Tensile Strains in Geomembrane Landfill Liners

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Abstract. A geomembrane (GMB) liner is a key component of the barrier system in many modern engineered landfills. In combination with a clay liner, the GMB minimizes contaminant migration to groundwater and surface water. GMBs in landfill applications are mostly made from high-density polyethylene (HDPE). When in contact with landfill leachate, the HDPE GMBs experiences significant aging and loss of mechanical properties with time. In particular, a loss in stress crack resistance combined with excessive tensile stress/strain can result in GMB cracking and ultimately failure. Thus, to ensure good long-term performance, the maximum tensile strain sustained by an HDPE GMB should be limited to an acceptable level. Both the local GMB indentations induced by gravel in an overlying drainage layer or underlying clay liner and the down-drag load in the GMB on side slopes with settlement of the waste can cause significant tensile strains in HDPE GMBs. This paper reviews key research examining tensile strains developed in GMBs from both sources.

Keywords: Geomembranes · Strains · Landfills · Indentations
Side slopes

1 Introduction

Modern engineered landfills generally require a barrier system below the waste to minimize contaminant escape to the groundwater and surface water, and therefore to reduce the potential impacts on the human health and surrounding environment [31]. A barrier system consists of a high permeable leachate collection system (LCS) and a low permeability liner system. As part of a landfill composite liner, high-density polyethylene (HDPE) geomembranes (GMBs) are excellent barriers for harmful inorganic substances (e.g., heavy metals) typically found in landfills, and when combined with an underlying geosynthetic clay liner or compacted clay liner can perform their intended functions extremely well [29]. However, with time, HDPE GMBs will experience a loss of their mechanical properties [18, 27, 32–34]. When a GMB degradation is such that it can no longer resist the tensile strains/stresses, fully penetrating cracks [1, 12] allow the escape of leachate. Once this escape exceeds allowable design values, the GMB is considered to have reached the end of its service-life [31].

Two key sources that have the potential to cause significant tensile strains in GMBs are: (a) local indentations in the GMB induced by the overlying drainage materials

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[4, 5, 30] and/or gravel in the underlying clay liner [6], and (b) down-drag load for GMBs on side slopes generated by waste settlement [2, 14, 15, 19, 21, 22, 37, 38, 40, 42, 44–46].

Short-term punctures can generally be minimized by providing sufficient protection to the GMB liner [9, 17, 23, 24, 28, 39], the magnitude of tensile strains that a GMB can sustain without compromising their intended long-term performance reported in the literature varies. To avoid premature GMB failure due to stress cracking, Seeger and Müller [36] indicated that the GMB strain should be less than 3%. Based on the GMBs examined under the simulated field conditions in the geosynthetic liner longevity simulator (GLLS) cells [1, 12, 30], it can be inferred that sustained tensions that induce tensile strains greater than 4–5% should be avoided by the use of a suitable protection layer [1, 12, 30], eliminating potentially problematic gravel from the upper layer of a clay liner or other subgrade, and designing to limit strains from other sources (such as down-drag by waste placement and subsequent settlement/degradation).

Giroud et al. [16] reported that strain concentrations in the vicinity of seams can give rise to failure adjacent to seams. Laboratory testing reported by Kavazanjian et al. [20] indicated that the stain magnification induced by a seam was even greater than estimated by Giroud et al. [16].

The objective of this paper is to summarize the research related to the generation of tensile strains in GMBs used in landfill liners associated with the local GMB indentations induced by granular materials and the down-drag load for GMBs on side slopes due to waste settlement.

2 GMB Tensile Strains from Indentations

2.1 GMB Indentations and Laboratory Testing Methods

A protection layer is required between the GMB and the drainage layer to prevent the short-term puncture of the GMB [24, 28] and to minimize the long-term tensile strains in the GMB [1, 12, 30]. Laboratory testing to establish the short-term (typically in a 10- to 100-h sustained pressure test) GMB tensile strains developed with a proposed protection layer over the GMB is currently the most feasible way to qualify the efficiency of protection layers in term of reducing/limiting the GMB tensile strains [7, 35].

Standard laboratory test methods [3, 10] can be used to examine the short-term GMB tensile strains with and without a protection layer. Large-scale laboratory test apparatus has also been developed to examine the influence of different protection layers on the GMB strains [4, 5, 9, 35]. A very thin lead sheet is used beneath the GMB to record the GMB deformations in these laboratory tests.

2.2 Strain Calculation Methods

The magnitude of the calculated GMB strains based on the indentations recorded in the lead sheet is highly dependent on the method used to calculate the strain [3, 8, 11, 25, 39]. The local membrane strain is calculated by fitting a circular segment to the indentation in the lead sheet used in the BAM [8] and ASTM D5514 [3] approaches (noting that there is an error in the equation given in ASTM D5514 [3]). The LEF-2 [25] strain calculation method estimates the incremental strains for each 3-mm segment of the measurement axes of the indentation. Recognizing that a 1.5 mm-thick (or greater) GMB has bending as well as membrane strains, an improved alternative approach to calculate the incremental strains was proposed in Tognon et al. [39] using the vertical deformed GMB profile recorded in the lead sheet to assess both membrane and bending incremental strains. All these methods err in underestimating the strains since they neglect the horizontal displacements; the Tognon et al. [39] method being the best of the methods based on vertical displacement. Eldesouky and Brachman [11] have recently proposed an alternative method to calculate the GMB incremental strains considering both the vertical and radial displacements of the GMB under the axisymmetric conditions. However, the method presented by Eldesouky and Brachman [11] is only suitable for the axisymmetric conditions and is not yet suitable to be used for GMBs under the gravel drainage layer for landfill applications.

2.3 Influence of Gravel Size on Maximum GMB Tensile Strain

Laboratory experiments reported by Brachman and Gudina [4] for two poorly graded and angular gravels (nominal grain sizes of 25 mm and 50 mm) directly on a 1.5 mm-thick GMB (i.e., no protection layer) over a compacted clay liner at an applied pressure of 250 kPa for 10 h (21 ± 2 °C). The average spacing between the gravel contacts was reported to be 37 mm with a maximum GMB tensile strains of 16% for the 25-mm gravel and 55 mm with maximum GMB tensile strains of 32% for the 50-mm gravel. These strains are unacceptable in landfill applications, necessitating the inclusion of a protection layer between the GMB and overlying gravel layer to limit the GMB tensile strains as discussed below.

2.4 Influence of Geotextile Protection on Maximum GMB Tensile Strain

The physical response of a 1.5-mm thick, HDPE GMB beneath the 50-mm gravel with and without a geotextile protection layer was reported by Brachman and Gudina [5], where the GMB was overlying a needle-punched geosynthetic clay liner (GCL) on a firm foundation layer and the gravel was subjected to an applied pressure of 250 kPa at 21 ± 1 °C.

Based on the physical testing results, the maximum GMB strain was 17% without a geotextile protection layer. Thus, increasing the stiffness of the foundation (a compacted clay liner [4] versus a GCL on the firm foundation [5]) reduced the maximum GMB strain from 32% [4] to 17% [5] when the other conditions were identical.

The use of a geotextile protection layer between the GMB and gravel resulted in smaller GMB strain. For similar needle punched geotextiles, the larger the mass per unit area of the geotextile, the smaller the GMB strain. When using a geotextile with the mass per unit area of 2200 g/m^2 (the highest among three geotextiles tested [5]), the GMB strains were just below 6% compared to 17% without a geotextile protection layer. However, even with a geotextile protection layer, the GMB strain is still considered too large because these strains are for the short-term loading conditions. For the long-term field conditions with elevated temperatures and chemical exposure in a landfill, GMB strains greater than 6% are expected [1, 12].

2.5 Influence of Alternative Protection Layers on Maximum GMB Tensile Strain

A 150-mm thick layer of sand as the protection layer on the GMB was also examined [4] under the same testing conditions as the geotextile protection layers. The use of a 150-mm-thick sand layer limited the maximum GMB tensile strain to less than 0.2%. Thus, the sand protection layer (150 mm thick) was very effective in terms of providing protection to the GMB under 50-mm gravel at the vertical pressure of 250 kPa. Laboratory experiments on sand, geocomposites, geonet, and rubber tire shreds as alternative protection layers for a composite GMB-GCL landfill barrier beneath 50-mm gravel [9] also confirmed that of all the protection layers examined, sand was the most effective at limiting strains, although a geocomposite was more effective than the traditional nonwoven.

2.6 Influence of Time and Temperature on Maximum GMB Tensile Strain

The laboratory experiments [4, 5, 9] were based on the applied pressure of 250 kPa held for a duration of 10 h at room temperature (21–22 ºC). However, under the field conditions in the landfill, the GMB is expected to be loaded for much longer and subjected to higher temperatures.

Small scale laboratory experiments [35] were performed with testing time up to 10,000 h and temperatures up to 85 °C for a 1.5-mm thick HDPE GMB overlying a compressible compacted clay liner, where the GMB was loaded by an overlying machined probe, simulating a gravel particle, with a sustained vertical force corresponding to that induced by an average applied stress of 250 kPa. The laboratory results indicated that the machined probe was able to closely reproduce the average strains from real 50-mm gravel. For a GMB without a protection layer, the GMB tensile strains increased from 14.9 to 18.0% at a temperature of 55 °C when time was increased from 10 to 10,000 h. Increasing the temperature from 22 to 85 °C increased the GMB tensile strain observed after 1000 h from 13.8% (22 °C) to 20.5% (85 °C).

3 GMB Tensile Strains on Side Slope

3.1 GMB Tears on Side Slope

The use of a proper protection layer between the GMB and gravel drainage layer can be very effective in minimizing the GMB punctures and limiting the GMB strains. However, the GMB can still fail on side slopes due to down-drag load from waste settlement. The field exhumation of a large landfill in South East Asia [14] revealed a failure of the GMB at the crest of the side slope near the bench. A well-documented slope failure of the waste at the Kettleman Hills Landfill [26] also showed tears in the

GMB liner on the side slope associated with the failure developed by sliding along the interfaces between the underlying liner system beneath the waste fill. These field observations of the GMB failures on side slopes highlight the importance of protecting the GMBs not just from the indentations caused by gravel particles but also from the down-drag forces acting on the GMB due to waste settlement.

3.2 Numerical Modelling

The failures of the GMB liners observed in the field are very valuable in terms of recognizing the limitations of the design practice for the geosynthetic liner systems. Field observations improve the understanding of failure mechanisms associated with geosynthetic liner systems [41, 46]. However, it is generally not feasible to conduct the field-scale tests because of the practical difficulties and associated costs of performing these tests. Thus, there is a paucity of field measurements associated with GMB liner strains due to waste settlement [43]. Numerical models are currently the only practical tools for engineers to explore the different design scenarios and to gain confidence when designing the geosynthetic liner systems. Both the finite element method (FEM; [13, 41]) and finite difference method (FDM; [2, 14, 15, 19, 22, 37, 38, 42, 44–46] have been used to numerically model the performance of geosynthetic liner systems. All these numerical models have assumed that the slopes had planar surfaces and the GMBs, according to good practice, were not welded across the side slopes.

3.3 Centrifuge Testing

Centrifuge modeling has also been used to examine the performance of GMB liners under waste settlement [21, 40]. These centrifuge tests used the scaled models and increased the body stresses by centrifugal acceleration. A FDM model [44] was used to model the GMB strains/loads developed in the large-scale centrifuge test of the geomembrane-lined landfill with benches on side slopes similar to those encountered in a canyon landfill subject to waste settlement [21]. The results showed that the calculated GMB strains on benches and waste surface settlement at the landfill centre were generally in good agreement with the measured data [44].

The numerical analyses [44] indicated that the GMB with an axial tensile stiffness J = 2000 kN/m yielded a maximum prototype tensile load equal to the tensile strength (i.e., T_y = 120 kN/m). If the GMB had a higher stiffness (e.g., J = 4000 kN/m) and strength (e.g., T_y = 240 kN/m), the GMB maximum tensile load was 205 kN/m (i.e., less than the yield strength 240 kN/m) and the maximum tensile strain was 5.1% (< yield strain ε_y = 6.0%; [44]). Thus a GMB with axial tensile stiffness J = 4000 kN/m could prevent the geomembrane from yielding and reduce the maximum strain to about 5% other things being the equal. However, this would imply the need for an unrealistically thick GMB liner to control the maximum tensile strain and an alternative approach is needed.

3.4 Influence of Slope Inclination on GMB Tensile Strains

Yu and Rowe [45] numerically examined a full-scale landfill profile with a slope inclination of 1H:1V and two 4-m wide intermediate benches below the ground surface. The foundation was competent rock and the GMB was 1.5 mm-thick [45]. The numerical results showed that the calculated maximum GMB tensile strain was 8.6% for the short-term waste settlement (Case 1) and increased to 19.8% for the long-term waste settlement (Case 2). Changing the slope inclination from 1H:1V to 2H:1V decreased the maximum GMB tensile strain from 8.6 to 4.4% for Case 1 and from 19.8 to 10.7% for Case 2. A further reduction in slope inclination to 3H:1V resulted in the maximum tensile strains of 2.0 and 2.1% for Case 1 and Case 2, respectively. Thus reducing the slope inclination had a very positive effect in terms of reducing maximum GMB tensile strains for both short-term and long-term waste settlement, and the use of a slope inclination of 3H:1V limited the maximum GMB tensile strains to acceptable design level for the conditions examined.

4 Conclusions

To ensure a long service-life of a high-density polyethylene geomembrane (GMB) exposed to leachate in a landfill, it is necessary to limit the tensile strains/stresses in the GMB to an acceptably low level. Two potential sources of strain have been considered herein; namely, (i) strains due to local GMB indentations induced by overlying coarse gravel in a leachate collection system or by gravel in an underlying compacted clay liner, and (ii) the down-drag load due to waste settlement for GMBs on side slopes. The key research related to limiting both sources of GMB strains was discussed. The findings associated with local GMB indentations induced by the gravel used in a modern leachate collection system under a 250 kPa vertical pressure (strains would be somewhat larger at higher pressures) are summarized below:

- Without a protection layer between the GMB and overlying gravel, GMBs over a compacted clay liner may experience short-term tensile strains of 16% for the 25 mm gravel and 32% for the 50 mm gravel under the short-term (10-h) physical loading conditions. These GMB strains are too large to be acceptable for landfill applications.
- Without protection and with 50 mm gravel, the maximum tensile strain of 32% for a GMB over a compacted clay liner was almost twice as high as the 17% for a GMB over a hydrated (water content 128%) geosynthetic clay liner (GCL) resting on a firm foundation.
- For GMBs over a needle-punched GCL with a geotextile protection layer, none of the geotextiles with the mass per unit area up to 2200 g/m^2 were able to reduce the short-term GMB strains to acceptable level for 50 mm gravel. The 2200 g/m^2 geotextile protection layer between the GMB and 50 mm gravel particles reduced the short-term GMB tensile strains to just below 6%.
- A multilayered geotextile with needle punched nonwoven core between two thinner and stiffer outer layers which enhanced tensile stiffness and a mass per unit area of about 1100 g/m^2 was effective in reduced the short-term GMB strains generated by

50 mm gravel to 3.9% and to 2.6% when the mass per unit area was increased to 3000 g/m^2.

- The use of a geonet as a protection layer was not acceptable since it was unable to limit the GMB strains to acceptable level, with maximum GMB strains of 13–15% being measured.
- A 150-mm thick layer of tire shreds limited the maximum GMB strains to 5.2–6.3%, and even lower to 2.3–2.8% when using a single layer of geotextile (with a mass per unit area of 570 g/m^2) was placed between the tire shreds and the GMB.
- A 150-mm-thick sand layer protection layer limited the maximum GMB tensile strain to less than 0.2%.
- The observed magnitude of GMB tensile strains was dependent on the length of sustained loading and the temperature. For a GMB without a protection layer overlain by 50-mm gravel, increasing the time of loading from 10 to 10,000 h at a temperature 55 °C increased the GMB tensile strain from 14.9 to 18.0%. An increase in temperature from 22 to 85 °C after 1000 h increased the GMB tensile strains from 13.8 to 20.5%.

For the cases and conditions examined, the key findings associated with the down-drag load for GMBs on side slopes are:

- Decreasing the slope inclination from 1H:1V to 3H:1V reduced the maximum GMB tensile strains for both short-term (e.g., immediately after landfill closure) and long-term waste settlement. For GMBs on side slopes without an axially stiff geotextile reinforcing layer above the GMB, the maximum GMB tensile strain was 8.6% for 1H:1V and decreased to 4.4% for 2H:1V and 2.0% for 3H:1V immediately after landfill closure. After long-term waste settlement, the maximum GMB tensile strains were 19.8, 10.7, and 2.1% for 1H:1V, 2H:1V, and 3H:1V, respectively. Thus, a slope inclination steeper than 3H:1V resulted in maximum GMB strains that were not acceptable for landfill applications without special measures being taken to limit the strains.
- The use of a high stiffness geotextile reinforcing layer above the GMB reduced the maximum GMB tensile strains to less than 2%. However, the geotextile itself became an engineering concern for a slope inclination 1H:1V. When using a geotextile with an axial tensile stiffness J_{gt} = 4200 kN/m, the maximum geotextile tensile strains were 5.0% for immediately after landfill closure and 9.1% after long-term waste settlement. An increase of the geotextile stiffness to J_{gt} = 8000 and 10000 kN/m resulted in a decrease of the maximum geotextile strain to 3.7 and 3.3% after landfill closure, respectively and to 6.1 and 5.3% after long-term waste settlement, respectively. Thus the maximum geotextile strains are likely too large to be acceptable when using a slope inclination of 1H:1V.
- Decreasing the slope inclination from 1H:1V to 2H:1V (with a geotextile J_{gt} = 8000 kN/m) reduced the maximum geotextile tensile strain from 3.7 to 2.5% immediately after landfill closure and from 6.1 to 3.7% after long-term waste settlement. Thus, a proper selection of the slope inclination and geotextile tensile stiffness can reduce both the GMB and geotextile strains to acceptable levels.

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