay liner, h_w = leachate head, C_{q0} = dimensionless coefficient, C_R = dimensionless coefficient, a = area of geomembrane hole, f = Frequency of geomembrane defect, W = landfill width, L = landfill length.

$$Q = f \times Q_0 \times W \times L \tag{6}$$

The leakage rate per unit area (or Darcy velocity, v_a) through the landfill liners can be expressed by:

$$v_a = f \times Q_0 \tag{7}$$

With the assumed parameters listed in Table 1, the leakage rates through the Chinese standard landfill liners and German standard landfill liner were calculated as shown in Fig. 2. Using the information from Giroud and Bonaparte (1989), the effective hydraulic conductivities of the geomembrane for the Chinese standard landfill liner and the German standard landfill liner were calculated as 2.0×10^{-14} m/s and 2.4×10^{-14} m/s, respectively for good contact condition, and 1.1×10^{-13} m/s and 1.3×10^{-13} m/s, respectively for poor contact condition.

Concentration and Total Mass in Aquifer

When the Chinese standard landfill liners Type 1, Type 2, and the German standard landfill liner are applied in assumed landfills, due to the transport of contaminant, landfill will impose impact on surroundings, such as the ground water quality of an aquifer which is below the

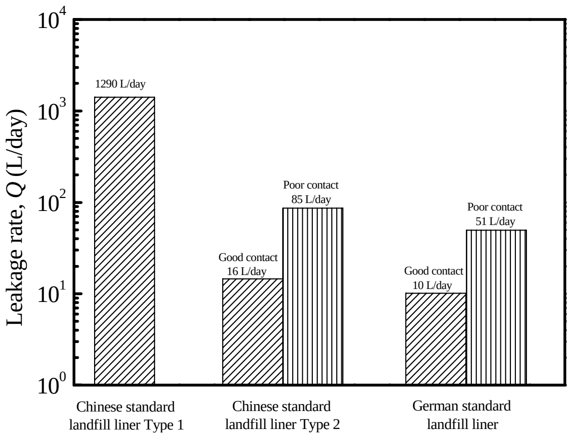

Fig. 2 Calculated leakage rates through the three standard MSW landfill liners

landfill, as shown in Figs. 3 and 4. To predict the impacts, it is necessary to model the transport of contaminants in the soil layers. In this study, a specific organic contaminant was selected as the target contaminant because that water and soil pollution by organic solid wastes in landfills is common in China (World Bank Report 2005).It was assumed that: 1) within each soil layer, the effective diffusion coefficient and sorption parameter were uniform. There was no fracture in the clay liner and the natural aquitard; 2) the flow in each layer was steady-stable. Transient flow was not considered; 3) the transport of the contaminant was controlling by advection-diffusion-dispersion. The effect of density of the contaminant (such as high density organic contaminants) on transport was not considered, and 4) the degradation of the target contaminant was not considered. In the previous studies, the transport of contaminant in landfill was modeled as three-dimension (Wang and Anderson 1982; Foose et al. 2002) or two and half dimension (Chai and Miura 2002). Rowe and

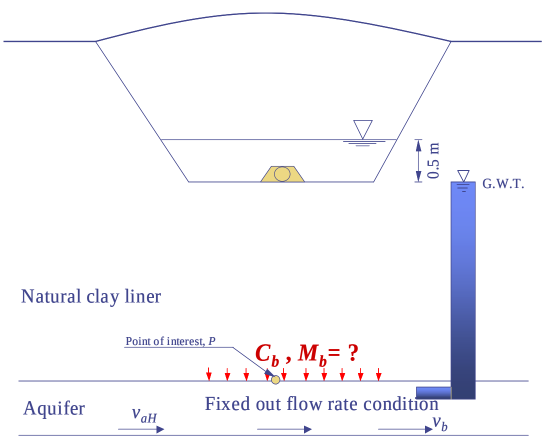

Fig. 3 An assumed landfill in which the Chinese standard landfill liner Type 1 is applied

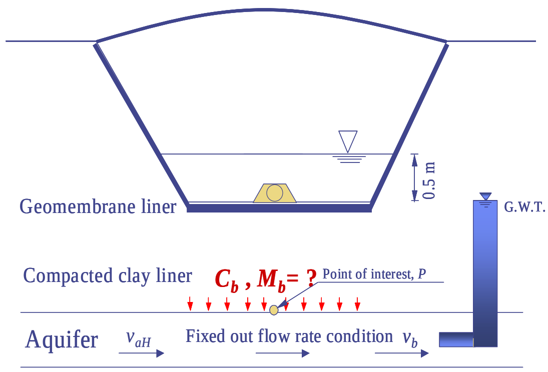

Fig. 4 An assumed landfill in which the Chinese standard landfill liner Type 2 or German standard landfill liner is applied

Booker (1987) indicated that a proper one-dimensional modeling would likely to give acceptable results for a preliminary analysis. Due to this reason, the one-dimensional vertical transport (in the *x*-direction) of the target contaminant through each intact soil layer is used as expressed by the advection-diffusion-dispersion equation as follows (Freeze and Cherry, 1979):

$$n\frac{\partial C}{\partial t} = nD\frac{\partial^2 C}{\partial x^2} - v_a\frac{\partial C}{\partial x} - \rho_d K_d\frac{\partial C}{\partial t} \tag{8}$$

where ρ_d = the dry density of the soil, n = the porosity, K_d = the distribution coefficient, C = the concentration, t = the time, v_a = the downward Darcy velocity, and D = the coefficient of hydrodynamic dispersion, expressed as:

$$D = D_e + D_{md} \tag{9}$$

where D_e = the effective diffusion coefficient, and D_{md} = the coefficient of mechanical dispersion, which is often modeled as a linear function of seepage velocity, v (Bear 1979; Freeze and Cherry 1979):

$$D_{md} = \alpha_L v \tag{10}$$

where α_L = the longitudinal dispersion (parallel to the contaminant flow direction). Since Rowe (1987) has shown that for clay liners, mechanical dispersion can be neglected, in this study, the mechanical dispersion in the clay liner was neglected. As a result, D = D_e, and Eq. 10 is expressed as:

$$n\frac{\partial C}{\partial t} = nD_e\frac{\partial^2 C}{\partial x^2} - v_a\frac{\partial C}{\partial x} - \rho_d K_d\frac{\partial C}{\partial t} \tag{11}$$

There are no published data showing the variation of concentrations of typical organic contaminants in the Chinese MSW landfills. In the previous studies, the upper boundary imposed by the landfill leachate was modeled as constant concentration condition (Katsumi et al. 2001; Foose et al. 2002), and finite mass condition (i.e., concentration decreases with the elapsed time) (Rowe and Booker 1985). In this study, the upper boundary imposed by the landfill leachate was modeled as two conditions: a) the constant concentration, $C(t) = C_0$, which represents a conservative design consideration; and 2) the finite mass condition which may represent a realistic condition as expressed by:

$$C(t) = C_0 - \frac{1}{H_r}\int_0^t J_T(\tau)d\tau - \frac{q_c}{H_r}\int_0^t C(\tau)d\tau \tag{12}$$

where $C(t)$ = the concentration of the target contaminant in landfill leachate, C_0 = the peak concentration, q_c = the leachate collected by the leachate collection system (per unit area), and H_r = the reference height of leachate in the landfill, which represents the leachate containing the total mass of the target contaminant, including the quantity that transports into the soil and collected by the leachate collection system at the peak concentration C_0. It is noted that the reference height is different from the leachate height in landfill. Using the reference height, it is easy to express the upper boundary condition as a finite condition. Considering the flow continuity and steady state flow condition, the leachate collected by the leachate collection system, q_c, is calculated using the following equation:

$$q_c = q_0 - v_a \tag{13}$$

where q_0 = the infiltration rate of rainfall through the landfill cover system. J_T is the mass flux from the leachate to the soil layer and is given by:

$$J_T(t) = v_a C - nD_e\frac{\partial C}{\partial x} \tag{14}$$

In the previously studies, the low boundary condition was modeled as zero concentration (Zheng and Bennett 1995) or semi-infinite soil layer beneath the composite liner (Foose et al. 2002). However, the former method has limitations in interpreting the variation of concentration in the aquifer and the latter one is far away from the assumed field hydrogeology presented in this study. Therefore, in this study, the lower boundary was modeled as fixed outflow rate condition, expressed by

$$C_b(t) = n\int_0^t \frac{J_b(t)}{n_b h_b}dt - \int_0^t \frac{v_b C_b(t)}{n_b L}dt \tag{15}$$

where C_b (t) = the concentration in the aquifer at any time of interest, n_b = the porosity of the aquifer, h_b = the thickness of the aquifer, L = the length of landfill, and v_b= the outflow horizontal Darcy velocity in the aquifer, which is given by the relationship with the consideration of the flow continuity:

$$v_b = v_a + \frac{L}{h_b}v_{aH} \tag{16}$$

where v_a = the downward Darcy velocity (or leakage rate), v_{aH} = the inflow horizontal Darcy velocity in the aquifer upgradient of the landfill, and J_b = the mass flux of contaminant entering the aquifer, which is given by:

$$J_b(t) = v_a C - nD_e\frac{\partial C}{\partial x} \tag{17}$$

The total mass of the target contaminant per unit area discharged into the aquifer at the time t of interest, M_b, can be calculated based on the following equation:

$$M_b(t) = \int_0^t J_b(t)dt \tag{18}$$

Equation 15 assumes that horizontal mechanical dispersion in the aquifer is not considered, which may represent a conservative design consideration (Rowe et al. 1995). A solution to Eqs. (11), (12), (14), (15), (17) and (18) is presented in the form of the commercial software program, *Pollute V 6.3* as described by Rowe and Booker (1994). The *Pollute V 6.3* uses a semi-numerical and semi-analytical method titled *finite-layer technique* developed by Rowe and Booker (1985). Unlike finite element and finite difference formulations, *Pollute V 6.3* does not require the use of a “time-marching” procedure. All of the input parameters for using *Pollute V 6.3* are listed in Table 2.

For the finite mass upper boundary condition, it was assumed that during the construction of the landfills, with the increase of the loading of the dumped solid waste, leaching of the target organic contaminant occurred due to the fact that rainwater infiltrated through the waste as well as the biochemical reaction occurred resulting in the decomposition of the solid waste. The concentration of the target organic contaminant was assumed to reach a peak at the closure of the landfill (i.e., C_0 = 2000 μg/L), and all of the target contaminant was soluble in the leachate.

The reference height H_r was assumed as 4.0 m in this study. The head difference between the landfill leachate

Table 2 Input parameters for numerical analysis

Parameter	CN 1	CN 2	GM
ρ_d (g/cm^3)	1.5	1.5	1.5
K_d (mL/g)	0.1, 1	0.1, 1	0.1, 1
n	0.4	0.4	0.4
k_s (×10^{-9} m/s)	1	1	0.5
D_e (×10^{-10} m^2/s)	4	4	4
H_s (m)	2.0	1.0	0.75
H_w (m)	--	0.5	0.5
D_a (×10^{-12} m^2/s)	--	1	1
GM thickness (mm)	--	1.5	2.5
f (holes/ha)	--	20	20
R_0 (mm)	--	3	3
C_0 (μg/L)	2000	2000	2000
Δh* (m)	0.5	0.5	0.5
q_0 (×10^{-9} m/s)	9.5	9.5	9.5
W (m)	100	100	
L (m)	100	100	100
h_b (m)	1	1	1
n_b	0.3	0.3	0.3
v_{aH} (×10^{-7} m/s)	1.59	1.59	1.59

Note: ρ_d = dry density, K_d = distribution coefficient, n = porosity, D_e = effective diffusion coefficient, H_w = leachate head on geomembrane liner, D_g = effective diffusion coefficient of geomembrane, f = Geomembrane defect frequency, R_0 = geomembrane defect radius, C_0 = initial concentration, Δh=head difference, q_0 = *r*ainfall infiltrate through cover, h_b = thickness of aquifer, n_b = porosity of aquifer, v_{aH} = inflow horizontal Darcy velocity in aquifer

and the groundwater table was assumed as 0.5 m. The effective diffusion coefficients of the target contaminant in the clay liner and geomembrane were assumed as 4×10^{-10} m^2/s and 10^{-12} m^2/s, respectively, which are within the range of values reported by Rowe (1998). The distribution coefficients of clay liners were arbitrarily assumed as 0.1 mL/g and 1 mL/g.

For geomembrane, it was arbitrarily assumed that the distribution coefficient was 0.001 mL/g. The defect radius and defect frequency of the geomembrane liner are shown in Table 2. Under the assumed condition shown in Figs. 3 and 4, with the back-calculated effective hydraulic conductivities of the geomembrane and the assumed hydraulic conductivities of the underlying CCLs tabulated in Table 2, the values of leakage rate per unit area (or Darcy velocity) through the Chinese standard landfill liner Type 2 and the German standard landfill liner were calculated as 6.5×10^{-12} m/s and 4.8×10^{-12} m/s respectively, for good contact condition, and 3.4×10^{-11} m/s and 2.5×10^{-11} m/s respectively, for poor contact condition. The leakage rates were calculated as 6.5×10^{-8} m^3/s and 4.8×10^{-8} m^3/s respectively, for good contact condition, and 3.4×10^{-7} m^3/s and 2.5×10^{-7} m^3/s respectively, for poor contact condition. Under the assumed hydrogeology condition shown in Fig. 3, the Darcy velocity through the liner was calculated as 5×10^{-10} m/s based on Eq. 1. The leakage rate through the Chinese standard landfill liner Type 1 was calculated as 5×10^{-6} m^3/s based on Eq. 2.

The background concentrations of the target contaminant in the soils and the aquifer layer were assumed to be zero. The simulation length was chosen to be 300 years. The failure of the leachate collection and removal system during this simulation period was not modeled. Under the constant concentration condition, the predicted concentrations (C_p) at the point of P in the aquifer during the 300 years of post-closure period were shown in Figs. 5, 6, and 7. The calculated total mass per unit area in the aquifer (M_b) was shown in Figs. 8, 9, and 10. The values of C_p and the maximum values of M_b during the simulation length are summarized in Table 2. Under the finite mass condition, the predicted concentrations (C_p) at the point of P in the aquifer during the 300 years of post-closure period were show in Figs. 11, 12, and 13. The calculated total mass per unit area in the aquifer (M_b) was shown in Figs. 14, 15, and 16.

RESULTS AND DISCUSSION

Leakage Rate

From Fig. 2, it can be seen that the leakage rates for the Chinese standard landfill liner Type 2 and Germany one under the good contact condition is almost one-fifth of those under the poor contact condition. The leakage rate through the Chinese landfill liner Type 1 is the highest, which is almost two-orders of magnitude greater than that of the Chinese standard landfill liner Type 2 and the German standard landfill liner under both good contact and poor contact conditions. The calculated leakage rates through the Chinese landfill liner Type 2 have the same order of magnitude (10^{-7} m^3/s) as those of the German one under either good contact or poor contact conditions. Based on the leakage rate, it would be likely that the performance of the Chinese standard landfill liner Type 1 is much less strict, while the performance of the Chinese standard landfill liner Type 2 is practically the same as that of the German one.

Constant Concentration Condition

Concentration at point P

From Fig. 5, 6, and 7, it can be seen concentration of the target contaminant increased with the elapsed time before reaching a peak. Except for the Chinese standard landfill liner Type 1 at K_d = 1 mL/g, the calculated concentrations at point P reached a steady state (or peak value, C_p) after certain time depending on the sorption ability of the clay liners (i.e., K_d). The corresponding arrival time to reach C_p increased with the increase in the sorption ability (i.e., K_d) of clay liners, implying that sorption ability of clay liners is one of the factors that affected the lifespan of the landfills.

The calculated values of C_p for the Chinese standard landfill liner Type 1 are 1.5 times and 1.7 times higher than those of the Chinese standard landfill liner Type 2 and German standard landfill liner under the condition of K_d = 0.1 mL/g and K_d = 1.0 mL/g, respectively (Table 3). For the Chinese standard landfill liner Type 2, the value of C_p is nearly the same with those of the German standard landfill liner. The results indicate that the performance of the Chinese standard landfill liner Type 1 is less effective, while the performance of the Chinese standard landfill liner Type 2 is practically the same as that of the German one, with regarding the peak concentration in the aquifer.

Although the calculated leakage rate under the good contact condition is about one-fifth of that under the poor contact condition for both the Chinese standard landfill liner Type 2 and the German standard landfill liner, the concentration changing tendency (Figs. 6 and 7) and the values of C_p between the good contact condition and poor contact condition did not differ considerably. This is mainly because that the flow rate per unit area (or Darcy velocity) through the two liners is very low ($\leq 4\times10^{-11}$ m/s), and diffusion would be the dominant process that controlled the migration of the target contaminant through the liners. Because the diffusion coefficients of geomembrane and clay liner were assumed to the same for both good contact and poor contact conditions, the concentration changing tendency and the values of C_p did not differ too much between the good contact and poor contact condition.

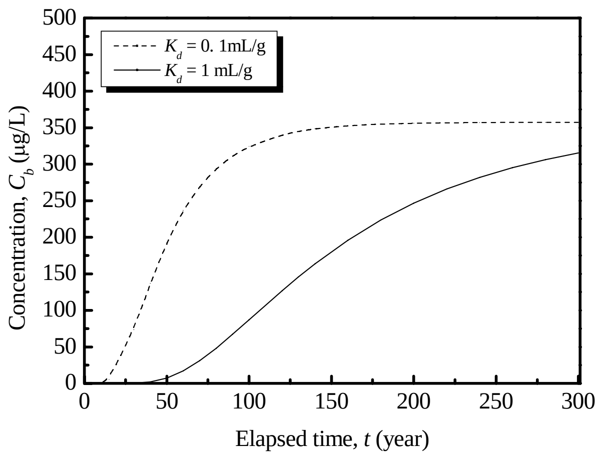

Fig. 5 Calculated concentration in the aquifer for Chinese landfill Type 1, constant concentration upper boundary condition

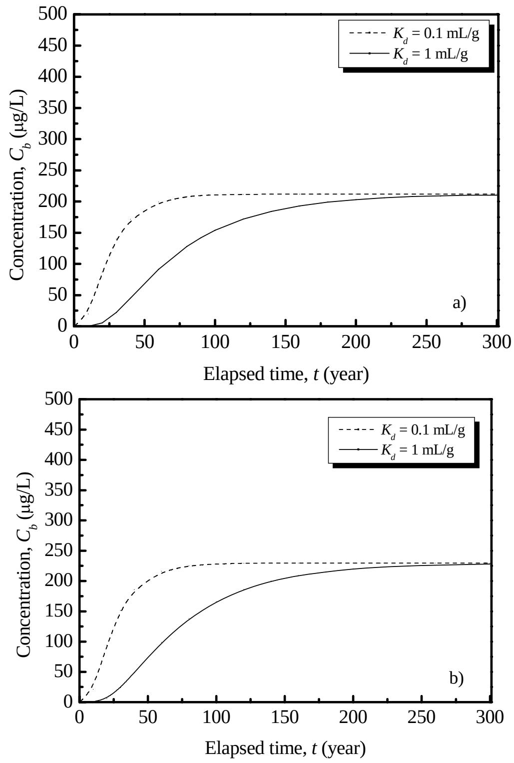

Fig. 6 Calculated concentration in the aquifer versus time for Chinese landfill Type 2, constant concentration upper boundary condition: 1) good contact; b) poor contact

Total mass per unit area in aquifer

From Figs. 8, 9, 10, it can be seen that for the three standard landfill liners, the total mass per unit area discharged into the aquifer increased with the elapsed time. With the increase in the sorption ability of clay liners (k_d), the value of m_b decreased. This observation is most significant for the Chinese standard landfill liner type 1.

At the time of 300 years, the values of reduction of M_b was nearly 44 %, 20 %, and 14 % when K_d increased from 0.1 mL/g to 1.0 mL/g for the Chinese standard landfill liner Type 1, Chinese standard landfill liner 2, and Germany standard landfill liner, respectively. For both Chinese standard landfill liner Type 2 and German standard landfill liner, the calculated value of M_b under the good contact condition is lower than that under the poor contact condition (Figs 9 and 10). At the time of 300 years, the value of M_b for the Chinese standard landfill liner Type 2 under the good contact condition is 92% of that under the poor contact condition, while the value of M_b for the German standard landfill liner under the good contact condition is 94% of that under the poor contact condition (see Table 3). This observation is mainly because that M_b was controlled both by the concentration in the aquifer and the downward

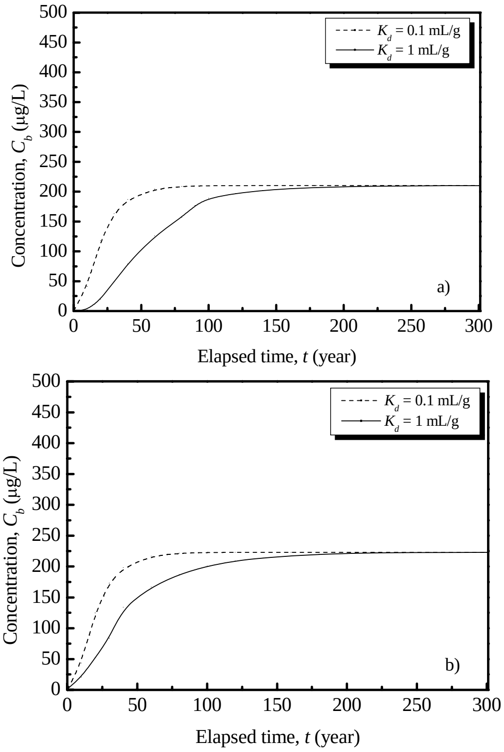

Fig. 7 Calculated concentration in the aquifer for German standard landfill liner, constant concentration upper boundary condition: a) good contact; b) poor contact

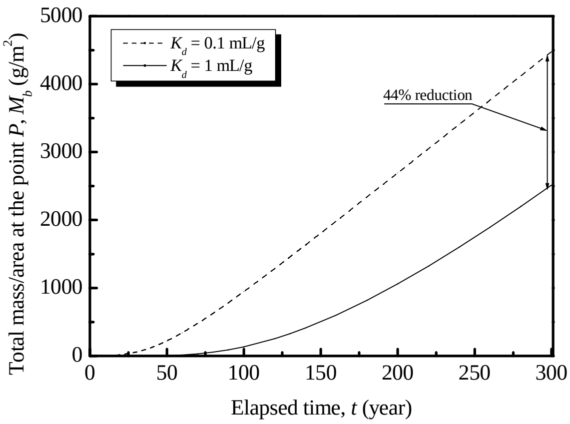

Fig. 8 Total mass per unit area discharged into the aquifer, Chinese standard landfill liner Type 1, constant concentration upper boundary condition

equivalent Darcy velocity through liners, as expressed by Eqs. 17 and 18. The value of M_b for the Chinese standard landfill liner Type 1 is higher than those for the Chinese standard landfill liner Type 2 and Germany standard landfill liner. At the time of 300 years, the values of M_b of the former are 1.5 times greater than those of the latter two standard liners at K_d = 0.1 mL/g, while nearly the same at K_d = 1.0 mL/g (Table 3).

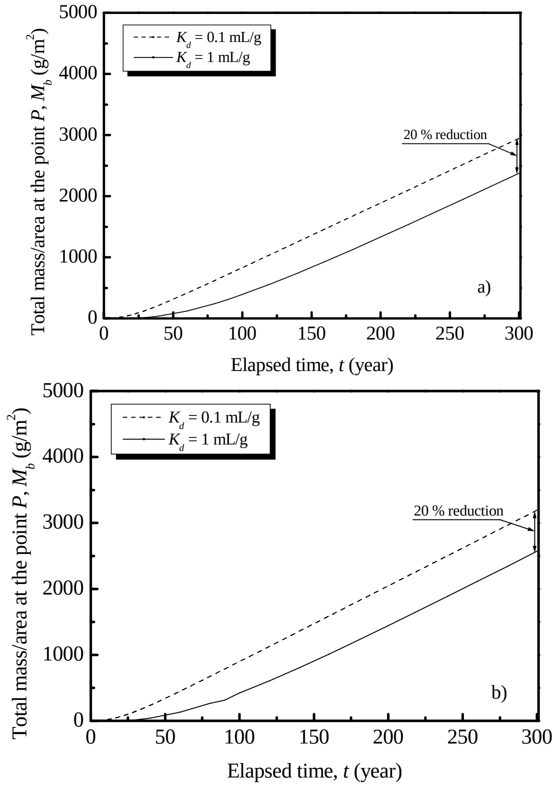

Fig. 9 Total mass per unit area discharged into the aquifer, Chinese standard landfill liner Type 2, constant concentration upper boundary condition: a) good contact; b) poor contact

Table 3 Calculated peak concentration and maximum total mass/area for three standard landfill liners under the constant concentration upper boundary condition

Quantity	Good contact		Poor contact	
K_d (mL/g)	0.1	1	0.1	1
C_p (μg/L)				
CN 1	315	357[i)]	--	--
CN2	212	212	229,	229
GM	210	210	223	223
CN 1/CN 2	1.5	1.7	--	--
CN 1/GM	1.5	1.7	--	--
CN 2/GM	1.0	1.0	1.0	1.0
M_b (μg/m^2)				
CN 1	4479	2512	--	--
CN 2	2948	2374	3194	2571
GM	2986	2562	3168	2717
CN 1/CN 2	1.5	1.1	--	--
CN 1/GM	1.0	1.0	--	--
CN 2/GM	1.0	0.9	1.0	0.9

Note: i) the value at the year of 300 years, C_p = peak concentration, M_b = maximum total mass/area

At the time of 300 years, the values of M_b for the Chinese standard landfill liner Type 2 are nearly the same with those of the German standard landfill liner under either good condition or poor contact condition (Table 3). This observation shows that the Chinese

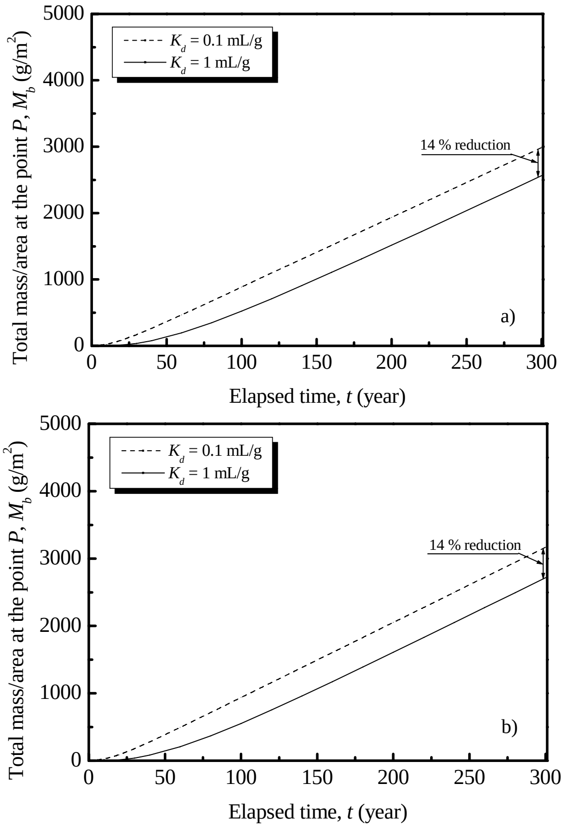

Fig. 10 Total mass per unit area discharged into the aquifer, German standard landfill liner, constant concentration upper boundary condition: a) good contact; b) poor contact

standard landfill liner Type 1 is less effective especially when the sorption ability of the clay liner is low, while the Chinese standard landfill liner Type 2 is same effective as that of the German standard landfill liner, regarding the mitigation of the total mass of the target contaminant discharged into the aquifer.

Finite Mass Condition

Concentration at point P

From Figs. 11, 12 and 13, it can be seen that for the three standard liners, there is a peak concentration (C_p) after certain time during the post-closure period. With the increase in the sorption of clay liners, the value of C_p reduced. The decrease in C_p for the cases of low sorption ability (K_d = 0.1 mL/g) and high sorption ability (K_d = 1 mL/g) of clay liners is most significant for the Chinese standard landfill liner Type 1. C_p decreased almost 3 times from 74 μg/L in the case of K_d = 0 to 28 μg/L in the case of K_d = 1 mL/g. This result indicates that the sorption ability of clay liners is one of the important the aquifer.

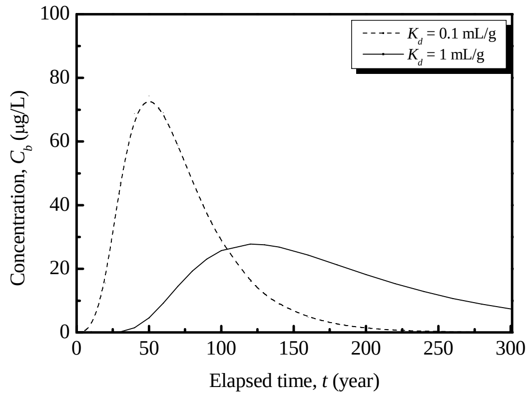

Fig. 11 Calculated concentration in the aquifer versus time for Chinese landfill liner Type 1, finite mass upper boundary condition

For both Chinese standard landfill liner Type 2 and German standard landfill liner, the difference of C_p between the good contact condition and the poor contact condition is not significant. This result is consistent with the observation in the case of the constant concentration condition, as discussed in the earlier part.

From Table 4, it can be seen that generally the difference of the predicted C_p between the Chinese standard landfill liner Type 1, Type 2, and the German standard landfill liner are not considerable. Although the analysis shows that under either the condition assumed by Giroud et al. (1992) (i.e., potentionmetric surface at the liner bottom is the same as the level of the liner base) and the assumed condition shown in Figs. 2 and 3, the leakage rate of the Chinese standard landfill liner Type 1 is 1 or 2 order of magnitude higher than that of the Chinese standard landfill liner Type 2 and the German standard landfill liner under the good contact condition and poor contact condition, respectively (see Fig. 2), the ratio of C_p of the Chinese standard landfill liner Type 1 to the Chinese standard landfill liner Type 2 (or the German standard landfill liner) varied only in a small range of 0.9 to 1.2. This observation indicates that an evaluation of liners performance only based on leakage rate may lead to an overestimate result. An analysis of the contaminant transport in the liner is of necessary, too.

Total mass per unit area in aquifer

Figures 14, 15, and 16 shows that after certain period, the total mass/area of the target contaminant discharged into the aquifer (m_b) almost reached a steady state except for the case of the Chinese standard landfill liner type 1 under the condition of k_d = 1ml/g. for the Chinese standard landfill liner type 2 and the German standard landfill liner, the maximum values of m_b in the case of

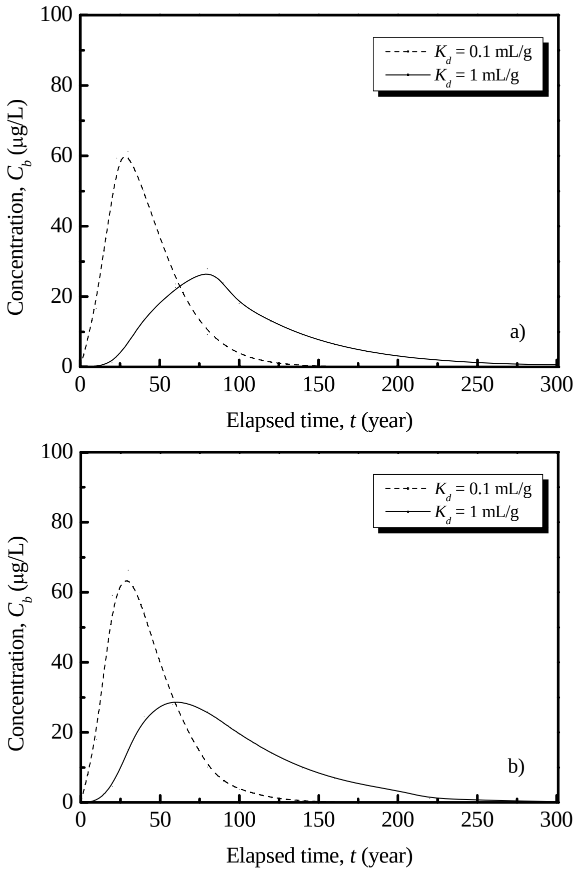

Fig. 12 Calculated concentration in the aquifer versus time for the Chinese standard landfill liner Type 2, finite mass upper boundary condition: a) good contact; b) poor contact

k_d = 0 and k_d = 1 ml/g are nearly the same, which is unlike the condition of c_p at the point of p (see Table 4). However, for the Chinese standard landfill liner type 1, the maximum value of m_b is almost 2 times higher than that of the Chinese standard landfill liner type 2 and the German standard landfill liner under both conditions of k_d = 0 and k_d = 1mg/l.

This is mainly attributed to the effect of the leakage rate, since Eqs. 16 and 17 indicate that both the leakage rate and concentration affect the total mass discharged into the aquifer. It would likely that the performance of the Chinese standard landfill liner type 1 is less strict, while the performance of the Chinese standard landfill liner type 2 is practically same as that of the German one, regarding the total pass per unit area discharged into the aquifer. For both the Chinese standard landfill liner type 2 and the German standard landfill liner, the maximum value of m_b under good contact condition is nearly the same with that under the poor contact condition. However, before reaching the maximum value, M_b for the good contact condition is lower than that under the poor contact condition such a result is consistent with the

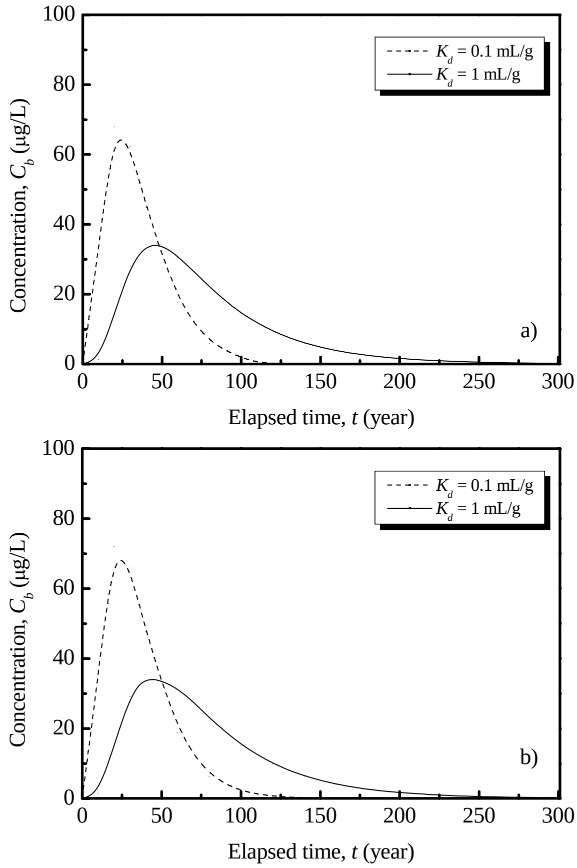

Fig. 13 Calculated concentration in the aquifer versus time for the German standard landfill liner, finite mass upper boundary condition: a) good contact; b) poor contact

Table 4 Calculated peak concentration and maximum total mass/area for three standard landfill liners under the finite mass upper boundary condition

Quantity	Good contact		Poor contact	
K_d (mL/g)	0.1	1	0.1	1
C_p (μg/L)				
CN 1	74	28		
CN2	61	28	66,	30
GM	68	34	72	36
CN 1/CN 2	1.2	1.0	1.1	0.9
CN 1/GM	1.2	1.	--	--
CN 2/GM	1.0	1.0	1.0	1.0
M_b (μg/m^2)				
CN 1	4479	2512	--	--
CN 2	2948	2374	3194	2571
GM	2986	2562	3168	2717
CN 1/CN 2	1.5	1.1	--	--
CN 1/GM	1.0	1.0	--	--
CN 2/ GM	1.0	0.9	1.0	0.9

Note: -- not obtained due to the unsteady state

observation that the difference of C_p between good contact condition and poor contact condition is not significant, as discussed in the earlier part of this paper.

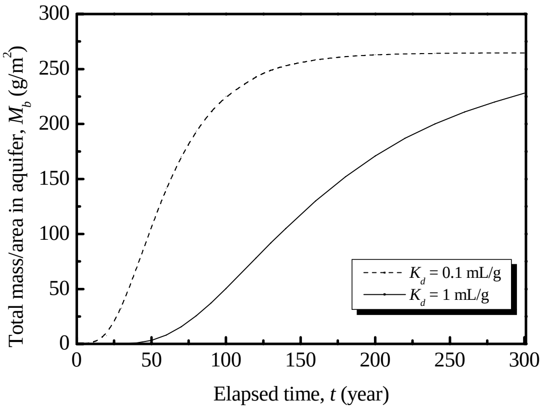

Fig. 14 Total mass per unit area into the aquifer in the case of the Chinese standard landfill liner Type 1, finite mass upper boundary condition

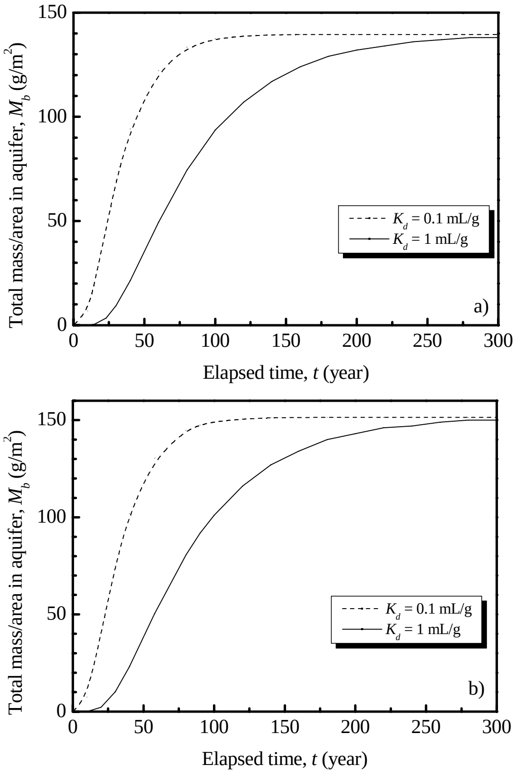

Fig. 15 Total mass per unit area into the aquifer in the case of the Chinese standard landfill liner Type 2, finite mass upper boundary condition: a) good contact; b) poor contact

From the aforementioned discussion on leakage rate, peak concentration at the point of p, and the total mass per unit area discharged into the aquifer, it is concluded that the evaluation of two types of Chinese standard landfill liners and German standard landfill liner should not be only based on the leakage rate through liners. The analysis of the contaminant transport in terms of the concentration and total mass per unit area discharged at the base of the liners should also be conducted under properly specific hydrogeology condition. Since the calculated maximum leachate head for the Chinese standard landfill liner systems is much higher than that of the German one, the overall performance of the Chinese standard landfill liner system is less strict.

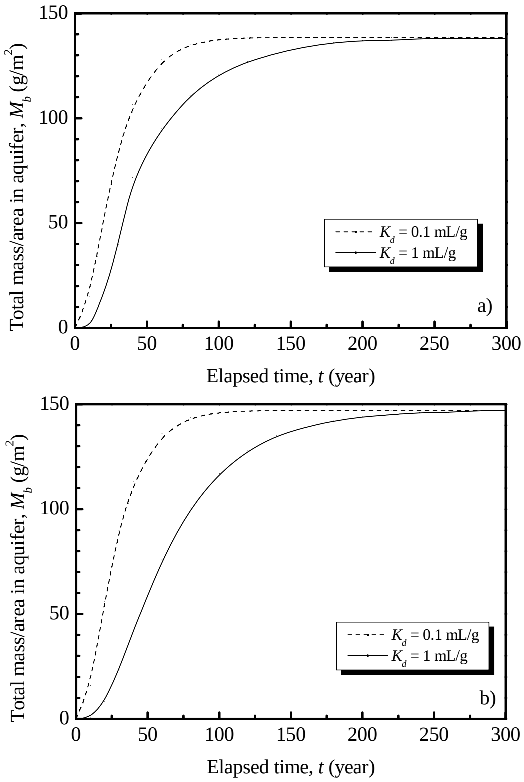

Fig. 16 Total mass per unit area into the aquifer in the case of the German standard landfill liner, finite mass upper boundary condition: a) good contact; b) poor contact

Practical Implications and Limitations

The upper boundary imposed by the landfill leachate was modeled as both constant concentration and finite mass conditions. The former was used in most literature studies (Katsumi et al. 2001; Foose et al. 2002), which may provide a conservative design consideration, while the latter one may provide a realistic design consideration (Rowe and Booker 1985). This study shows that the former will result in relatively higher values of C_p and maximum M_b than those of the later (see Tables 3 and 4). Therefore, in practice, the combination of these two analytical method is recommended for a preliminary design of landfill liners or evaluation of performance of landfill liners.

Previous studies on the effectiveness of landfill liners only focused on the leakage rate (Giroud et al. 1994; Giroud 1997; Richardson 1997). However, the analysis presented in this study indicated that information based only on the leakage rate through liners would result in the overestimated result. As a result, the analysis of the leakage rate should be combined with the analysis of contaminant transport using the analytical methods presented in this study.

A limitation of this study is that field data are unavailable regarding contaminant transport from Chinese landfill liner system, since there are no official reports so far in China. Additionally, the uncertain of the limited service life of the leachate collection and removal system was not considered in this study. Rowe (2005) showed that under some condition, the leachate collection and removal system would fail to work. The effect of such an uncertain failure on the contaminant mitigating performance of landfill liners should be investigated in the further study.

CONCLUSIONS

Following conclusions can be drawn from this study:

1) The leakage rate through the Chinese standard landfill liner Type 1 is much higher than that of the Chinese standard landfill liner Type 2 and the German standard landfill liner. The leakage rate of the Chinese standard landfill liner Type 2 is nearly the same with that of German one.

2) Under both the constant concentration and finite mass upper boundary conditions, C_p and maximum M_b of the target contaminant discharged at the liner base for the Chinese standard landfill liner Type 1 are higher those for the Chinese standard landfill liner Type 2 and German standard landfill liner, while the values of C_p and M_b are nearly the same for Chinese standard landfill liner Type 2 and German one.

3) With the consideration of the calculated leakage rate, C_p and the maximum M_b at the liner base, it can be concluded that the performance of the Chinese standard landfill liner Type 1 is less effective, while the performance of the Chinese standard landfill liner Type 2 is practically the same with that of the German one.

4) Since the Chinese standard landfill liner systems have shortcomings in the maximum design requirement on hydraulic conductivity of the drainage layer, grain size of the gravels around the leachate collection pipes, and the method for calculation of maximum leachate head in landfill as compared with the German standard landfill liner system, the overall performance of the Chinese standard landfill liner system is less strict than that of the German one.

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REFERENCES

Bear J. (1979). Hydraulics of Groundwater. McGraw-Hill Pub. Co.

Chai, J. C. and Miura, N. (2002). Comparing the performance of landfill liner systems. Journal of Mater Cycles Waste Management, 4 (2): 135-142.

Du, Y.J., Hayashi, S. and Suetsugu, D. (2007). Evaluation of performance of Chinese landfill bottom liner systems. Proceedings of Japan Geotechnical Society Annual Conference, Nagoya, Japan: 2127-2128.

European Environmental Agency (EEA) (2000). Dangerous substances in waste, Technical report No. 38, European Environment Agency.

Foose, G.J., Benson, C.H. and Edil, T.B. (2002). Comparison of solute transport in three composite liners, Journal of Geotechnical Engineering and Geoenvironmental Engineering, 128(5): 391-403.

Freeze, R. A. and Cherry, J.A. (1979). Groundwater. Prentice Hall, Inc.

Giroud, J.P. (1997). Equations for calculating the rate of liquid through composite liners due to geomembrane defects. Geosynthetics International, 4(3): 335-348.

Giroud, J.P. and Bonaparte, R. (1989). Leakage through liners constructed with geomembranes – Part I. Geomembrane liners; Part II. Composite liners. Geotextiles and Geomembranes 8(1): 71-112.

Giroud, J.P., Badu-Tweneboah, K. and Bonaparte, R. (1992). Rate of leakage through a composite liner due to geomembrane defects. Geotextile & Geomembranes 11(1): 1-28.

Giroud, J.P., Badu-Tweneboah, K. and Soderman, K.L. (1994). Evaluation of landfill liners. Proceedings of the 5th International Conference on Geotextiles, Geomembranes and Related Products, Singapore: 981-986.

GLR (1993): Geotechnics of landfill design and remedial work, technical recommendations, Second edition, German Geotechnical Society, Ernst & Sons

Berlin.:158 .

Katsumi, T., Benson, C.H., Foose, G.J. and Kamon, M. (2001). Performance-based design of landfill liners, Engineering Geology, 60(1): 139-148.

Richardson, G.N. (1997). GCLs: Alternative Subtitle D liner systems, Geotechnical Report, 36-42.

Rowe, R.K. (1987). Pollutant transport through barriers. In: Woods, R. D. (Ed.), Geotechnical Practice for Waste Disposal '87. Special Geotechnical Publication, ASCE, 13: 159-181.

Rowe, R.K. (1998). Geosynthetics and the minimization of contaminant migration through barrier systems beneath solid waste. Proceedings of the 6th International Conference on Geosynthetics, Atlanta, USA: 27-102.

Rowe, R.K. (2005). Long-term performance of contaminant barrier systems, Geotechnique, 55(9): 631-678.

Rowe, R.K., Armstrong, M.D. and Cullimore, D.R. (2000). Particle size and clogging of granular media permeated with leachate. Journal of Geotechnical and Geoenvironmental Engineering, ASCE 126(9): 775-786.

Rowe, R.K. and Booker, J.R. (1985). 1-D pollutant migration in soils of finite depth. Journal of Geotechnical Engineering, ASCE 111 (4): 479-499.

Rowe, R.K. and Booker, J.R. (1987). An efficient analysis of pollutant migration through Soil. In: Lewis, R.W., Hinton, E., Bettess, P., Schrefler, B.A. (Ed.), Numerical Methods in Transient and Coupled Systems. John Wiley & Sons: 13-42.

Rowe, R.K. and Booker, J.R. (1994). Pollute V 6.3 User's Guide. GAEA Environmental Engineering Ltd, Canada.

Rowe, R.K., Quigley, R.M. and Booker, J.R. (1995). Clayey Barrier Systems for Waste Disposal Facilities. E & FN SPON, UK.

Technical Code for Municipal Solid Waste Sanitary Landfill CJJ 17-2004 (2004). Chinese Building Press, Beijing, China.

Wang, H.F. and Anderson, M.P. (1982). Introduction to Groundwater Modeling: Finite Difference and Finite Element Methods. Freeman and Co: 237.

World Bank Report (2005). Waste Management in China: Issues and recommendations May 2005. Urban Development Working Papers East Asia Infrastructure Department World Bank Working Paper No. 9.

Zhang, Z.Y. and Chen, Y.M. (2005). Study on compressibility and settlement of landfill with municipal solid waste. Chinese Journal of Geotechnical Engineering, 27(1): 116-120.

Zheng, C. and Bennett, G. D. (1995). Applied contaminant transport modeling, theory, and practice, Van Nostrand Reinhold, New York.