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Performance-based Design for Geosynthetic Liner Systems in Landfills

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ABSTRACT: Municipal solid waste landfill is a new type of geotechnical structures occurring with the urbanization development, the functions of which are to contain municipal solid waste and protect natural environment. The geosynthetic liner system consisting of geomembrane and geosynthetic clay liner is widely used to separate the waste and the associated leachate in landfills from the surrounding environment. This paper addresses some issues for the geosynthetic liner system based on its performances, including: (1) breakthrough time, the contaminants cannot transport through the geosynthetic liner system during the service life; (2) sliding failure along the geosynthetic liner system interfaces; (3) tensile failure in the geosynthetic liner system resulting from the waste deformations. These issues are investigated and their associated design criteria are discussed based on theoretical analysis and experimental results, which would be useful for the state-of-the-practice designs of landfills.

1. INTRODUCTION

Municipal solid waste (MSW) sanitary landfill is a new type of geotechnical structure occurring with the urbanization development, which may consist of a barrier system, a leachate collection-drainage system, a gas collection-treatment system and a final cover system. The barrier system is one of the most important components in landfills, and its main function is to separate the waste and the associated leachate from the groundwater and surrounding natural soil. There is a wide variety of possible barrier systems (Rowe et al., 2004), but most of them are geosynthetic liner system (GLS) composed with soils and geosynthetic materials. The use of GLS brings many benefits for the construction and operation of landfills, e.g. ease of placement, uniform quality controlled predictable properties. The GLS design requirements by the Chinese government regulation and standards (CJJ 113-2007; GB 5749-2006) include provisions of a leachate collection system capable of maintaining a head less than 0.30 m, the GLS should be a single or double composite liner, the geomembrane thickness must be at least 1.5 mm, and the compacted clay liner (CCL) must be 0.75 m. Nonetheless, defects in the geomembrane (GM), high leachate level, low shear resistance within GLS and tensile strains due to MSW deformations (shown in Fig. 1) in landfills can cause failure of the GLS. The design of the GLS should be based upon its performance during the service life in landfills.

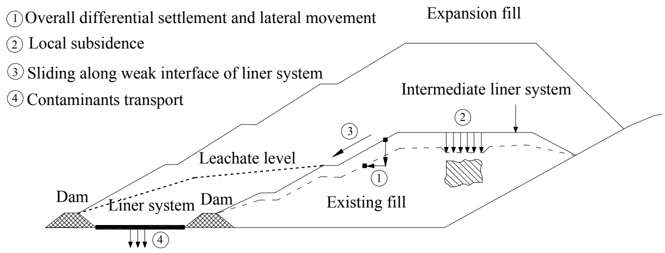


Figure 1. Geo-environmental issues associated with the GLS used in landfills

Defects in GM (see Fig. 2) cannot be completely avoided in the field. The organic and inorganic constituents in the landfill leachate will transport through these defects in GM by leakage (Rowe et al., 2004; Rowe et al., 2007; Chen et al., 2009c). Furthermore, the organic contaminants can readily diffuse through the molecular pores in GM (Nefso and Burns, 2007; Foose et al., 2002). The leachate level generated in landfills tends to be very high and the frequency of GM defects can reach up to hundreds or even thousands per hectare in the developing countries. More attention should be paid to this problem.

Figure 2. The defect in geomembrane

The shear resistance at soil-geosynthetic and geosynthetic-geosynthetic interfaces is generally low. These interfaces with low shear strength have led to slippage and slope failure at many landfills (Koerner and Soong, 2000). The high leachate head would also exert significantly effects on the landfill stability along the liner system (Blight, 2008; Chen et al., 2010b). Most of these interfaces exhibit strain-softening behavior, which makes the sliding failure of landfills along the interfaces more complex. Furthermore, the interfaces within GLS may be ‘wetted’ during construction and operation of landfills, which can influence the shear strength of these interfaces. Consideration of working conditions of the GLS is required for the stability analysis of landfills.

The addition of waste through the vertical landfill expansion will result in differential settlement and lateral deformation in the existing landfill, which could cause a large tensile strain for GMs in the GLS (named “intermediate liner system”) between the existing and expanded landfills. In addition, localized subsidence and some other voids (holes or caves) are often caused by progressive degradation and collapse of large-sized objects buried in the existing landfill. Such localized subsidence in underlying waste can also cause a “localized” deformation and large tensile strain in geosynthetic materials (Giroud and Soderman, 1995; Qian et al., 2001a and 2001b). Thus, the serviceability and structural integrity of geosynthetic materials in the GLS subjected to these MSW deformations is one of the most important design issues for landfill expansions. The induced tensile strains in geosynthetic materials should be controlled in their allowable tensile strains.

This study addresses these issues mentioned above, i.e., (1) transportation of contaminants through the GLS during the service life; (2) sliding failure of MSW along the GLS interfaces; and (3) tensile strains of GLS subjected to MSW deformations. In addition, their associated design criteria are discussed to improve the sustainable landfill technologies.

2. BREAKTHROUGH TIME OF CONTAMINANTS THROUGH GLS

Up to now only limited studies have been carried out for the resistance of liners subjected to a high leachate mound. In this section, effects of leachate head height on leakage rate and breakthrough time for four types of regulatory liners in China were investigated. The compositions of the four types of liners are summarized in Table 1, and the material parameters are given in Table 2. It is assumed that the number of defects for the GM is 20 holes/ha and the area of each defect is 1 cm^2. Four different leachate head heights, i.e. 0.3 m, 1.0 m, 3.0 m and 10.0 m, are considered in this study.

Table 1. Compositions for the four types of regulatory liners in China

Liner type	Composition
1	1.5 mm GM+75 cm CCL
2	1.5 mm GM+75 cm AL
3	1.5 mm GM+13.8 mm GCL
4	2 m CCL

Note: GM = geomembrane; CCL = compacted clay liner; AL = attenuation layer; GCL = geosynthetic clay liner.

The solution for a composite liner having a total head of zero at the base of the liner (Rowe, 1998) is used to calculate the leakage rate for the composite liners and the results are summarized in Table 3. For the composite liners, the calculated leakage rate increases almost proportionally with the increase of the leachate head height, and the leakage rates for 10.0 m-high leachate level is 24-31 times of those for 0.3 m-high leachate level. Hence, the control of leachate head height may effectively reduce the leakage through composite liners. For the 2.0 m CCL liner, the influence of leachate head height on the leakage rate is not as significant as the composite liners, and its leakage rate, however, is much larger for a same leachate head height. In terms of the calculated leakage rates, the liner type 3 (GM+GCL) has the smallest, followed by the liner type 2 (GM+AL) and then the liner type 1 (GM+CCL), and the liner type 4 (CCL) has the largest, which is consistent with the report of Rowe (2005).

Table 2 Material and transport parameters for the four liners

Parameter		GM	CCL	GCL	AL
Porosity		/	0.32	0.86	0.40
Hydraulic conductivity (cm/s)		/	1.0×10^{-7}	5.0×10^{-9}	1.0×10^{-5}
Dry density (g/cm^3)		/	1.79	0.79	1.62
Diffusion coefficient (m^2/s)	Cd^{2+}	6.0×10^{-15}	1.76×10^{-10}	3.6×10^{-10}	8.9×10^{-10}
	benzene	3.5×10^{-13}	5.0×10^{-10}	3.3×10^{-10}	8.9×10^{-10}
Partitioning coefficient S (-)	benzene	30.0	/	/	/
Sorption coefficient K_d (mL/g)	Cd^{2+}	/	0.36	6.5	0
	benzene	/	0.7	20	0.28

Table 3. Calculated leakage rate through four types of regulatory liners subjected to different leachate head

Liner type	θ (m^2/s)	Leakage rate (m/year)			
		h_w=0.3m	h_w=1.0m	h_w=3.0m	h_w=10.0m
1 (GM+ CCL)	1.6×10^{-8}	3.8×10^{-4}	1.2×10^{-3}	3.2×10^{-3}	1.0×10^{-2}
2 (GM+ AL)	1.6×10^{-8}	6.5×10^{-4}	1.9×10^{-3}	5.0×10^{-3}	1.6×10^{-2}
3 (GM+ GCL)	6.0×10^{-12}	3.5×10^{-7}	1.1×10^{-6}	3.4×10^{-6}	1.1×10^{-5}
4 (CCL)	/	3.6×10^{-2}	4.7×10^{-2}	7.9×10^{-2}	1.9×10^{-1}

Note: θ indicates the interface contact condition between GM and the underlying layer with lower value for a good contact; h_w represents the leachate head above the liner.

Based on the calculated leakage rates mentioned above, the breakthrough time of heavy metal and volatile organic compound through the four liners shown in Table 1 was investigated. Cadmium (Cd^{2+}) and benzene are chosen to represent inorganic and volatile organic compound contaminants, respectively. Their transport parameters are listed in Table 2. The one-dimensional analytical model for analyzing contaminant transportation through defects in the geomembrane component of composite liners and diffusion of volatile organic compounds through intact composite liners (Xie et al., 2010) is used herein. The concentrations of Cd^{2+} and benzene are assumed to maintain as 0.5 mg/L and 0.05 mg/L, respectively, at the top of the liners (Kjeldsen et al., 2002). The concentration of breakthrough is 0.005 mg/L for both Cd^{2+} and benzene, respectively (USEPA, 2002), at the bottom of the liners.

The calculated breakthrough times are summarized in Table 4. It is noted that the calculated breakthrough time may be influenced by the ratio of the specified concentration at the top and bottom of the liner. For the liner type 1 (GM+CCL), type 2 (GM+AL) and type 4 (CCL), the increase of the leachate head height from 0.3 m to 10.0 m results in a considerable decrease in breakthrough time for Cd^{2+} while a slighter decrease in breakthrough time for benzene. For the liner type 3 (GM+GCL), the leachate head height has a slight effect on the migration of both of Cd^{2+} and benzene, the latter of which can readily break through the liner. This finding is consistent with that of Foose et al. (2002). It might be concluded that the liner type 1 (GM+CCL) is the best barrier for volatile organic contaminants especially for cases of high leachate level, and the liner type 3 (GM+GCL) provides the best barrier for inorganic contaminants but the worst one for organic contaminants even if the leachate level is very slow. However, according to the authors' knowledge, the liner type 3 (GM+GCL) is widely used in China for the fact of its easy construction. It is suggested that an attenuation layer should be placed beneath GCL to give better barriers for the organic contaminants, more importantly the leachate head should be controlled at a low level to make the GLS meet the service life in landfills.

Table 4 Breakthrough time of Cd^{2+} and benzene for the four liners

Liner type	Breakthrough time (year)			
	Cd^{2+}		Benzene	
	h_w=0.3m	h_w=10m	h_w=0.3m	h_w=10m
1 (GM+ CCL)	57.4	19.8	35.0	25.5
2 (GM+ AL)	10.7	3.5	8.7	6.7
3 (GM+ GCL)	77.1	72.6	0.37	0.37
4 (CCL)	31.1	13.6	52.0	17.5

3 STABILITY OF MSW ALONG GLS

3.1 Interface Shear Strength of GLS

Figure 3 shows a comparison of stress-deformation curves for different materials and interfaces, which are commonly found in landfills (Chen and Zhan, 2007). The interfaces include textured GM/CL, textured GM/GT and textured GM/GCL. It can be seen that the MSW, exhibiting a strain-hardening behavior, poses higher ultimate shear strength than the CCL and the interfaces. The peak values of shear strength of the interfaces （textured GM/CL, textured GM/GT and textured GM/GCL） are close to that of the CCL. However, all the interfaces show a strain-softening behavior, and hence have lower shear strength than the CCL when the shear displacement is large. A difference in the shear strength is also observed among different interfaces.

The interfaces within composite liners may be 'wetted', due to rainfall during liner placement, squeezing of water from the liner clay itself during consolidation under the fill overburden pressures, and/or water ponding in the vicinity of the leachate collection system sump. In general, they have relatively low shear strength (Mitchell et al., 1990). It is also found that bentonite from the GCLs may extrude into the GCL/GM interface resulting in a significant reduction in interface shear strength. According to the results of laboratory tests (Chen et al., 2010a), the bentonite extrusion may cause a loss of 7.6° in terms of interface friction angle for the large-displacement shear strength of the GCL/GM interface (τ_{ld}) and 3.5° for the peak shear strength (τ_p), as shown in Table 5. Hence, consideration of the working condition of the composite liner is required for the laboratory tests on its shear strength.

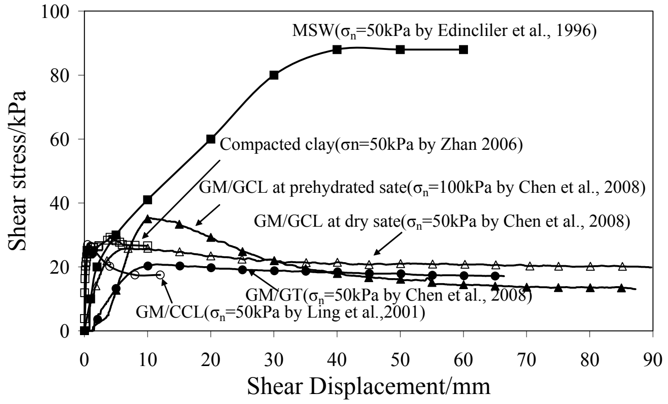


Figure 3. Shear stress-displacement relationships for MSW, CCL and interfaces within GLS

Table 5. Peak and large displacement shear strength parameters for GM/GCL interface

Interface	State	Normal stress range (kPa)	Peak Strength Parameters		Large Displacement (100 mm) Strength Parameters	
			c_p	φ_p	c_{ld}	φ_{ld}
GM/GCL	Dry	50~200	0	24.4	0	16.9
	Hydrated	50~200	0	20.9	0	9.3

Note: It is assumed that the cohesion is equal to zero.

3.2 Stability of Qizishan Expanded Landfill

The Qizishan landfill is located in a valley surrounded by hills, about 13 km from Suzhou City. The landfill has reached its maximum design level (i.e. +80 m, ordnance datum) by the end of 2008. The preliminary design involves the vertical expansion of the existing landfill from 80 m to 120 m, and an outward expansion of 400 m from the present landfill boundaries (see Fig. 4). In accordance with the new regulation, the bottom of the expanded waste body will be lined with a GLS, and the liner type 3 (GM+GCL) was adopted by the preliminary design. In this section, the effects of interface shear strength for the liner type 1 (GM+CCL) or type 3 (GM+GCL) and the leachate level on landfill stability are investigated. Finally, some other engineering measures are also advised to improve the stability for Qizishan expanded landfill.

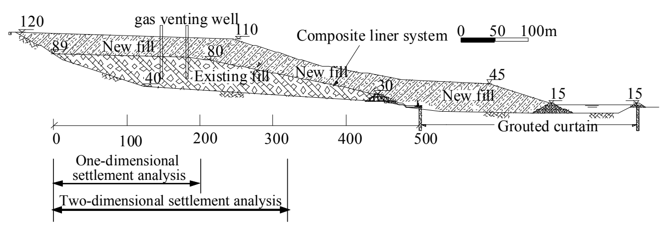


Figure 4. A preliminary design of landfill expansion in Suzhou, China

The liner type 1 or type 3 includes interfaces of GT/GM, GM/CCL and GM/GCL. The shear strength parameters for these interfaces are shown in Table 6. Parameters of the waste mass with a unit weight of 12 kN/m^3, a cohesion of 5 kPa and an internal friction of 28° suggested by Zhan et al. (2008) were used. For the purpose of comparison, a fixed slip surface (see Fig. 5) mainly along the intermediate liner system was assumed for the translational failure analyses. If the effect of leachate level is not taken into account, the analysis results are shown in Table 6. If the shear strength parameters at a large shear displacement are used, the factor of safety for the slippage along the hydrated GM/GCL interface is the lowest (i.e., Fs = 1.017), followed by the GM/GT, the dry GM/GCL, and GM/CCL in succession. It can be seen that the factor of safety against the GM/GCL interface is significantly affected by both the hydration state of GCL and the shear displacement occurring to the interface. The analysis results indicate that it should be paid more attention when using the GM/GCL as a liner on the sloping ground, particularly in a landfill without an effective water management system. It was suggested that the liner type 1 instead of the liner type 3 should be used for Qizishan expanded landfill.

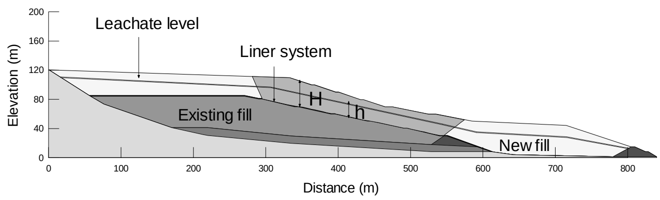


Figure 5. Model for expanded landfill stability analysis along the liner system

Table 6 Factor of safety for the slide along the intermediate liner at the Qizishan Landfill

Interface	State	Shear strength parameters corresponding to large displacement		Factor of safety
		c (kPa)	φ (°)	
GM/GT	-	5	12.8	1.247
GM/CCL	-	11.4	23.6	2.141
GM /GCL	Dry	0	16.9	1.487
GM /GCL	Hydrated	0 (peak value)	20.9 (peak value)	1.746
		5	9.3	1.017

According to the authors' in situ investigations, high leachate mounds are very common for the landfills in the humid regions of China. For example, an up to 15 m leachate head was found over the base in Qizishan old landfill, as shown in Fig. 6. Development mechanism of high leachate mounds in humid regions of China was investigated by Chen et al. (2010b). A lack of assessment of the effect of leachate level is the primary factor leading to the catastrophic failures of MSW dumps and landfills (Blight, 2008). The effect of leachate level on the stability of waste mass along the GT/GM interface of the liner type 1 is investigated and the results of stability analyses for different normalized height of leachate level (i.e. h/H) are illustrated in Fig. 7 for the preliminary design (see Fig. 5), where h and H are the height of leachate mound and the maximum waste thickness, respectively. The factor of safety Fs is less than the corresponding Chinese criteria (Fs=1.3), and the additional fill (20 m height and 120 m long) was suggested to be added at the slope toe as shown in Fig. 8 to improve the stability of the expanded landfill. Fig. 7 also shows the effect of leachate level for stability of the proposed design, which indicates that stability of the expanded landfill would be improved dramatically. According to the current Chinese criteria, 0.5H may be regarded as the warning leachate level for the consideration of stability along the GLS.

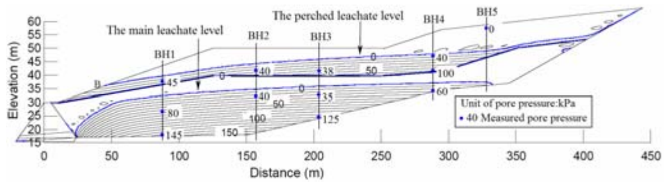


Figure 6. Pore pressures measured in field of Qizishan old landfill, China (Chen et al., 2010b)

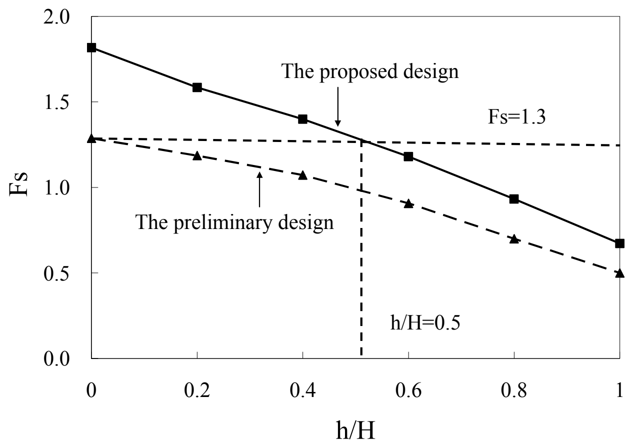


Fig. 7 Effect of leachate level on the landfill stability

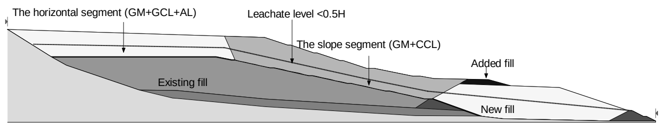


Fig. 8 The proposed design for Qizishan expanded landfill

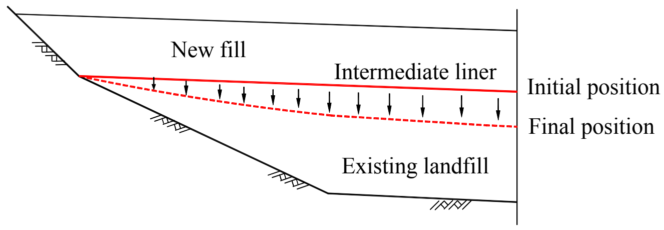
4. TENSILE STRAINS OF GLS

The deformation of GLS under a variety of factors is one of the most important issues to be considered in the design of an expanded landfill. In this study, its two strain-related problems subjected to deformation of the landfill and localized subsidence of underlying MSW were investigated, respectively. These two problems are of more importance for the vertically expanded landfills.

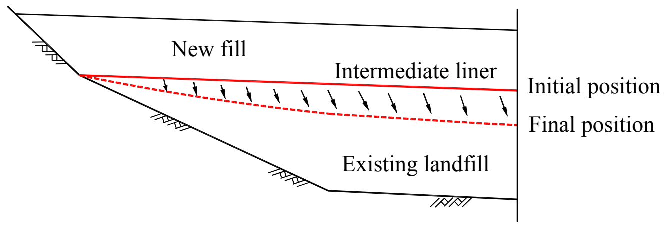
4.1 Liner Strains Subjected to Deformation of Landfill

The evaluation of potential liner strains subjected to deformation of landfills requires a reliable deformation prediction on landfills. Qian et al. (2001a) presented a simple equation to estimate the tensile strains of liners subjected to global settlements roughly. The equation is based on the assumption that the landfill has a negligible lateral movement and no slippage occurs on the interface between liner system and waste body. The tensile strains in the intermediate liner can be evaluated by comparing the pre-settlement liner configuration to the post-settlement liner configuration (see Fig. 9(a)). It should be noted that the strain level of the liner may be significantly underestimated by this method. The existing landfill sitting on a sloping ground must suffer from a lateral movement during the vertical expansion. Thus, considerable lateral movement will also take place on the intermediate liner assuming the intermediate liner and the underlying MSW deforms compatibly as shown in Fig. 9(b).

As for the Qizishan expanded landfill, to predict primary settlement behavior of the existing landfill and calculate tensile strains of the intermediate liner by the one-dimensional method of Qian et al. (2001a), borehole samples were brought to laboratory to carry out primary compression tests (Chen et al., 2009d). For the purpose of illustration, a cross section with a horizontal length of 200 m with significant differential settlement (see Fig. 4) was chosen to perform settlement analyses. Fig. 10 shows the calculated primary settlements of the existing landfill and associated with its induced liner strains. It can be seen that the surcharge loading of the expanded landfill can result in a maximum settlement of about 3.9 m for the existing landfill. The maximum tensile strain in the intermediate liner estimated by Qian et al. (2001b) is only about 0.8%.



(a) Settlement of intermediate liner



(b) Settlement and lateral movement of intermediate liner

Figure 9. Deformation of intermediate liner

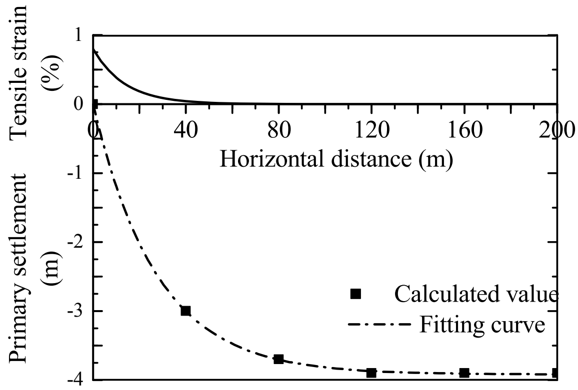


Figure 10. Primary settlements of the existing landfill and induced liner strain (Chen et al., 2009a)

At present, no analytic or empirical methodology has been established for evaluating the lateral movement of a landfill. However, numerical modeling could be adopted to solve this two-dimensional (2D) problem, in which the constitutive model for MSW is important. Based on large-size triaxial tests on MSW, a composite exponential strain-hardening model for MSW was proposed (Chen et al., 2009b). It was incorporated into numerical modeling code FLAC to analyze the potential tensile strains in the intermediate liner induced by differential settlement and lateral movements of the existing landfill. The main part of the Suzhou landfill (see Fig. 4) with large differential settlement and lateral movement is taken into consideration in the analysis. Fig. 11 shows the numerical analysis results computed by the proposed composite exponential strain-hardening model and compared with those of linear-elastic model and Mohr-Coulomb model (Gao, 2009). It can be seen that the maximum lateral movement of the existing landfill is 2.44 m, which happens on the top of the front slope, and the maximum settlement is 4.55 m.

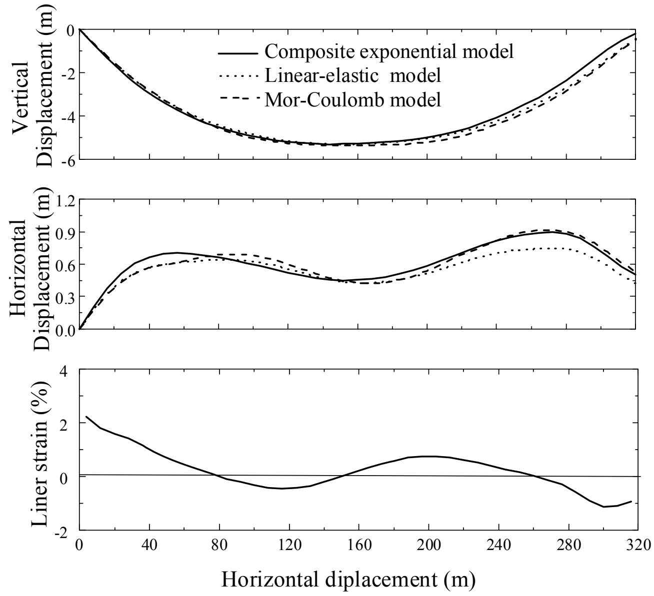


Figure. 11 Deformation of intermediate liner system and induced tensile strains

Fig. 11 shows the strain distributions of the intermediate liner in the range of 320 m horizontal distance from the left of the existing landfill (Chen et al., 2009a). The maximum tensile strain of the liner is 2.06%, which appears near the anchor trench in the back slope of the existing landfill. The tensile strains subjected to both of lateral movement and differential settlement of the existing landfill are lower than allowable tensile strains of GCL and LLDPE, and it would not cause tensile damage of geosynthetics in the intermediate liner. Compressive strains occur in the front slope of the existing landfill, which means that the liner system in these areas will be relaxed. It is found that lateral movement of the existing landfill heavily affects on the strain magnitude and strain distribution of the liner system. Further theoretical and experimental studies involving time-dependent degradation of MSW are required for an improved understanding on this problem.

4.2 Liner Strains Subjected to Localized Subsidence

At present, reinforcing the liner system with a geogrid or high strength geotextile is commonly used to resist the subsidence effects in engineering practice. The current state-of-the-practice design considers a 1.8-2.4 m diameter void (refrigerator effect). The design of the geosynthetic reinforcement is based on a worst-case scenario assumption that a void is located immediately underneath the liner as illustrated in Fig. 12.

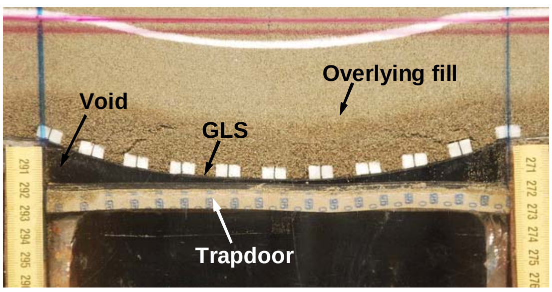


Figure 12. Geosynthetic laid on landfill voids

The design method has been developed considering arching theory for the fill materials overlying on geosynthetics including the reinforcement with the tensioned membrane theory (Giroud et al., 1990). A default assumption in this method is that the soil deformation required to generate the soil arch is compatible with the tensile strain required to mobilize the geosynthetic tension. However, it is possible that the degree of the soil arching depends on the geosynthetic vertical deflection. In order to study the effect of geosynthetic deformations on soil arching, a total of four model tests were conducted as shown in Figs. 12 and 13 (Gao et al., 2009). A miniature soil pressure cell is lying on the GM modeling the GLS to measure the vertical soil pressure on the GLS during the localized subsidence applied a trapdoor. Fig. 14 shows variation of soil pressures acted on the deflected GM for different filling height. It can be seen that the soil pressures decrease rapidly when the GM deflection y is less than 2 mm. With the further development of GM deflection, the soil pressures decrease slower and reach a stable value finally.

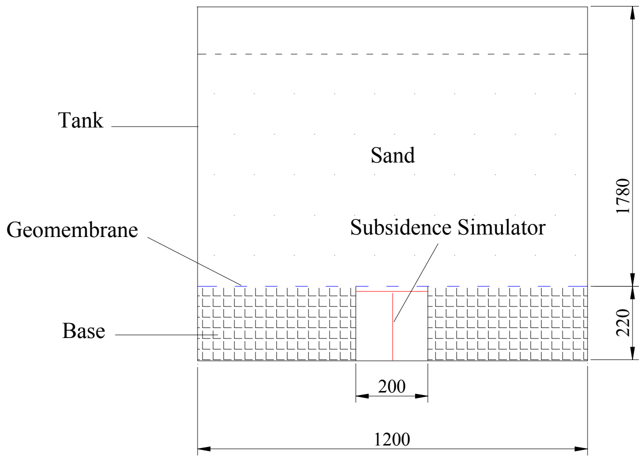


Figure 13. Layout of test device (Unit, mm)

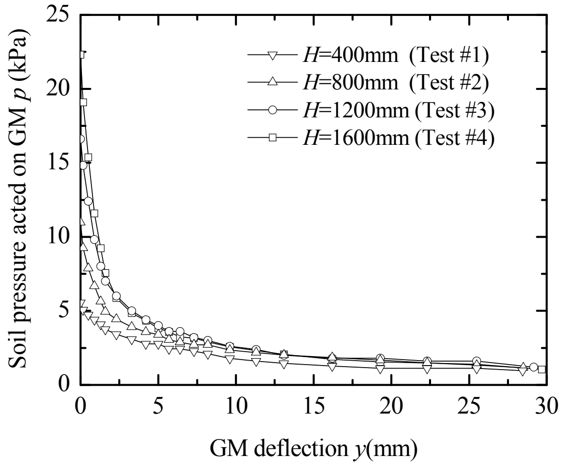


Figure 14. Soil pressures acted on the deflected GM for different filling height

The measured GM strains caused by the localized subsidence are shown Fig. 15. With the increase of filling height, the average GM strains are quite similar to each other. The maximum GM strains range from 8.58% to 9.88%. These values have reached or exceeded the allowable strains of many sealing materials such as HDPE GM. Based on these test results, an analytic model which could take the displacement-related vertical earth pressure applied on GLS into consideration was proposed by Gao et al. (2009). The calculated tensile loads T_r of the geosynthetic reinforcement are shown in Fig. 16 and compared with those of Giroud et al. (1990). The radius of the void is selected to be 0.9 m. The allowable design strain ε is considered to be 7%. The method of Giroud et al. (1990) is conservative if the overlying waste thickness is less than about 42 m, however, it might significantly underestimate the value of T_r when the overlying waste thickness is larger than 42 m. This is because that the Giroud et al. (1990) method cannot consider the displacement-related vertical earth pressure applied on the GLS, and it may underestimate this value for a large overlying waste thickness. For the Qizishan expanded landfill (H=40 m), the calculated geosynthetic tensile load is 12.2 kN/m. Considering the reduction factors RF_{CR} accounting for creep of geosynthetic (RF_{CR}=2.5), RF_{ID} accounting for installation damage (RF_{ID}=1.5) and RF_{CBD} accounting for chemical biological degradation (RF_{CBD}=1.2), the long-term allowable design tensile load is equal to 54.9 kN/m. If the considered void radius is 1.2 m, this value would be about 100 kN/m, and one layer of geogrid with high tensile strength can almost satisfy the design requirement.

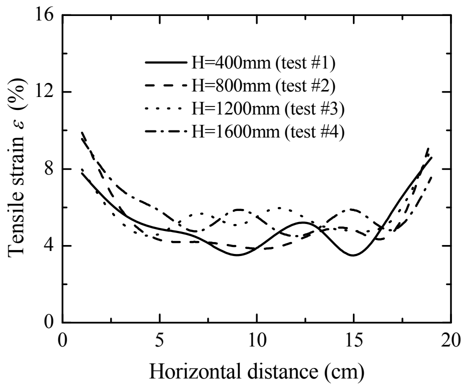


Figure 15. GM strains for different filling heights

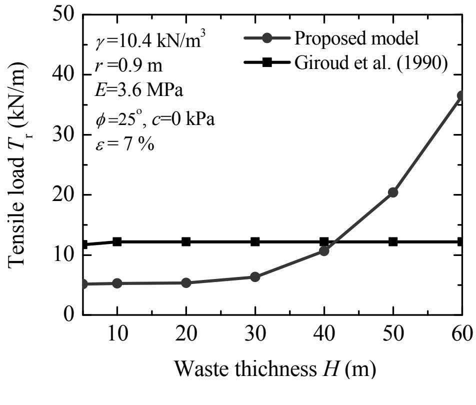


Figure 16. Comparison of geosynthetic tensile loads calculated by different methods (Chen et al., 2009a)

4.3 Tensile Tests and Design Criteria for GLS

The allowable strains in geosynthetic materials ε_{allow} can be evaluated by wide-width tensile tests. Fig. 17 shows the behavior of axial tensile strength versus axial strain for some geosynthetic materials from our tests. It can be seen that the curves for the HDPE and LLDPE GMs show an obvious yield points. According to Qian (2001a) the allowable tensile strain of a CCL is usually less than 1%, and that of a GCL is 6%–20%. Thus, it is likely that the effectiveness of a CCL served as a hydraulic barrier would not be appropriate for a vertically expanded landfill, and the GCL may be considered as an alternative. Two types of GMs, HDPE and LLDPE, are recommended for the GM component of the composite liner systems. However, HDPE has a much larger potential for stress cracking and lower allowable strain than LLDPE (Stulgis et al., 1996). Peggs et al. (2005) presented some general guidance for the maximum allowable strains of GMs, with values ranging from 4% to 8% for HDPE and 8% to 12% for LLDPE.

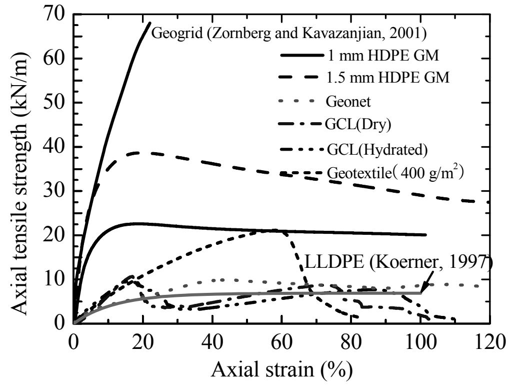


Fig. 17 Tensile strength-axial strain behaviors of geosynthetics (Chen et al., 2009a)

4.4 Proposed Geosynthetic Liner System for the Qizishan Expanded Landfill

As shown in Figs. 10 and 11, the maximum tensile strain subjected to both differential settlement and lateral deformation of the existing landfill is lower than the allowable tensile strains of LLDPE and GCL. Based on the analysis results of liner strains subjected to localized subsidence, at least one layer of geogrid would be used to mitigate the tensile strain of GLS. As a result, the proposed composite liner system for the horizontal area on the existing landfill includes a thick bedding layer (acting as a buffer beneath the GMs), two layers of geogrid reinforcement, an LLDPE GM and a GCL, as shown in Fig. 18. Also, there are some engineering measures for stabilizing existing MSW fill before the construction of an intermediate liner system: preloading with excess mass, deep dynamic compaction, and lime/fly ash slurry injection, etc. Jang et al. (1993) stated that placing controlled fill (soil or waste) above an existing landfill is a feasible and economical method to protect a non-reinforced liner system from the impact of localized subsidence. It can provide a thick buffer or a strain-transition zone for prevention of large tensile strains in GLS.

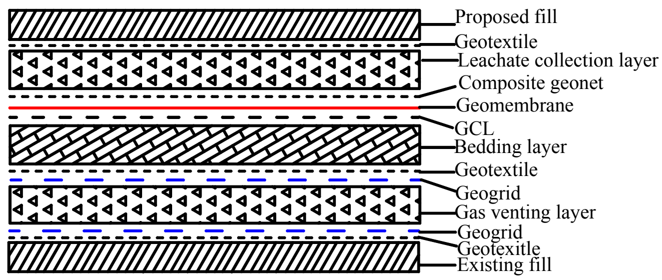


Figure 18. Illustration of the proposed liner system for the horizontal area

5. CONCLUSIONS

This paper investigated the effects of leachate head height on leakage rate and breakthrough time for four types of regulatory liners in China. The impacts of interface shear strength within the GLS and high leachate mounds on landfill stability were then discussed. Finally, for the vertically expanded landfills, the tensile strains in the intermediate liner system subjected to deformation of existing landfill and localized subsidence are studied. It was shown that the design of the GLS must be based upon its performance in the landfill. Some conclusions are summarized as follows:

(1) High leachate head on liners may accelerate the leachate leakage (nearly proportionally) and shorten the breakthrough time of contaminants through the liners. It is concluded that the control of leachate head at a low level is of critical importance to make the liners meet the service life.

(2) Stability of the expanded landfill along weak interfaces within the intermediate liner system should be concerned, especially when the GM/GCL liners are used. According to the calculated results, the liner type of GM+CCL was recommended to be used instead of the liner type of GM+GCL for the intermediate liner system on the slope. The leachate level controlled under 0.5H was suggested to improve the stability of Qizishan expanded landfill along the intermediate liner system.

(3) Case study shows that the lateral movement of the existing landfill has a greater effect on liner strains than the differential settlement does. The largest tensile strain appears near the anchor trench in the back slope, and it is small enough compared with the allowable tensile strains of GMs and GCL.

(4) The displacement-related earth pressure calculation method is recommended for the design of the GLS subjected to a localized subsidence. Based on the analysis results, a new intermediate liner system in horizontal areas for the Qizishan expanded landfill is proposed.

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