# Evaluation of the Performance of Contaminant Mitigation of Chinese Standard Municipal Solid Waste Landfill Liner Systems

## Évaluation de l'exécution de la réduction de contaminant des systèmes municipaux standard chinois de recouvrement de remblai de déchets solides

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ABSTRACT

In this paper, the Chinese stanadrd Municipal Solid Waste (MSW)landfill liner systems are introduced. Two types of the standard liners are composed of a natural clay layer with a thickness of 2 m (herein titled CN 1 liner), and a composite liner (a geomembrane (GM) liner underlain by a compacted clay liner (CCL) with a thickness of 1 m) (herein titled CN 2 liner), respectively. The performance of these two types of liners are evaluated based on three criteria: 1) maximum landfill leachate head ($y_{max}$) over the liners; 2) leachate rate through liner systems; 3) peak concentration and mass of the targeted contaminant (dichloromethane, DCM) discharged in to an aquifer below the assumed landfill. To calculate $y_{max}$, the Giroud's 1992 method is adopted. It is assumed that there a certain number of holed wrinkles in the geomembrane liner. The Rowe's 1998 analytical method is used to calculate the leachate leakage through the GM/CCL system. The results show that the value of $y_{max}$ for Chinese standard liner systems are much higher than the limited value regulated by most European and northern American countries. The caclualted leakage rate, peak concentration and maximum mass at the aquifer for CN 1 are greater than that for CN 2, indicating that the former is less strict than the latter one.

RÉSUMÉ

Dans ce document, les systèmes standards chinois de revêtement de remblai de solides déchets municipaux (MSW) sont présentés. Deux types des revêtement standard de composent de couche d'argile naturelle avec une épaisseur de 2 m (ci-dessus intitulés revêtement de CN 1), et de revêtement composé (un revêtement de geomembrane (GM) été à la base par un revêtement compact d'argile (CCL) avec une épaisseur de 1m) (ci-dessus intitulé revêtement de NC 2), respectivement. La performance de ces deux types de revêtements sont évaluées a basé sur trois critères: 1) maximum hauteur de lixiviation (ymax) au-dessus des revêtements, 2) le taux de lixiviation par des systèmes de revêtement, 3) le pic de concentration et le mass de la contaminant (dichlorométhane, DCM) déchargé à un aquifère au-dessous du remblai assumé. Pour calculer ymax, la méthode du Giroud 1992 est adoptée. On suppose qu'il existe un certain nombre des rides perforées dans la géomembrane. La méthode analytique du Rowe 1998 est employée aussi pour calculer la fuite de lixiviation par le système de GM/ CCL. Les résultats prouvent que la valeur du ymax pour les systèmes standard chinois de revêtement est plus élevée que la valeur limitée réglée par la plupart des pays européens et des pays d'Amérique du Nord. Le taux calculé de fuite, la concentration et la masse maximale à l'aquifère pour NC 1 sont plus grands que celui pour le CN 2, indiquant que l'ancien est moins stricte que la dernière.

## 1 INTRODUCTION

Recently, the contamination of surroundings from the Chinese open dumped municipal solid wastes (MSW) or poorly constructed landfills has become a serious problem (World Bank Report, 2005). Although Chinese Government prescribed standard MSW landfill bottom liners (CNMC, 2004), very limited research has been conducted to evaluate the performance of the standard liners. In this study, the Chinese standard landfill liner systems are introduced. The shortcomings of the landfill liner system are discussed. The performance of Chinese standard landfill liner systems are evaluated based on the maximum leachate head ($y_{max}$), leakage rate, and peak concentration as well as mass per unit area of a target contaminant discharged in the aquifer overlain by the standard landfill liners.

## 2 CHINESE STANDARD LANDFILL LINER SYSTEM

Figure 1 shows the minimum design requirement on two types of Chinese standard MSW landfill liner system. In Type 1 (herein labeled as CN 1) liner, a natural clay deposit with a thickness larger than 2 m and a hydraulic conductivity less than $10^{-9}$ m/s is used as a containment barrier. In Type 2 (herein labeled as CN 2) liner, a composite liner system is used. The thicknesses of the high-density polyethylene (HDPE) geomem-

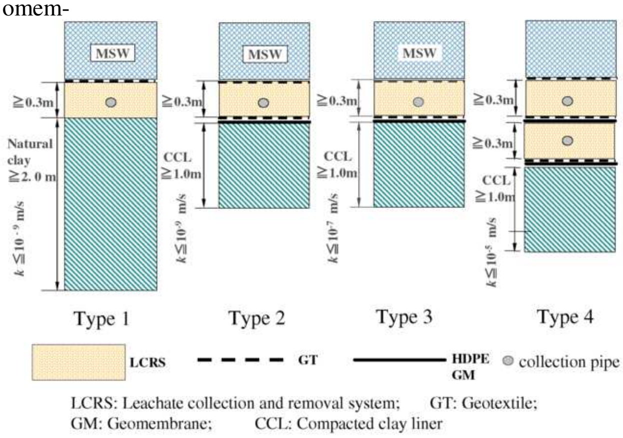


Figure 1. Illustration of Chinese standard landfill liner system

brane liner (GM) and compacted clay liner (CCL) are greater than 1.5 mm and 1m, respectively. The hydraulic conductivity of CCL is less than $10^{-9}$ m/s. In Type 3 and Type 4, a composite liner including a HDPE GM liner and a CCL is used. The requirement of thickness of the GM liner and CCL are the same

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with those in Type 2, while the hydraulic conductivity of CCL is less than $10^{-7}$ m/s and $10^{-5}$ m/s for Type 3 and Type 4, respectively. Generally, compared with liners regulated by most European countries and US EPA, Chinese standard liner system has following shortcomings:

1) The maximum landfill leachate $y_{max}$ is not regulated, whereas it is limited less than 0.3 m by US EPA standards;

2) GM liner is not used in Type 1, which may result in greater leakage rate through Type 1, as discussed in later section;

3) In Type 3 and Type 4, hydraulic conductivity of CCL is much higher (two and four orders of magnitudes higher, respectively) than that of US EPA liner ($k = 10^{-9}$ m/s) and liners regulated by most European countries (e.g., $k = 5\times10^{-10}$ m/s for German liner). As a result, in the case that there are holed wrinkles in GM, leakage rate through GM/CCL will be greater;

4) The hydraulic conductivity of granular drainage material is regulated greater than $10^{-7}$ m/s, whereas it is regulated greater than $10^{-4}$ m/s for US EPA liner system and German liner system. Less hydraulic conductivity of granular drainage material will result in greater $y_{max}$, as discussed in the later section;

5) For Chinese standard liner systems, the grain size of granular material around leachate drain pipes is not regulated, while it is regulated as 16 mm-32 mm for German liner system (EEA, 2000). Drainage granular materials with smaller grain size will be easily clogged due to the presence of organic matters contained in solid wastes. As a result, a leachate mound will easily develop in landfills (Rowe, 2005).

## 3 ANALYTICAL METHODS

### 3.1 *Calculation of maximum leachate head $y_{max}$*

In this study, the analytical method proposed by Giroud (1992) method was used for a calculation of $y_{max}$ in assumed landfills (see Figures 3 and 4), as expressed by Eqs. 1 and 2.

$$y_{\max} = j \cdot L \cdot \left[\left(4 \cdot r / k + S^2\right)^{1/2} - S\right] / (2 \cdot \cos\alpha) \qquad (1)$$

$$j = 1 - 0.12 \cdot \exp\left\{-\left[\log(1.6 \cdot r / k / S^2)^{5/8}\right]^2\right\} \qquad (2)$$

in which $L$ = the horizontal drain distance (mm, 25000 mm is this study), $r$ = the rate of vertical leachate inflow to drainage layer (mm/s, 3.5 $\times10^{-4}$ m/s (30 mm/day), $3.5\times10^{-5}$ m/s(3 mm/day), and $3.5\times10^{-6}$ m/s (0.3 mm/day) in this study), $k$ = the hydraulic conductivity of the drainage layer (mm/s), $S = \tan\alpha$, $\alpha$ = the slope of drainage layer (2% in this study). The calculated values of $y_{max}$ versus various values of the hydraulic conductivity of the drainage layer are shown in Fig. 2.

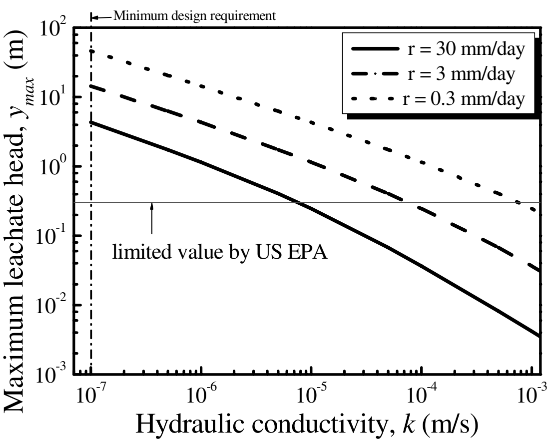


Figure 2. Calculated maximum leachate head versus hydraulic conductivity of granular drainage materials

### 3.2 *Calculation of leakage rate through liners*

To evaluate effectiveness of Chinese standard landfill liners, it was assumed that CN 1 and CN 2 liners were applied in assumed landfills illustrated in Fig. 3 and Fig. 4. It is assumed that there is a confined aquifer under landfill. The clay liners were saturated and the potentiometric surface at the liner bottom is the same as the liner base level. The leachate head on liners CN 1 and CN 2 was assumed to be 0.3 m. For CN 1, downward Darcy velocity ($v_a$) is calculated as $1.2\times10^{-9}$ m/s based on Darcy law. There will be unavoidable holes in GM liners during construction. Rowe (2005) pointed out that wrinkles will easily develop in landfill GM liners. Therefore, it is necessary to assume that there will be holed wrinkles in GM liner for the case of CN 2 liner. To calculate leakage rate $Q_0$ and total leachate rate ($Q$) through CN 2 liner where GM has holed wrinkles, Rowe's 1998 method as expressed by Eq. (3) was used in this study:

$$Q_0 = 2L\left[kb + (kD\theta)^{0.5}\right]\frac{h_d}{D}, \qquad Q = f \times Q_0 \qquad (3)$$

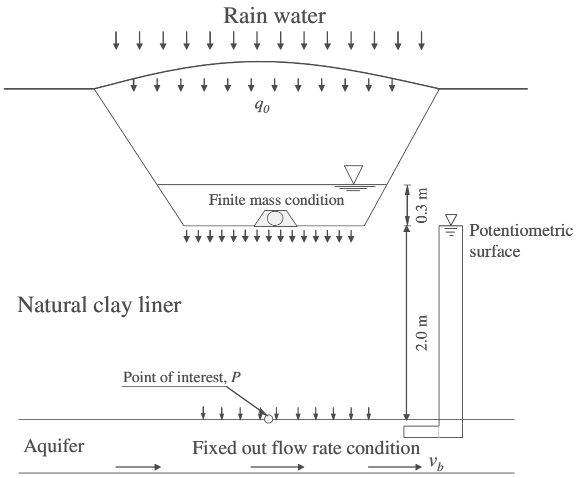


Figure 3. Assumed landfill in which CN 1 liner is used

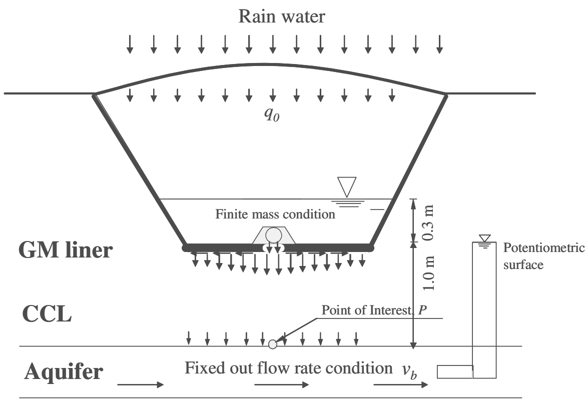


Figure 4. Assumed landfill in which CN 2 liner is used

in which $L$ = the length of the wrinkle, $2b$ = the width of the wrinkle, $k$ = the hydraulic conductivity of the CCL, $D$ = the thickness of the CCL, $\theta$ = the transmissivity of the GM-CCL interface, $h_d$ = the head loss through the composite liner, and $f$ = the number of holes per area in wrinkles of geomembrane. All of the parameters are listed in Table 1. In particularly, the GM-CCL interface ($\theta$) were assumed as $1.6\times10^{-8}$ m$^2$/s and $1.0\times10^{-7}$ m$^2$/s, corresponding to the "good" contact and "poor" contact conditions. The calculated leakage rates through CN 1 and CN 2 are shown in Fig. 5.

Table 1. Assumed parameters for calculation of leakage rate

| Parameters | MSW landfill liner type | |
|---|---|---|
| | CN 1 | CN 2 |
| $D$ (m) | 2.0 | 1.0 |
| $k$ (m/s) | $10^{-9}$ | $10^{-9}$ |
| $h_d$ (m) | 0.3 | 0.3 |
| $L$ (m) | -- | 10 |
| $2b$ (m) | -- | 0.2 |
| $r_0$ (mm) | 1 | 1 |
| $f$ (number/ha) | -- | 12 |
| $\theta$ (m$^2$/s) | | $1.6\times10^{-8}$ i), $1.0\times10^{-7}$ ii) |
| $W$ (m) | 100 | 100 |
| $L$ (m) | 100 | 100 |

$r_0$ = radius of hole in geomembrane; $W$ = landfill width;
$L$ = landfill length; other parameters are defined in Eqs. 3 & 4.
i) good contact condition; ii) poor contact condition.

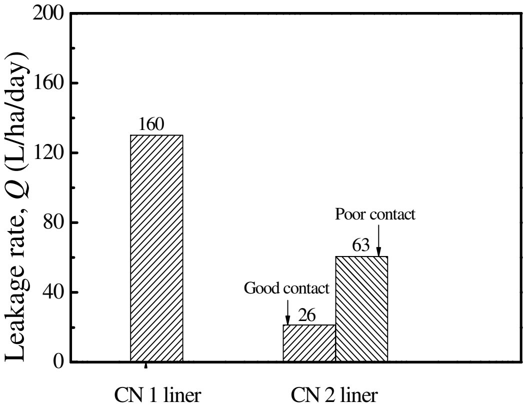


Figure 5. Calculated leakage rate through CN 1 & CN 2 liners

### 3.3 *Calculation of concentration at aquifer*

As illustrated in Figs. 3 and 4, due to the transport of contaminants out of landfills, there will be a risk that the ground water in the aquifer may be polluted by contaminants. In this study, the target contaminant is assumed to be dichloromethane (DCM). To evaluate the concentration of the target contaminant in the aquifer at any specified time, the one dimensional vertical advection-diffusion-dispersion theory for contaminant transport was used in this study. The program *Pollute* v6.3 was used to conducted the numerical analysis. In the program, the upper boundary imposed by the landfill leachate was modeled as a finite mass condition. The lower boundary imposed by the aquifer is modeled as a fixed out flow rate condition.

For the calculation using *Pollute* v6.3, all of the parameters are listed in Table 2. The landfill was assumed to have a length of 100 and width of 100 m. Supposing that the concentration of the target organic contaminant reached a peak at the closure of the landfill (i.e., $C_0$ = 3500 μg/L) and all of the target contaminant was soluble in the leachate, the reference height of landfill leachate ($H_r$) was therefore calculated as 4 m according to Rowe and Booker (1994). The head difference between the landfill leachate and the potentiometric surface of the aquifer was assumed as 0.3 m. Biodegradation of DCM in the landfill leachate was considered with a half-life of 10 years (Rowe and Branchman, 2004). Biodegradation of DCM in the CCL was considered with a half-life of 50 years (Rowe and Branchman, 2004). No sorption of DCM was modeled for the CCL or natural aquitard. The properties of the holed GM wrinkles in the case of CN 2 liner are listed in Table 1. The calculated leakage rates (or Darcy velocity) through the three standard landfill liners were used in the *Pollute V6.3* program to conduct the calculation of transport of the target contaminant. In *Pollute v6.3*, the geomembrane liner was modeled as a liner with the effective diffusion coefficient of $6\times10^{-13}$ m$^2$/s and the partition coefficient ($S_{gf}$) of 6 according to Rowe and Brachman (2004). The limited service life of HDPE GM is not modeled in this study because that there is no published report of temperature in Chinese landfills. The failure of the leachate collection and removal system was not modeled due to no published data available by far. The calculated concentrations of DCM during the 200 years of landfill closure are shown in Fig. 6 and Fig. 7 for CN 1 liner and CN 2 liner, respectively. The calculated total mass per unit area ($M_b$) at the aquifer for CN 1 liner and CN 2 liner is shown in Fig. 8 and Fig. 9, respectively. The calculated peak concentration ($C_p$) and the maximum total mass ($M_{bmax}$) are summarized in Table 3.

Table 2. Parameters used for using program *Pollute* v6.3

| Parameters | landfill liner type | |
|---|---|---|
| | CN 1 | CN 2 |
| $D_e$ ($\times10^{-10}$ m$^2$/s) | 4.0 | 4.0 |
| Head loss across liner (m) | 0.3 | 0.3 |
| Darcy velocity ($\times10^{-11}$ m/s) | 15 | 2.95 i); 7.24 ii) |
| $D_g$ ($\times10^{-13}$ m$^2$/s) | - | 6 |
| $S_{gf}$ | - | 6 |
| $t_g$ (mm) | - | 1.5 |
| Initial concentration (μg/L) | 3500 | 3500 |
| Thickness of aquifer (m) | 1 | 1 |
| Porosity of aquifer | 0.3 | 0.3 |
| Outflow velocity, $v_b$ ($\times10^{-7}$ m/s) | 1.59 | 1.59 |

$D_g$ = the effective diffusion coefficient of GM liner; $S_{gf}$ = the partition coefficient of GM liner, $t_g$ = the thickness of GM liner; other parameters are defined in Eq. (5) and Table 1.
i) good contact condition; and ii) poor contact condition

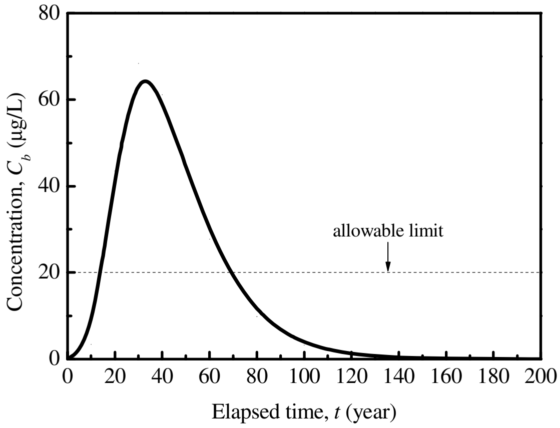


Figure 6. Change of calculated concentration at aquifer with time for CN 1 liner

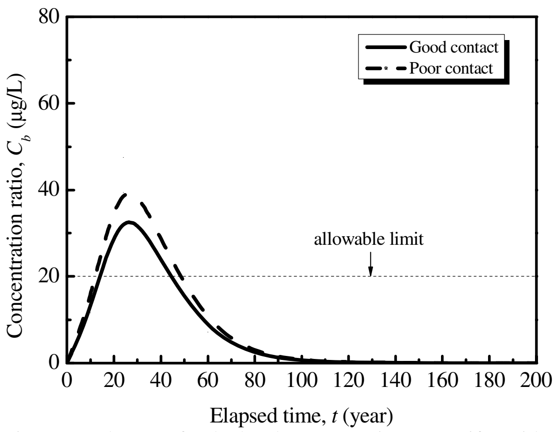


Figure 7. Change of calculated concentration at aquifer with time for CN 2 liner

## 4 RESULTS AND DISCUSSION

From Fig. 2, it can be seen that at relatively high leachate inflow rate value ($r$ = 30 mm/day), the calculated value of $y_{\max}$ for the CN liner systems (46 m) is almost 150 times higher than that the limited value regulated by US EPA and most European countries (0.3 m). At a relatively low vertical rainfall inflow rate ($r$ = 0.3 mm/day), the calculated value of $y_{\max}$ for CN liner system (4 m) is nearly 13 times higher than limited value regulated by US EPA and most European countries (0.3 m). Therefore, it can be concluded that the minimum design requirement of CN liner system is much less strict. It is suggested that the minimum design requirement of $k$ of drainage granular materials should not be less strict than that regulated by US EPA and most European countries. In other words, $k \geq 10^{-4}$ m/s is suggested instead of the current design criteria, $k \geq 10^{-7}$ m/s.

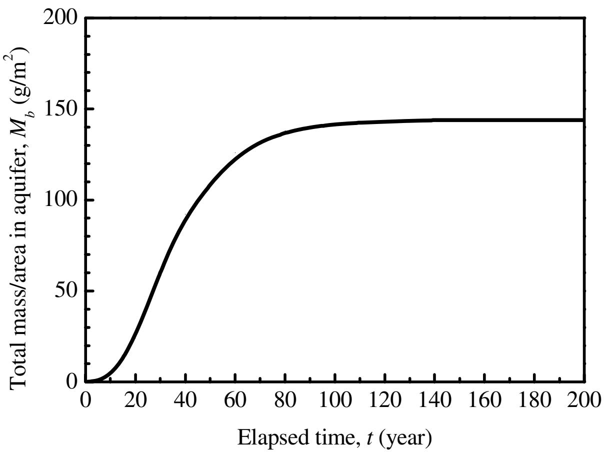


Figure 8. Change of total mass per unit are discharged into aquifer with time for CN 1 liner

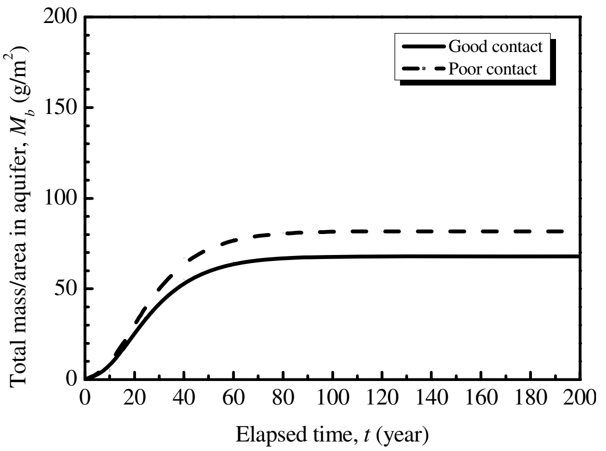


Figure 9. Change of total mass per unit are discharged into aquifer with time for CN 2 liner

Table 3. Summary of calculated values of $C_p$ and maximum $M_b$

| Quantity | Good contact | Poor contact |
|---|---|---|
| Peak concentration, $C_p$ | | |
| CN 1 liner (μg/L) | 70 | |
| CN 2 liner (μg/L) | 39 | 48 |
| CN 1/ CN 2 | 1.8 | 1.5 |
| Maximum $M_b$ (μg/m$^2$) | | |
| CN 1 liner | 144 | |
| CN 2 liner | 68 | 82 |
| CN 1 / CN 2 | 2.1 | 1.8 |

From Fig. 5, it can be seen that the leakage rates for the CN Type 2 liner under the good contact condition are almost one-third of those under the poor contact condition. The leakage rate through the CN Type 1 liner is the highest, which is almost 5 times greater than that of the CN 2 liner under the good contact condition, and 2 times greater than that of the CN 2 liner under the poor contact condition. The result shows that CN 1 liner is less effective than CN 2 liner in terms of leakage rate through landfill liners.

From Figs. 6 and 7, it can be seen that for both CN 1 and CN 2 liners, there is a peak concentration ($C_p$) after certain time during the post-closure period. The values of $C_p$ for both CN 1 and CN 2 are higher than the allowable limit (20 μg/L) prescribed by the standards for drinking water quality issued by the Ministry of Health of The People's Republic of China, indicating undesirable conditions. For CN Type 2 liner, the difference of $C_p$ between the good contact condition and the poor contact condition is not significant (see Table 3), which is mainly due to that the transport of DCM is mainly controlled by diffusion.

From Figs. 8 and 9, it can be seen that for the CN 1 liner, the maximum value of $M_b$ is greater than that for the CN 2 liner. The former are 2.1 times or 1.8 times greater than that of the latter under the good contact condition and poor contact condition, respectively (Table 3). For CN Type 2 liner, the maximum value of $M_b$ under the good contact condition is nearly the same with that under the poor contact condition. This result is consistent with the observation that the difference of $C_p$ between the good contact condition and poor contact condition is not significant, as discussed in the earlier part.

From the analysis mentioned above, it is concluded that the CN 1 liner is less effective in mitigating the landfill contaminent. In practice, CN 2 is suggested to be used.

## 5 CONCLUSIONS

Following conclusions can be drawn from this study:

1) Under the condition presented in this study, the calculated value of $y_{max}$ of the Chinese standard landfill liner system is almost one or two orders of magnitude greater than the limited value regulated by most developed countries.

2) The leakage rate through CN 1 liner is much greater than that through CN 2 liner. The predicted $C_p$ and calculated maximum value of $M_b$ for CN 1 liner are greater than that for CN 2 liner, indicating that performance of CN 1 liner is less effective.

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