Chapter 23
Modelling of Leachate Leakage and Contaminant Migration Through Municipal Solid Waste Landfill Liner Systems

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Abstract Low permeability liners are generally used at the bottom of modern engineered landfills for minimizing leachate leaking and contaminant migrating from landfills into the surrounding environment (e.g., groundwater and surface water). For a single liner system, there are three commonly used design options: (1) a compacted clay liner (CCL), (2) a high density polyethylene (HDPE) geomembrane (GMB) on a CCL, (3) a HDPE GMB on a geosynthetic clay liner (GCL) overlying a CCL. This paper numerically examines the leakage of leachate and the migration of contaminant through all three liner systems provided by the Chinese national standard using a finite element method (FEM) computer program. The results show that the calculated leachate leakages from the FEM generally agree well with those from the Rowe's analytical solution, and the amount of leakage rates through the liner is dependent on the type of the liner. The calculated contaminant concentrations in aquifer indicated that the time for contaminant to reach the peak value is quite different among the three liners. The paper demonstrates that the three design options for a single liner system in the Chinese national standard have quite different performance in terms of minimizing groundwater contamination below the MSW landfill liner.

Keywords Landfills · Low permeability liners · Leachate leakage · Contaminant migration

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23.1 Introduction

Landfilling is one of key waste management approaches for municipal solid waste (MSW) in China as well as in other countries around the world (Hu et al. 2024). At the bottom of MSW landfills, low permeability liners are generally required to prevent the migration of harmful contaminants into the surrounding environment (Rowe et al. 2004; Rowe 2005). Three types of low-permeability liners for MSW landfills are provided in the Chinese national standard (MOHURD 2021; see Fig. 23.1): (1) a compacted clay liner (CCL) with a minimal thickness of 2 m and a maximum hydraulic conductivity of $k_{CCL} = 1 \times 10^{-9}$ m/s, (2) a high density polyethylene (HDPE) geomembrane (GMB) with a minimal thickness of 1.5 mm on a CCL ($\geq$ 0.75 m thick and $k_{CCL} \leq 1 \times 10^{-7}$ m/s), (3) a HDPE GMB ($\geq$ 1.5 mm thick) on a geosynthetic clay liner (GCL) with a maximum hydraulic conductivity of $k_{GCL} = 5 \times 10^{-11}$ m/s overlying a CCL ($\geq$ 0.3 m thick and $k_{CCL} \leq 1 \times 10^{-7}$ m/s). At present, it is not clear whether these liners are equivalent and effective at controlling seepage of leachate and migration of contaminants through the MSW landfill liner.

Intact GMBs are almost impermeable to water and inorganic contaminants (Rowe et al. 2004). However, defects in GMBs have been observed in the field even with careful manufacturing and installation process (e.g., Giroud and Bonaparte 1989). Field studies have showed that HDPE GMBs upon heating can experience thermal expansion resulting in formation of wrinkles (e.g., Giroud and Peggs 1990; Rowe et al. 2012; Chappel et al. 2012a, b). Once the defects coincide with the GMB wrinkles, they become the main pathways for contaminants in landfills leaking through the GMB liners.

This paper examines the performance of low permeability liners (see Fig. 23.1) from the Chinese national standard for preventing the leakage of leachate and the migration of contaminants into the aquifer, and compares the maximum base concentration at the downgradient edge of the landfill and the time to reach this maximum value among the three types of MSW landfill base liners. The influence of the GMB-GCL interface transmissivity on the effectiveness of MSW landfill composite liners is also performed.

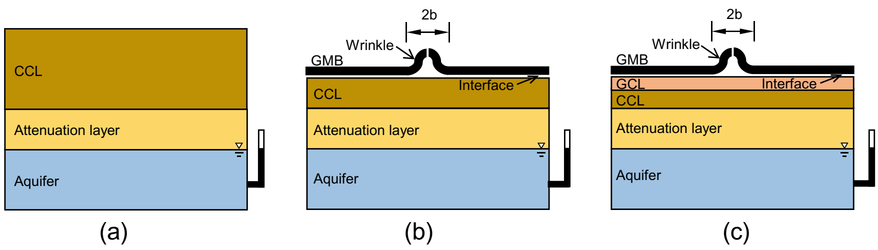

Fig. 23.1 Three types of the single liner in MSW landfills: **a** CCL + AL, **b** GMB + CCL + AL composite liner, and **c** GMB + GCL + CCL + AL composite liner

23.2 Liner Cases and Associated Parameter Values

23.2.1 Landfill Liner Cases

This study examined three landfill liner cases: (1) a 2 m CCL, (2) a 1.5–mm GMB with a 0.75 m CCL, and (3) a 1.5 mm GMB with a 7 mm GCL ($k_{GCL} = 5 \times 10^{-11}$ m/s) and a 0.3 m CCL. The CCL in the composite liner is assumed to have the same k_{CCL} (i.e., 1×10^{-9} m/s) as a single CCL in this investigation. In all three cases an attenuation layer (AL) below the liner was considered to be 1 m thick with $k_{AL} = 1 \times 10^{-7}$ m/s, based on the requirement that the bottom of the MSW landfill liner above the highest groundwater table at least 1 m (MOHURD 2021). The aquifer thickness was 1 m with $k_{Aq} = 1 \times 10^{-3}$ m/s (Rowe and AbdelRazek 2019).

23.2.2 Source Concentration in Landfill

MSW landfill leachate generally contains dissolved salts, volatile fatty acids, volatile organic compounds and heavy metals. The chloride in leachate was selected in this investigation because of its negligible sorption, biodegradation and precipitation when passing through the liner (Rowe and AbdelRazek 2019). The dilution of chloride in the MSW landfill decreases the concentration over time expressed as (Rowe 1991):

$$c_T(t) = c_0 e^{-\lambda t} \tag{23.1}$$

where $c_T(t)$ is the chloride concentration in the landfill at time t, c_0 is the initial chloride concentration ($c_0 = 1500$ mg/L), $\lambda = q_0 c_0 A_0 / m_{TC}$ is the first–order decay constant because of chloride dilution, q_0 is the infiltration rate through the cover into the landfill, A_0 is the base area of a MSW landfill, and m_{TC} is the total chloride mass (mg) in a MSW landfill (i.e., based on the total MSW waste mass in kg and the chloride mass per unit compacted MSW waste mass $p = 1800$ mg/kg; see MoE 2011).

23.2.3 Finite Element Model and Associated Parameter Values

Figure 23.2 shows a landfill liner example and associated boundary conditions examined. The groundwater flow was coupled with the contaminant transport for modelling chloride migrating from the landfill into the aquifer. The MSW waste loading was assumed to be 100,000 m^3/ha (Rowe and AbdelRazek 2019). The model total length was 300 m and the landfill length was $L_f = 100$ m. The holed wrinkles were assumed to be distributed periodically and the wrinkle spacing was 50 m based on Rowe et al. (2012). Each wrinkle had a length of $L_w = 100$ m perpendicular to the direction of the groundwater flow (Rowe and AbdelRazek 2019). The wrinkles had a width of $2b = 0.1$ m according to Rowe and AbdelRazek (2019). The height of leachate above the liner was set to be $h_w = 0.3$ m (Rowe and AbdelRazek 2019; MOHURD 2021). A constant horizontal Darcy velocity ($v_b = 1$ m/year) within the aquifer was modelled by specifying the required hydraulic heads at the right and left aquifer boundaries. The source concentration (Eq. 23.1) was applied at the holed wrinkles. The right boundary in the aquifer was a free exit boundary for contaminant transport.

The porosity values were 0.7, 0.4, 0.3, and 0.3 for the GCL, CCL, AL, and aquifer, respectively. (Rowe and AbdelRazek 2019). The effective diffusion coefficient for chloride in the GCL was assumed to be $D_e = 5 \times 10^{-3}$ m^2/year, and the CCL, AL, and aquifer had an effective diffusion coefficient of $D_e = 2 \times 10^{-2}$ m^2/year (Rowe et al. 2004). The longitudinal dispersivity was $\alpha_L = 0.2$ m with a transverse to longitudinal dispersivity ratio of 1.0 for the GCL, CCL, and AL (Rowe and AbdelRazek 2019). The transmissive layers between the GMB and CCL and between the GMB and GCL had a thickness of 0.25 mm, a thinner transmissive layer had insignificant influence on the chloride concentrations in the aquifer. The interface transmissivity was $\theta = 1.6 \times 10^{-8}$ m^2/s for the GMB + CCL + AL composite liner, and decreased to $\theta = 1 \times 10^{-11}$ m^2/s when using the GMB + GCL + CCL + AL composite liner (Rowe 2012).

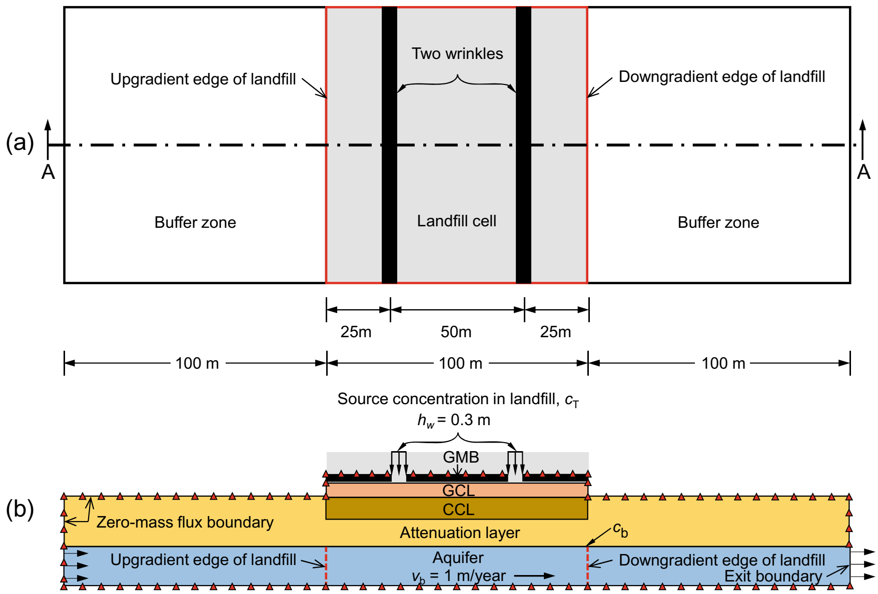

Fig. 23.2 Example of a landfill liner system on an aquifer with bounary conditions: **a** plan view and **b** cross section

Table 23.1 Calculated leakage based on finite element model (Q_{FE}) and analytical equation (Q_{EQ}) from Rowe (1998)

Case	Liner type	Leakage length, $2L_w$ (m/ha)	Q_{FE} (lphd)	Q_{EQ} (lphd)
1	CCL + AL	200	1437	1418
2	GMB + CCL + AL	200	332	330
3	GMB + GCL + CCL + AL	200	19	14

Note lphd is commonly used by landfill liner designers for litres per hectare per day

A total of 150,276 linear triangular and quadrilateral elements were used for the composite liner (GMB + GCL + CCL + AL). The size of elements was finest near the area under wrinkles and coarsest in the buffer zones. The number of elements was slightly different for the cases of CCL + AL and GMB + CCL + AL. The modelling of landfill liners was based on a finite element program COMSOL.

23.3 Results and Discussion

23.3.1 Case 1 with CCL + AL

The leakage of leachate through the CCL + AL liner (Table 23.1) was Q = 1418–1437 lphd. The concentration of chloride at the landfill downgradient edge increased to a maximum value of $c_{b,max}$ = 1129 mg/L at time t_{max} = 41 years, and thereafter it decreased gradually. Based on the maximum contaminant level (MCL = 250 mg/L) specified by the drinking water standards (MOH 2006; MoE 2011), the use of a 2 m thick CCL was not acceptable as a low permeability liner for MSW landfills ($c_{b,max}$ = 1129 mg/L exceeding MCL = 250 mg/L) based on the case and situations examined here. The results shown in Fig. 23.4 also indicated that the concentration of chloride in the aquifer beneath the landfill cell remained relatively constant with a maximum difference of no more than 20 mg/L, which further demonstrated that the 2 m thick CCL (overlying a 1 m thick AL) was unable to prevent groundwater contamination by the leakage of landfill leachate.

23.3.2 Case 2 with GMB + CCL + AL

The second type of the single liner examined was the GMB + CCL + AL composite liner. The rate of leakage was Q = 330–332 lphd through this GMB + CCL + AL composite liner, a significant reduction from Q = 1418–1437 lphd for the CCL + AL liner (Table 23.1). A GMB overlying a CCL resulted in a maximum chloride concentration at the landfill downgradient edge of $c_{b,max}$ = 615 mg/L (compared with $c_{b,max}$ = 1129 mg/L for the CCL + AL liner; Fig. 23.3). Thus, the composite liner

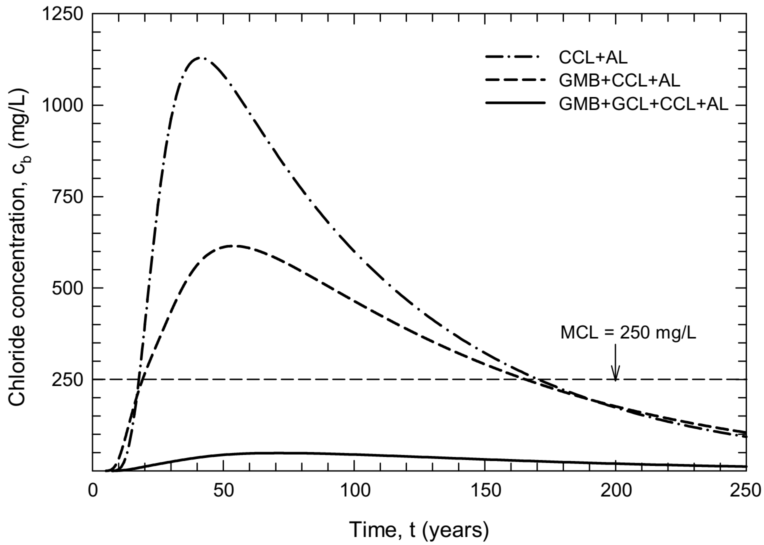

Fig. 23.3 Variation of the concentration of chloride with time at the downgradient edge of landfill for three low permeability liners

consisting of a GMB with a CCL and an AL was very effective in terms of reducing groundwater contamination under landfills. For the composite liner with GMB + CCL + AL shown in Fig. 23.4, the concentration of chloride below the landfill cell in the aquifer distributed nonuniformly, especially in the aquifer zone below the holed wrinkles due to local leachate leakage through the holed GMB wrinkles. However, the composite liner with GMB + CCL + AL was unable to reduce the maximum concentration of chloride to the acceptable level in the aquifer in this study.

23.3.3 Case 3 with GMB + GCL + CCL + AL

The previous sections have indicated that both the CCL + AL liner (Case 1) and the composite liner (GMB + CCL + AL; Case 2) were not acceptable as low permeability liners at the bottom of MSW landfills. For Case 3 with the GMB + GCL + CCL + AL composite liner, the rate of leakage was $Q = 14$–19 lphd (about 20–fold reduction from $Q = 330$–332 lphd for GMB + CCL + AL; Table 23.1), and the maximum concentration of chloride at the landfill downgradient edge was $c_{b,max} = 49$ mg/L (about 12–fold reduction from 615 mg/L for GMB + CCL + AL; well below the MCL = 250 mg/L as shown in Fig. 23.3), and the chloride concentration in the aquifer under the landfill cell was nonuniformly distributed with local concentration increase below the holed wrinkles (Fig. 23.4). The results showed that Case 3 (GMB + GCL + CCL + AL) performed better than Case 1 (CCL + AL) and Case 2 (GMB

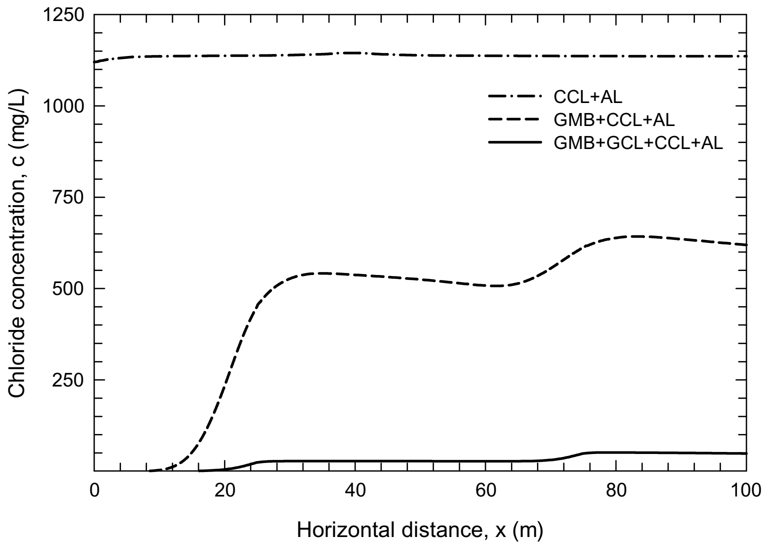

Fig. 23.4 Chloride concentration in aquifer from landfill upgradient to downgradient edge at time t_{max} (the time when the concentration of chloride reached the maximum value at the downgradient edge of landfill)

+ CCL + AL) in terms of controlling the concentration of chloride in the aquifer to the acceptable level based on parameter values considered in this study. Thus, the three types of low permeability liners provided by MOHURD (2021) performed quite differently in reducing the leakage of leachate and the migration of chloride into the aquifer.

The interface transmissivity between the GMB and GCL was set to $\theta = 1 \times 10^{-11}$ m^2/s for a good contact condition (Rowe 2012). However, increasing interface transmissivity increased the maximum concentration of chloride in the aquifer (Fig. 23.5). When the interface transmissivity was $\theta = 7 \times 10^{-10}$ m^2/s for a poor contact condition (Rowe 2012), the maximum concentration of chloride in the aquifer was still below the MCL = 250 mg/L. Thus, the results shown in Fig. 23.5 demonstrated the superior performance of using the composite liner of GMB + GCL + CCL + AL for controlling the groundwater contamination in the aquifer under landfill sites.

23.4 Conclusions

Municipal solid waste (MSW) landfills contain toxic contaminants that have the potential influence on the quality of groundwater. The Chinese national standard provides three types of low permeability liners to be constructed at the bottom of MSW landfills for minimizing the groundwater contamination because of the leakage of landfill leachate. These low permeability liners examined in this study are: (1) a 2

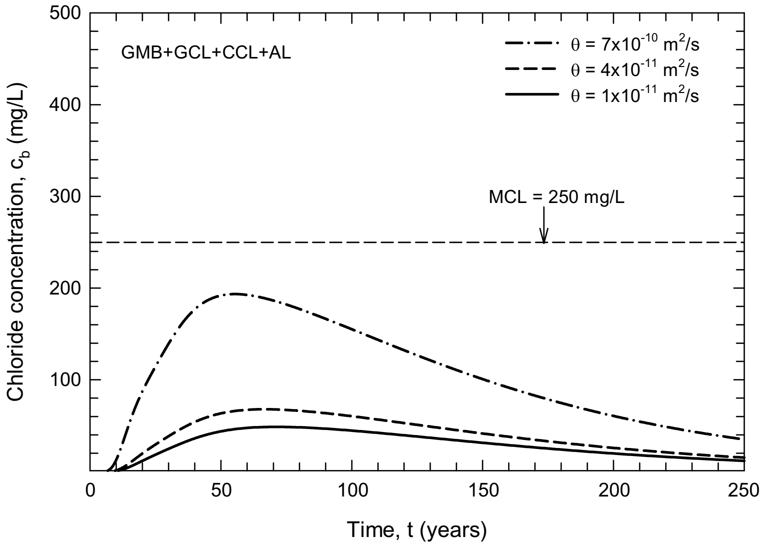

Fig. 23.5 Influence of GMB-GCL interface transmissivity on chloride concentration at the landfill downgradient edge

m thick compacted clay liner (CCL), (2) a 1.5 mm thick high density polyethylene (HDPE) geomembrane (GMB) on a 0.75 m thick CCL, and (3) a 1.5 mm thick HDPE GMB overlying a geosynthetic clay liner (GCL) on a 0.3 m thick CCL. This paper examined the performance of these low permeability liners with a 1 m thick attenuation layer (AL) for minimizing the leakage of leachate and migration of chloride into the aquifer. The results showed that the CCL + AL liner and GMB + CCL + AL composite liner were unable to limit the maximum chloride concentration in the aquifer to below the maximum contaminant level (MCL) required by the Chinese drinking water standard. The GMB + GCL + CCL + AL composite liner performed much better than the CCL + AL liner and GMB + CCL + AL composite liner for reducing the leakage of leachate and for controlling the maximum concentration of chloride below the MCL in the aquifer.

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