Tension in geomembranes on landfill slopes under static and earthquake loading—Centrifuge study $\stackrel{\text{transform}}{\sim}$

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Abstract

Geomembranes are some of the most commonly used geosynthetics in landfill liner systems. Geomembranes may experience harsh environmental conditions such as extreme temperatures or earthquake loading. Earthquake loading can be an extreme loading case for landfills located in seismic regions. This study, based on dynamic centrifuge testing, investigates the effects of simulated earthquake loading on the tension experienced by the geomembrane on a landfill slope. The landfill modelled in the dynamic centrifuge tests was a 7 m high municipal solid waste (MSW) landfill with a single geomembrane-clay liner system (45° side slope and 10 m slope length). Results show that moderate earthquake loading (base acceleration between 0.1 and 0.3 g) can result in a permanent increase in geomembrane tension of 5–25%.

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1. Introduction

Modern landfills have many components such as base and side liner systems, leachate collection and removal systems, gas collection and control systems and top cover systems (Rowe et al., 2004). The liner system of a landfill performs the vital task of retaining the leachate produced by the waste. The overall stability of a landfill may also be determined by the liner system. Unlike the early landfills constructed before 1980s, which only had a single clay liner, modern landfills have multilayered liner systems with geosysthetics and compacted clay. Geomembranes are some of the most commonly used geosynthetics in landfill liner systems. They are laid above the clay liner and often followed by a geonet/geotexile and granular drainage layer (Jaisi et al., 2005; Dickinson and Brachman, 2006; Junqueira et al., 2006) as shown in Fig. 1(a). Geomembranes may experience harsh environmental conditions such as extreme high and low temperatures or excessive loading in their life time (Rowe, 2005; Akpinar and Benson, 2005; Koerner and Koerner, 2006). Such harsh conditions may result in the failure of the geomembrane and the liner system.

Geomembranes placed on side slopes of a landfill can experience tension due to various factors. For example, during construction of the liner systems, wind up-lift on uncovered areas, movement of heavy vehicles such as bulldozers and frictional forces from the cover soil can all cause tension in the geomembrane. After the closure of a landfill, the down-drag caused by settling waste (Jones and Dixon, 2005) also induces tension in the geomembrane. For landfills located in seismic regions, the most critical loading to the liner system and the geomembrane may be expected during an earthquake. Earthquake loading induces tension in the geomembrane in addition to the tension it experiences from the down-drag of settling waste (Thusyanthan, 2005). Geomembranes are commonly anchored at the crest level of each bench (Fig. 1(b)), hence an increased geomembrane tension can lead to geomembrane

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Notations

- *K* earth pressure coefficient
- *K*_o earth pressure coefficient when one dimensionally consolidated*T* geomembrane tension
- *h* height of waste fill
- *n* neight of waste im

- φ slope angle
- ρ density θ mobilise
 - mobilised friction angle of model waste
- $\delta_{mU,} \delta_{U}$ mobilised and limiting interface friction angle geomembrane/waste
- δ_{mL} , δ_{L} mobilised and limiting interface friction angle geomembrane/clay



Fig. 1. (a) Typical side liner cross section of a landfill and (b) geomembrane anchored at bench levels.

slippage/failure, anchor failure or liner system instability (Hullings and Sansone, 1997). Any of these events can impair the functionality of the liner and cause leakage of leachate leading to ground water pollution or a catastrophic failure of landfill. Hence it is important to understand both the static and seismic performance of geomembranes in landfill liner systems.

The tension in the geomembrane on a landfill side slope due to down drag of waste has been studied by many researchers in the past. The limit equilibrium method was used in the early work evaluating the tension in geomembranes on landfill fill side slopes (Giroud and Beech, 1989; Koerner and Hwu, 1991). Kodikara (2000), Chia Nan Liu (2001) and Liu and Gilbert (2003, 2005) have presented analytic solutions for the tension developed in geomembranes on landfill slopes. Kanou et al. (1997) performed field tests to measure geomembrane tension due to temperature change and waste settlement. More recently, Xu et al. (2002) used centrifuge testing to determine the tension in a geomembrane and presented a modified method to evaluate the geomembrane tension due to down drag. However, they used ash as the waste material and supported the geomembrane on a wooden frame.

This paper investigates the seismic behaviour of a geomembrane on a landfill side slope using dynamic centrifuge testing. Two different scenarios were investigated:

- 1. A completed landfill with a single geomembrane-clay liner system with 45° side slope and 7 m deep waste.
- 2. A landfill cell, with a single geomembrane-clay liner system with 45° side slope, 40° waste slope and 7 m deep waste.

The landfills modelled in the dynamic centrifuge tests were municipal solid waste (MSW) landfills with prototype slope length 9.9 m. The tension in the model geomembrane was measured while the geomembrane was subjected to static loading by the weight of the model waste and by earthquake loadings of varying intensity, frequency and duration. Thusyanthan et al. (2005) presented data from the landfill cell model centrifuge test.

2. Theory

Geomembranes on landfill slopes experience tension when the frictional forces on it are unbalanced. Fig. 2 shows the static forces on a geomembrane. F_w is the downward frictional force exerted by the cover soil (or geotextile/waste) on the upper part of geomembrane and F_c is the upward frictional force exerted by the clay on the lower part of the geomembrane. Tension is experienced by the geomembrane when F_w is greater than F_c (i.e. $T = F_w - F_c$). Tension in geomembrane is a function of weight of waste above the geomembrane, mobilised upper and lower interface friction angles of geomembrane and the slope angle.

$$T = f(W, \delta_{\rm mU}, \delta_{\rm mL}, \varphi),$$

where W is vertical net force on geomembrane, δ_{mU} is the mobilised interface friction angle of geomembrane's upper surface (with cover soil, geotextile or waste) and δ_{mL} is the mobilised interface friction angle of geomembrane's lower surface (with clay), φ is slope angle. (δ_U and δ_L are limiting frictions angle of geomembrane's upper surface and lower surface, respectively).

$$T = F_{\rm w} - F_{\rm c},$$

= $W \cos \varphi \tan \delta_{\rm mU} - W \cos \varphi \tan \delta_{\rm mL}$
= $W \cos \varphi (\tan \delta_{\rm mU} - \tan \delta_{\rm mL}).$ (1)

For given vertical force W and friction angles δ_U and δ_L , we can plot the variation of tension in geomembrane with



Fig. 2. Forces acting on geomembrane placed on a landfill side slope.



Fig. 3. Tension in geomembrane vs. slope angle.

slope angle. Fig. 3 shows such a plot with δ_U equal to 25° and δ_L equal to 7°. There are three distinct regions in the plot,

- 1. *Region* (*a*): When the slope angle is less than the lower interface friction angle ($\varphi < \delta_L$), the frictional forces are balanced ($F_w = F_c$) and the geomembrane is in a state of pure shear and experience no tension.
- 2. Region (b): when the slope angle is greater than the lower interface friction angle but less than the upper interface friction angle ($\delta_{\rm L} < \varphi < \delta_{\rm U}$), the geomembrane experience shear of magnitude $F_{\rm c}$ and tension of magnitude $F_{\rm w}-F_{\rm c}$.
- 3. *Region* (*c*): when the slope angle is greater than both the lower interface friction angle and the upper interface friction angle, the frictional force on the upper surface of geomembrane has reached the limiting value. In this region friction alone is not sufficient to keep the waste on the slope. An additional force from the nearby waste is required for equilibrium.

It is evident from Fig. 3 that the anchor level tension in geomembrane, for a given load W acting on it, is maximum when the slope angle is equal to the upper interface friction

angle of the geomembrane (i.e. 25°). The limited size of the available centrifuge model container meant that it was impractical to model small slope angles. Hence in the centrifuge tests reported in this paper a slope angle of 45° will be used.

3. Centrifuge modelling of landfill components

The main difficulty associated with centrifuge modelling of landfills is the physical modelling of landfill components, mainly geomembrane, clay liner and MSW. Researchers in the past have used consolidated clay to model the compacted clay liners (Jessberger and Stone, 1991) and processed MSW to model the waste (Syllwasschy et al., 1996). The scaling laws of centrifuge modelling are given by Schofield (1980) and Taylor (1995). The following sections explain how the MSW, clay liner and the geomembrane are modelled in the centrifuge test described in this paper.

3.1. Modelling municipal solid waste

MSW is usually highly heterogeneous and variable in its content. Thus the use of real MSW in experiments raised concerns such as the dependence of test results on the source and age of the MSW and the particle size of the real MSW being large relative to the size of experimental equipment. Health and safety issues also arise in handling real MSW under laboratory conditions. It is therefore preferable to be able to perform the experiments using a model waste that can be reproduced under laboratory conditions and whose main engineering properties closely match those of real MSW. Such a model waste was developed using a mixture of peat, E-grade kaolin clay and fraction-E fine sand (Thusyanthan et al., 2004, 2006a, b) and was used in the centrifuge tests described here.

3.2. Modelling clay liner

In practice, compacted clay liners are usually constructed by compacting clay in lifts of about 150 mm to form a minimum of 0.6 m thick liner with a hydraulic conductivity of less than 1.0×10^{-9} m/s. In the present study, the compacted clay liner was modelled using a strip of consolidated kaolin clay. The model clay liner was produced using one-dimensionally consolidated E-grade kaolin clay. 100% water content kaolin slurry was one-dimensionally consolidated to an effective stress of 500 kPa in a consolidation unit. The consolidated clay has a liquid limit of 51% and plastic limit of 30% and permeability of the order of 10^{-9} m/s. The consolidated clay was then trimmed into 2 cm thick strips. A 2 cm thick layer represents a 1 m clay liner in a 50g centrifuge test. The final water content of consolidated clay was 36%.

3.3. Modelling geomembrane

High-density polyethylene (HDPE) is one of the most commonly used geomembranaes (others include linear lowdensity polyethylene (LLDPE), flexible polypropylene (FPP), polyvinyl chloride (PVC) and chlorosulphonated polyethylene (CSPE)). An actual geomembrane specimen cannot be used in centrifuge testing because the forces developed in the centrifuge model are N^2 times smaller, where $N \times q$ is the centrifugal acceleration (here N = 50). Hence, in a centrifuge test, the geomembrane has to be scaled so that it will experience the same strains as in a real landfill. Thus, a model geomembrane, which is smaller in thickness but exhibits similar stress-strain behaviour and interface frictional angles as the real geomembrane is required for centrifuge testing. The tension measured in centrifuge model is N^2 times smaller but the width of the geomembrane is also N times smaller so that the geomembrane tension per unit width measured in centrifuge model is N times smaller.

3.3.1. Matching stress-strain characteristics of real geomembranes

Tensile testing (200 mm wide-width testing) was performed on several thin HDPE sheets and a 0.1 mm thick HDPE sheet was identified as a suitable model geomembrane. This, for a 50g test, represents a 5 mm thick geomembrane in the filed. In Fig. 4 the stress-strain behaviour of the model geomembrane is compared with that of real geomembranes given by Koerner (1998). Widewidth test on model geomembrane was carried out at a strain rate of 30% per minute (upper limit of testing equipment). This high strain rate was chosen to reflect the fact that during simulated earthquake loading the model geomembrane can experience such high strain rates. It is difficult to quantify the exact strain rate in the centrifuge test. While it is clear from Fig. 4 that the model geomembrane's stress-strain behaviour does not exactly match those tested by Koerner (1998), it is within the range of stiffness exhibited by typical geomembranes for strains up to about 10%. As the strains obtained in the centrifuge tests are much less than 10%, it is considered satisfactory for the present study. Hence, the model geomembrane was used to model a typical geomembrane in the centrifuge tests.

3.3.2. Matching interface friction angle of real geomembrane

Geomembranes on landfill slopes experience tension when the friction angle with clay is less than the friction angle with the material above (geonet or geotextile). Some of the interface friction angles reported in the literature are given in Table 1. Modern liner systems are multilayered and may consist of clay liner, geomembrane, geonet, geotextile and granular soil layer. It is impractical to recreate such a complex liner system for centrifuge testing. Hence a simple liner system of model geomembrane/clay was used in the dynamic centrifuge test. The main aim in this study is to understand the tension developed in the geomembrane, so it is sufficient if the model geomembrane exhibits a typical interface friction angle with the clay liner below and the down drag force from settling waste can be transferred into the model geomembrane. The effective friction angle between interfaces from waste to geomembrane in a multi liner system can be as high as $20-30^{\circ}$ (Table 1). In order to model a realistic friction angle on the waste side, the upper surface of the model geomembrane was glued with sand. This increases the interface friction angle between the model geomembrane and model waste



Fig. 4. Stress-strain behaviour of model geomembrane (200 mm width specimen test) compared with the results reported by Koerner (1998).

(Fig. 5). The sand was glued to upper side of model geomembrane with aquarium sealant (Fig. 6(a)).

The interface friction angles of the model geomembrane with clay and model waste were tested using a modified shear box of dimensions $100 \text{ mm} \times 100 \text{ mm} \times 50 \text{ mm}$. Shear

Table 1			
Reported	interface	friction	angles

Interface	Friction angle	Source
Soil-geotextile	23-30° 25-32°	Martin et al. (1984) Tan et al. (1998)
Granular layer–geotextile Geotexile–geonet Geonet–geomembrane	29° 20° 7.6–9° 11–18° (dynamic friction)	Villard et al. (1999) Mitchell et al. (1990) Mitchell et al. (1990) De and Zimmie (1998)
Geotextile-geomembrane	6–28° 16–23° 6.6–28.1°	Martin et al. (1984) Briancon et al. (2002) Jones and Dixon (1998)
Geomembrane-clay	9° 6.8–15.8°	Villard et al. (1999) Seed and Boulanger (1991)

tests were carried out at a rate of 0.48 mm/min. Perspex block was fixed to the lower half of the shear box and geomembrane pasted on to it as shown in Fig. 6(b). The test results showed that the model geomembrane/clay interface has a peak friction angle of 7.3° and a residual friction angle of 6.3° (Fig. 7). This measured friction angle is typical of the values reported for real geomembrane/clay interface (Table 1). The interface friction angle between model geomembrane (sand glued side) and model waste was 24.9° with no discernable peak. This higher friction angle represents a realistic 'worst-case' scenario for the effective friction angle of a multi layered liner system.

3.4. Tension measuring setup

The model geomembrane is very thin (0.1 mm) to accommodate the centrifuge scaling laws. Consequently it is not possible to strain gauge the model geomembrane as the process of fixing the strain gauges will significantly alter the strength and stiffness of the geomembrane. This is Heisenberg's uncertainty principle, as the act of measuring forces in the geomembrane this way will change the tensile



Fig. 5. Landfill liner system and centrifuge model liner system.



Fig. 6. (a) Preparation of model geomembrane and (b) modified shear box with geomembrane and model waste.

forces we wish to measure. A new tensile load measuring setup, with a load cell, was developed to measure the geomembrane tension at anchor level of a landfill. In this setup, the model geomembrane is clamped by two aluminium strips and attached to a load cell as shown in Figs. 8(a) and (b). Silicon grease was applied at the clamp support/clamp interface to reduce the friction. The setup is capable of measuring up to 400 N with an accuracy of ± 0.2 N.

4. Centrifuge testing

Two centrifuge tests were performed to study the seismic performance of geomembranes on landfill slopes in two different cases

- 1. *Test IT04*: A completed landfill with a single geomembrane–clay liner system with 45° side slope and 7 m deep waste (Fig. 9).
- 2. *Test IT06*: A landfill cell, with a single geomembrane– clay liner system with 45° side slope and 40° waste slope (Fig. 10).



Fig. 7. Summary of shear box test results.

4.1. Model preparation IT04 and IT06

4.1.1. Model IT04

The schematic cross section of the centrifuge model is shown in Fig. 9. The model was prepared in a equivalent (ESB) of internal dimensions shear beam box $235 \text{ mm} \times 560 \text{ mm} \times 222 \text{ mm}$ as described in Thusvanthan (2005). The top edge of the model geomembrane was clamped and attached to a load cell as shown in Fig. 8. A metal support was used to guide the clamp in the slope direction. The model waste was placed into the landfill, on top of the model geomembrane, in layers; each layer was compacted by static load to produce a unit weight of 9 kN/m³. Linearly variable displacement transducers (LVDT) were mounted on the top of the container to measure the model waste settlement during swing up and during earthquake loading. The slope length in prototype scale is 9.9 m.

4.1.2. Model IT06

A schematic cross section of the centrifuge model is shown in Fig. 10. The model preparation was similar to model IT04 described in the above section. Firstly, fraction-E dry silica sand was air pluviated to a depth of 200 mm (relative density 45%). Accelerometers were placed at the locations shown in Fig. 10 during the sand pouring stage. The sand was then saturated with water, drained and excavated to obtain the 45° slope. The 2 cm thick clay strips were placed on the base and the side slope of the excavation. Model geomembrane was placed on top of the clay liner and attached to the clamp and the load cell. The model waste was then placed into the model in layers, creating a 40° slope. Each layer was compacted by static load to produce a unit weight of 9 kN/m^3 . Linearly variable displacement transducers (LVDT) were mounted as shown in Fig. 10 to measure the model waste settlement while the centrifuge was being accelerated, and during earthquake loading. Fig. 11 shows the model preparation sequence.

4.2. Testing procedure

Testing procedure was similar for both IT04 and IT06 tests. Completed model was loaded into the centrifuge.



Fig. 8. Tension measuring setup and comparison with real landfill anchor. (a) Schematic cross section of load measuring setup, (b) Photo of tension measuring setup.



Fig. 9. Schematic cross section of centrifuge model IT04.



Fig. 10. Schematic cross section of centrifuge model IT06.

A pre-tension of about 10 N was applied to the model geomembrane by tightening the load cell fitting. This pretension is required to remove any slag in the geomembrane and clamp attachment to load cell. The model was swung up to 50g in stages of 10g (i.e., 10, 20, 30, 40 and 50g). Load cell, LVDT and pressure cell measurements were all recorded throughout the swing up. Once the consolidation of waste had finished at 50g, earthquakes of varying intensity and magnitude were fired using the stored angular momentum (SAM) earthquake actuator, Madabhushi et al. (1998). Tables 2 and 3 provide the details of the fired model earthquakes in test IT04 and IT06, respectively. Enough time (10–20 min) was allowed between the model earthquakes for the geomembrane and instruments to reach equilibrium.

5. Tension in geomembrane due to static loading

5.1. Results from test IT04—a completed landfill

Tension in the geomembrane is measured by the load cell. However, the load cell reading is the sum of geomembrane tension plus mounting weight, both of which increase during swing up. To obtain the component due to mounting alone, a separate test (swing up 2) with no geomembrane was carried out after the end of the



Fig. 11. Centrifuge model IT06 preparation sequence.

Table 2 Simulated earthquakes in test IT04, prototype scale (model scale)

Model earthquake number	Driving frequency (Hz)	Duration (s)	Maximum base acceleration— Acc.1 (g)	Average of max. base acceleration at Acc.1 (g)
E.1	0.6 (30)	15 (0.3)	0.091 (4.55)	0.080 (4.00)
E.2	0.8 (40)	15 (0.3)	0.126 (6.30)	0.100 (5.00)
E.3	1 (50)	15 (0.3)	0.214 (10.70)	0.125 (6.25)
E.4	1 (50)	15 (0.3)	0.184 (9.20)	0.110 (5.50)
E.5	1 (50)	15 (0.3)	0.252 (12.60)	0.160 (8.00)
E.6	1 (50)	25 (0.5)	0.310 (15.50)	0.210 (10.50)
E.7	1 (50)	15 (0.3)	0.320 (16.00)	0.225 (11.25)

experiment IT04 (swing up 1). Both total and mounting forces are shown in Fig. 12. The actual geomembrane tension is the difference between the two readings. The model geomembrane experienced 49.5 N at 50g. This corresponds to a geomembrane tension of 12.35 kN/m in prototype scale (49.5 N is experienced by 0.2 m strip of model geomembrane. Therefore, tension per meter is 247.5 N and this corresponds to $247.5 \times 50^2 \text{ N}$ at prototype scale for 50 m width of geomembrane. Thus the prototype tension per unit width is 12.35 kN/m). Table 4 summaries the LVDT readings and actual tension in geomembrane during swing up.

Table 3							
Simulated	earthquake	loading in	test IT06	, prototype	scale	(model	scale)

Model earthquake number	Driving frequency (Hz)	Duration (s)	Maximum base acceleration— Acc.1 (g)	Average of max. base acceleration at Acc.1 (g)
E.1	0.6 (30)	15 (0.3)	0.065 (3.25)	0.050 (2.50)
E.2	0.8 (40)	15 (0.3)	0.122 (6.10)	0.100 (5.00)
E.3	1 (50)	15 (0.3)	0.194 (9.70)	0.125 (6.25)
E.4	1 (50)	15 (0.3)	0.160 (8.00)	0.150 (7.50)
E.5	1 (50)	15 (0.3)	0.250 (12.5)	0.190 (9.50)
E.6	1 (50)	25 (0.5)	0.246 (12.3)	0.210 (10.50)

5.2. Results from test IT06—a landfill cell

Fig. 13 shows the tension measured during the swing up of test IT06 together with the tension due to the mounting alone. Table 5 summaries the actual tension in the model geomembrane along with prototype tension and depth of landfill in IT06 swing up. The model geomembrane experienced 156.6 N at 50g. This corresponds to a stress level of 7830 kPa which is well below the yield stress of the model geomembrane (11 MPa). The tension experienced by the geomembrane at 50g (156.6 N) in the landfill cell (test IT06) is almost three times the tension measured (49.4 N) in the completed landfill model (test IT04).

5.3. Discussion

5.3.1. Comparing the tension measured with limitequilibrium prediction

The tension experienced by the model geomembrane during swing up in test IT04 and IT06 can be predicted by Limit-Equilibrium analysis of the triangular block of waste on top of the side-slope.

Fig. 14(a) shows the free-body diagrams of the triangular block of waste and the geomembrane alone with the Limit-Equilibrium equations. The Limit-Equilibrium analysis was carried out using earth pressure coefficient for waste as a variable.

Fig. 14(b) shows the predicted tension and the measured tension for test IT04. The results show that the predictions with K value of 0.4 are in good agreement with the experimental measurements. Similarly,

Fig. 14(c) shows the predicted tension (with K = 0 and 0.3) and the measured tension for test IT06. The prediction with K value of 0.3 was in good agreement with the measured tension in test IT06. In

Fig. 14(c), the predicted tension with K = 0 shows the case if no horizontal force is provided to the triangular waste block (i.e. *R* and *S* are zero in Fig. 14(a)).

It is clear from Figs. 14(b) and (c) that the coefficient of earth pressure K of the waste is an important parameter determining the tension induced in the geomembrane. The K values of 0.4 and 0.3 provided the best prediction of tension in test IT04 and IT06, respectively. In test IT04, the horizontal stress on the ESB container's side wall was measured by stress cells as shown in Fig. 9. Pressure sensor PS.5 failed to work properly in the test IT04. Fig. 15(a) shows the pressure recorded by PS.6 in swing up 1 and 2. Fig. 15(b) shows the earth pressure coefficient (K) values obtained from the PS.6 reading at each *q* level in swing up 1 and 2. During swing up 1, the model waste would be consolidating and be coming into better contact with PS.6, hence the true horizontal pressure is read by PS.6 at higher g levels. In swing up 2, the model waste has already been consolidated to 50g, thus the contact with PS.6 would be better and hence it would record the true horizontal pressures from the start. This is clear from Fig. 15(b), the K values for swing up 2 are more consistent (0.7-0.9) and close to the K values recorded at higher q levels in swing up 1. K value of the model waste near the ESB container's side wall can be taken as 0.8. Since the K value of 0.4 provided the best tension prediction in test IT04, the mobilised K value in the model waste near the side-slope is almost



Fig. 12. Tension measured during test IT04 swing up.

Table 4 Tension and waste settlement during IT04 swing up



Fig. 13. Tension measured during test IT06 swing up.

g level	Model scale settle	ments		Actual tension in model geomembrane (N)	Prototype tension (kN/m)	Prototype slope length (m)
	LVDT.1 (mm)	LVDT.2 (mm)	LVDT.3 (mm)			
1	0	0	0	10	0.05	0.2
10	1.1	0.7	0.4	11.4	0.57	1.98
20	3.5	2	1	14.4	1.44	3.96
30	6.1	3.2	1.7	24.1	3.62	5.94
40	8.7	4.5	2.5	40.6	8.12	7.92
50	11.2	5.8	3.2	49.4	12.35	9.90

g level	Model settlements		Actual tension in	Prototype tension	Prototype waste	Prototype slope
	LVDT.1 (mm)	LVDT.2 (mm)	- model geomembrane (N)	(kN/m)	height (m)	length (m)
1	0	0	10.3	0.05	0.14	0.2
10	0.4	0.75	18	0.9	1.40	1.98
20	0.9	1.7	42.7	4.3	2.80	3.96
30	2.1	3.3	79.5	11.9	4.20	5.94
40	3.7	5.1	124.7	24.9	5.60	7.92
50	5.4	7	156.6	39.1	7.00	9.90

Table 5 Tension in geomembrane during IT06 test swing up



Fig. 14. (a) Limit equilibrium analysis, (b) comparison of measured tension with limit-equilibrium prediction in IT04, and (c) comparison of measured tension with limit-equilibrium prediction in IT06.

half of that near the rigid wall of the ESB container. This may be because of the model waste has consolidated and strained more near the container wall.

In test IT06 which modelled a landfill cell, the waste is not fully filled. Therefore the horizontal pressure on the triangular waste block on the side-slope is expected to be less than that in model IT04 (i.e. lower K value). This is evident as the K value of 0.3 provided the best prediction of the tension in geomembrane. This value of K is close to the $K_{\rm o}$ value of 0.29 that can be estimated by $1 \sin \theta_{\rm crit.}$ with the $\theta_{\rm crit.}$ of waste as 45°.

The results from tests IT04 and IT06 have shown that a geomembrane on a landfill slope ($\varphi = 45^{\circ}$) can experience higher (as much as three times) tension during the cell construction stage (filling up stage) than after the completion of the landfill. The results have also shown that the

earth pressure coefficient K of the waste near the slope is an important factor that determines the tension induced in the geomembrane.



Fig. 15. (a) Stress recorded by PS.6 in swing up 1 and 2 in test IT04 and (b) K calculated at each q level.

5.3.2. Effect of slope angle on geomembrane tension at anchor level

The slope angle of a landfill is one of the factors that determine the tension experienced by the geomembrane at the anchor level. Using limit equilibrium analysis as shown in Fig. 14(a), it is possible to evaluate the variation of geomembrane tension at the anchor level with slope angle for a given depth of waste h, K, interface angles. Fig. 16 shows such a variation of geomembrane tension at anchor level with slope angle obtained by limit equilibrium analysis for the prototype scale landfill modelled in test IT04 and IT06. Fig. 16 also shows the static tension measured in test IT04 and IT06. The tensions measured in test IT04 and IT06 are well predicted by the limit equilibrium analyses. Fig. 16 shows that the geomembrane tension at anchor level, for a given bench height (Fig. 1(b)), interface friction angles (waste/geomembrane and clay/geomembrane) and a triangular waste profile (Fig. 2), is maximum when the slope angle is close to the waste/geomembrane interface friction angle. The maximum allowable tension in geomembrane at anchor level is limited by the yield strength of geomembrane. Thus, Fig. 16 can be used to obtain the two possible slope angles for a given design tension. The ultimate factor for determining the slope angle will of course depend on the soil conditions and the over all slope stability.

6. Tension in geomembrane due to earthquake loading

The load cell attached to the top ring of the ESB box experienced similar accelerations as the top soil surface during shaking (this was confirmed by the dynamic centrifuge test results). Hence the load cell experiences similar acceleration as an anchor would experience in a real landfill while measuring the tension in the geomembrane. Thus, the tension measured in the test is a realistic value that would be experienced by the geomembrane in field at anchor level during an earthquake.



Fig. 16. Variation of geomembrane tension at anchor level with slope angle.

6.1. Results from test IT04—a completed landfill

Fig. 17 shows the base excitation and the actual tension in geomembrane (corrected as described in Section 5 to eliminate tension measured due to mounting load) at prototype scale during the model earthquakes in test IT04.

Model earthquake E.1 can be associated with a new landfill experiencing an earthquake for the first time. E.2–E.7 can be associated with old landfills that can experience several earthquakes. E.1 of maximum acceleration 0.091g induced maximum additional tension of about 25% of pre-earthquake tension and a permanent additional tension of about 20% of pre-earthquake tension. Permanent increase in tension was calculated by subtracting the pre-earthquake tension from post-earthquake (after about 10 min) tension.

All model earthquakes show that both the transient and permanent tension induced in the geomembrane increases with the duration of the earthquake loading. This is confirmed by E.6, which is of longer duration than the rest of the earthquakes. Fig. 17 shows that an earthquake loading induces additional tension in the geomembrane even if it has previously experienced earthquake loading of higher magnitude (E.3 and E.4). Permanent increase in the geomembrane tension is observed in all model earthquakes. It can also be observed that there is a drop in tension between the final and initial values of consecutive earthquakes. This is a realistic behaviour present in real geomembranes as well and is attributed to creep (stress relaxation) in the geomembrane and also to creep at the interfaces. The geomembranes creep at constant stress (Berg and Bonaparte, 1993; Merry and Bray, 1997). In other words, the stress in a geomembrane deceases with time if strain is fixed.

6.2. Results from test IT06—a landfill cell

Fig. 18 shows the base excitation and the actual tension in geomembrane at prototype scale during the model earthquakes in test IT06. As with test IT04, model earthquake E.1 in test IT06 can be associated with a new landfill cell experiencing an earthquake loading for the first time while E.2-E.6 can be associated with a landfill cell experiencing multiple earthquake landings (aftershocks). Results of test IT06 show similar characteristics as the results from test IT04. Permanent increase in the geomembrane tension is observed in all simulated earthquakes. Fig. 18 shows that even a small magnitude earthquake loading (E.1) induces tension in the geomembrane. The results also show that an earthquake loading induces additional tension in the geomembrane even if it has previously experienced multiple earthquake loadings. All model earthquakes show that the tension induced in the geomembrane increases with the duration of the earthquake loading. This is supported by comparing E.6 (25s duration and 8% permanent tension increase) with E.5, which had the same peak acceleration but only lasted 15s and only produced 3% increase in permanent tension.

6.3. Discussion

6.3.1. Effect of strain rate on geomembrane tension

The stress experienced by a HDPE geomembrane depends on the applied strain rate (Merry and Bray, 1997; Wesseloo et al., 2004). HDPE consists of polymers that align when strained. This alignment of polymers requires time and it reduces the stress in HDPE. Hence, when a HDPE is stretched quickly to a given strain, it exhibits higher stiffness (and stress) as polymer alignment has not taken place fully. As the polymers in HDPE align with time, stress relaxation occurs in HDPE. If the strain is induced very slowly, the HDPE exhibits lower stiffness and stress but also lower stress relaxation.

In the present dynamic centrifuge tests IT04 and IT06, the strain rate experienced by the model geomembrane is 50 times faster than that would be experienced by a geomembrane in prototype scale. Hence, the maximum tension measured during simulated earthquake loading in the centrifuge would be an over estimate to those that would occur in the field. However, the permanent increase in tension obtained from the tests are more realistic values of real geomembrane experiencing earthquake loading. This is because; the stress in HDPE after stress relaxation would be similar to the stress if it was loaded to that strain slowly. Sufficient time was allowed between successive earthquake loading for the stress relaxation to occur. Fig. 19 summaries the tension in the geomembrane in tests IT04 and IT06 as a function of earthquake peak acceleration.

Fig. 20 summarises the earthquake-induced tension in the geomembrane as a percentage of pre-earthquake geomembrane tension in test IT04 and IT06. There is no apparent relationship between the magnitude of the base excitation and the tension induced on the geomembrane. However, it is clear that the tension induced is maximum during the earthquake loading and it decreases with time due to creep.

6.3.2. Effect of earth pressure coefficient of waste on geomembrane tension

It has been shown that earthquake loading induces additional tension in the geomembrane on the side slope of a landfill. The magnitude of the increase depends mainly on the characteristics of the earthquake loading. The ability to evaluate the magnitude of the increase in geomembrane tension is useful for side-slope and anchor designs for landfills in seismic regions. The tension in the geomembrane under static loading is mainly determined by slope angle φ , density of the waste ρ , earth pressure coefficient of waste *K*, mobilised friction angle of the waste θ , mobilised upper and lower interface friction angles (δ_{mU} and δ_{mL}) of the geomembrane and the waste profile on the slope (or the height of the waste *h*). Out of these seven parameters it is



Fig. 17. Test IT04 base excitation (acc. 1) and corresponding increase in geomembrane tension.

the earth pressure coefficient of waste 'K' that changes significantly during earthquake loading. Thus the increase in the geomembrane tension due to earthquake loading can be a direct result of the decrease in K (say from K_0 at rest towards K_a) that is caused by the earthquake loading. Therefore, a chart which reflects the effect of change in *K* on the geomembrane tension is useful for understanding the earthquake induced geomembrane tension. Fig. 21 shows such a chart for the prototype landfills tested in IT04 and IT06 with varying *K* values. The chart also shows the increase in the geomembrane tension due to E6 (magnitude $\sim 0.21g$) in tests IT04 and IT06.



Fig. 18. Test IT06 base excitation (Acc. 1) and corresponding increase in geomembrane tension.

From Fig. 21, it is clear that the increase in the geomembrane tension due to earthquake loading E.6 is equivalent to the increase that would occur when K decreases by 0.025 in both cases of prototypes IT04 and IT06. This supports the hypothesis that the decrease in earth pressure coefficient of waste K during an earthquake loading is the main cause for the increase in geomembrane

tension. Fig. 22 shows the relationship between the increase in geomembrane tension during E.2, E.3 and E.6, in both tests IT04 and IT06, and change in K that would be required to produce such an increase in tension. E.2, E.3 and E.6 had the same characteristics (magnitude and duration) in both IT06 and IT04 so they were compared whereas other earthquakes could not be compared as they



Fig. 19. Summary of results from test IT04 and IT06.



Fig. 20. Percentage increase in geomembrane tension vs. base acceleration (a) IT04 and (b) IT06.

were of different magnitude in tests IT06 and IT04. In the earthquakes loadings E.2, E.3 and E.6 in tests IT04 and IT06, which had similar magnitude and duration, the change in K that was required to predict the increase in geomembrane tension was equal. This suggests that the

change in K due to earthquake loading depends only on the characteristics of the earthquake and not on the preearthquake K value of the waste. If the decrease in K in waste due to an earthquake loading is known then the increase in geomembrane tension can be predicted. Further



Fig. 21. Effect of K and earthquake loading on geomembrane tension for IT04 and IT06 landfill.



Fig. 22. Comparison of measured geomembrane tension with prediction based on earth pressure coefficient K.

research in this area is needed to confirm the findings in this study.

The line of K equals 0.17 in Fig. 21 represents the upper limit on the geomembrane tension, as this line represents the maximum force that can be transferred to the geomembrane by the waste when the triangular block of waste on the slope is experiencing active pressures $(K_a = 0.17$ for waste with friction angle $\theta = 45^\circ$). The main design concern on the upper limit on the geomembrane may come from the yield strength of the geomembrane and for the model geomembrane used in the present study was 55 kN/m as shown in Fig. 21.

A chart such as Fig. 21 for a project-specific landfill will be helpful for evaluating increase in geomembrane tension due to earthquake loading and for design/analysis of anchor and side-slopes of a landfill in seismic region. This figure shows that for the landfills analysed in this study (IT04 and IT06) the maximum increase in geomembrane tension for any given earthquake loading would occur when the slope angle is about 27° .

7. Conclusions

The physical modelling techniques required for centrifuge testing of a geomembrane on MSW landfills side slopes has been presented in this paper. A tension measuring setup has been designed and calibrated to accurately measure the tension developed in a model geomembrane on the side slope in a centrifuge landfill model. This setup is attached to the top ring of the ESB model container that experiences similar acceleration as the surface soil during model earthquake loading. Hence the measurement from this setup is a realistic value of geomembrane tension at anchor level during an earthquake.

Tension experienced by geomembranes on side slopes of a landfill depends on many factors such as friction angle of waste, interface friction angles, earth pressure coefficient of waste, slope angle, the weight of the waste above the slope and the waste profile above the slope. Limit equilibrium analysis with slope angle as the only variable shows that the tension in geomembrane is maximum when the slope angle near the upper interface friction angle of the geomembrane. Yield strength of the geomembrane will limit the possible slope angles when all the other factors are fixed.

Tension measured in the model geomembrane when subjected to model earthquakes of varying intensity and duration showed that

Earthquake loading induces additional permanent tension in the geomembrane. For the case of

- 1. A completed landfill (test IT04): for an earthquake loading of 0.08g and 15s duration at the foundation level, the tension in the side slope geomembrane (slope angle 45° and slope length ~10 m) can increase up to 25% of the pre-earthquake value during the earthquake loading and have a permanent increase of 15% of preearthquake value. For earthquake loading of higher intensity, such as 0.2–0.3g at the foundation level, the tension in the geomembrane can increase up to 40% of the pre-earthquake value during the earthquake loading and have a permanent increase of up to 25% of preearthquake value.
- 2. A landfill cell (test IT06): For an earthquake loading of 0.05-0.2g at the foundation level, on average the tension in the side slope geomembrane (slope angle 45° and slope length ~ 10 m) can increase to a maximum about 10% of pre-earthquake tension and have a permanent increase in tension of about 5% of pre-earthquake tension.

In addition, it was observed that permanent tension developed in the geomembrane increases with the duration

of the earthquake loading (for example E.6 and E.7 in Fig. 17, E.6 in Fig. 18). The results (E.2–E.7 in Fig. 17, E.2–E.6 in Fig. 18) also showed that earthquake loading induces additional tension in the side-slope geomembrane even if the landfill has previously experienced higher magnitude earthquake loadings).

Centrifuge modelling and dynamic centrifuge testing has been shown to be an effective tool to evaluate the tension developed in a geomembrane placed on a landfill slope. It can be concluded from this study that earthquake loading induces permanent additional tension in the geomembrane on landfill side-slopes and that the magnitude of the induced tension depends on many factors such as slope angle, earthquake intensity and duration of the earthquake both of which causes K to decrease. Site-specific studies can be undertaken using the techniques outlined in this paper to investigate the increase in geomembrane tension during earthquake loading and/or to determine the seismic vulnerability of a geomembrane liner system of a landfill.

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References

- Akpinar, M.V., Benson, C.H., 2005. Effect of temperature on shear strength of two geomembrane—geotextile interfaces. Geotextiles and Geomembranes 23 (5), 443–453.
- Berg, R.P., Bonaparte, R., 1993. Long-term allowable tensile stress for polyethylene geomembranes. Geotextiles and Geomembranes 12, 287–306.
- Briancon, L., Girard, H., Poulain, D., 2002. Slope stability of lining systems—experimental modeling of friction at geosynthetic interfaces. Geotextiles and Geomembranes 20, 147–172.
- De, A., Zimmie, T.F., 1998. Estimation of dynamic interfacial properties of geosynthetics. Geosynthetics International 5 (1&2), 17–39.
- Dickinson, S., Brachman, R.W.I., 2006. Deformations of a geosynthetic clay liner beneath a geomembrane wrinkle and coarse gravel 24(5), 285–298.
- Giroud, J.P., Beech, J.F., 1989. Stability of soil layers on geosynthetic lining systems. In: Proceedings of Conference Geosynthetics 1989, IFAI, San Diego, CA, USA, pp. 35–46.
- Hullings, D.E., Sansone, L.J., 1997. Design concerns and performance of geomembrane anchor trenches. Geotextiles and Geomembranes 15, 403–417.
- Jaisi, D.P., Glawe, U., Bergado, D.T., 2005. Hydraulic behaviour of geosynthetic and granular landfill drainage materials in the Sa Kaeo landfill, Thailand. Geotextiles and Geomembranes 23 (3), 185–204.
- Jessberger, H.L., Stone, K.J.L., 1991. Subsidence effects on clay barriers. Geotechnique 41 (2), 185–194.

- Jones, D.R.V., Dixon, N., 1998. Shear strength properties of geomembrane/geotextile interfaces. Geotextiles and Geomembranes 16, 45–71.
- Jones, D.R.V., Dixon, N., 2005. Landfill lining stability and integrity: the role of waste settlement. Geotextiles and Geomembranes 23 (1), 27–55.
- Junqueira, F.F., Silva, A.R.L., Palmeira, E.M., 2006. Performance of drainage systems incorporating geosynthetics and their effect on leachate properties. Geotextiles and Geomembranes 24 (5), 311–324.
- Kanou, H., Doi, Y., Imaizumi, S., Tsuboi, M., 1997. Evaluation of geomembrane stress on side slope caused by settlement of wastes. In: Proceedings Sarinia 97, Sixth International Landfill Symposium, Italy, pp. 525–534.
- Kodikara, J., 2000. Analysis of tension development in geomembranes placed on landfill slopes. Geotextiles and Geomembranes 18, 47–61.
- Koerner, R.M., 1998. Designing with Geosynthetics, fourth ed. Prentice-Hall, Upper Saddle River, NJ.
- Koerner, R.M., Hwu, B.L., 1991. Stability and tension considerations regarding cover soild on geomembrane lined slopes. Geotextiles and Geomembranes 10, 335–355.
- Koerner, G.R., Koerner, R.M., 2006. Long term temperature monitoring of geomembranes at dry and wet landfills. Geotextiles and Geomembranes 24 (1), 72–77.
- Liu, C.N., 2001. Tension of geosynthetic material regarding soils on landfill liner slopes. In: Proceedings of National Science Council, Republic of China, vol. 25, no. 4, pp. 211–218. http://nr.stic.gov.tw/ ejournal/ProceedingA/proceedings_a_e.htm>.
- Liu, C.N., Gilbert, R.B., 2003. Simplified method for estimating geosynthetic loads in landfill liner side slopes during filling. Geosynthetics International 10 (1), 24–33.
- Liu, C.N., Gilbert, R.B., 2005. Graphical solution for estimating geosynthetic load in geosynthetic-soil layered systems on slopes. Geosynthetics International 12 (4), 208–214.
- Madabhushi, G.P.S., Schofield, A.N., Lesley, S., 1998. A new stored angular momentum based actuator. In: Kimura, T., Kusakabe, O., Takemura, J. (Eds.), International Conference on Centrifuge 98, IS-Tokyo '98, Proceedings. A.A. Balkema, Rotterdam.
- Martin, J.P., Koerner, R.M., Whitty, J.E., 1984. Experimental friction evaluation of slippage between geomembranes, geotextiles and soils. In: Proceedings of International conference on Geomembranes, IFAI, Denver, CO, pp. 191–196.
- Merry, S.C., Bray, J.D., 1997. Time-dependent mechanical response of HDPE geomembranes. Journal of Geotechnical and Geoenvironmental Engineering 123 (1), 57–65.
- Mitchell, J.K., Seed, R.B., Seed, H.B., 1990. Kittleman hills waste landfill slope failure-I. Liner-system properties. Journal of Geotechnical Engineering 116 (4), 647–668.
- Rowe, R.K., 2005. Long-term performance of contaminant barrier systems, 45th Rankine Lecture. Geotechnique 55 (9), 631–678.
- Rowe, R.K., Quigley, R.M., Brachman, R.W.I., Booker, J.R., 2004. Barrier Systems for Waste Disposal Facilities. Taylor and Francis Books Ltd. (E&FN Spon.), London, 587pp.
- Schofield, A.N., 1980. Cambridge geotechnical centrifuge operations. Geotechnique 30 (3), 227–268.
- Seed, R.B., Boulanger, R.W., 1991. Smooth HDPE-clay liner interface shear strengths:compaction effects. Journal of Geotechnical Engineering 117 (4), 686–693.
- Syllwasschy, O., König, D., Jessberger, H.L., 1996. Centrifuge model tests on leachate collection shafts in landfills. International congress on environmental geotechnics, 1, IS-Osaka '96, Osaka, vol. 2, pp. 673–678.
- Tan, S.A., Chew, S.H., Wong, W.K., 1998. Sand-geotexile interface shear strangth by torsional ring shear tests. Geotextiles and Geomembranes 16, 161–174.
- Thusyanthan, N.I., 2005. Behaviour of landfill systems under monotonic and earthquake loadings. Ph.D. Thesis, University of Cambridge, UK.
- Thusyanthan, N.I., Madabhushi, S.P.G., Singh, S., 2004. Modelling the seismic behaviour of municipal solid waste. In: Eleventh International

Conference on Soil Dynamics and Earthquake Engineering, Berkeley, USA.

- Thusyanthan, N.I., Madabhushi, S.P.G., Singh, S., 2005. Seismic performance of geomembrane placed on a slope in a MSW landfill cell—a centrifuge study. In: Proceedings of ASCE *Geo-Frontiers 2005*, 2005, Austin, TX, USA, 12pp.
- Thusyanthan, N.I., Madabhushi, S.P.G., Singh, S., 2006a. Centrifuge modeling of solid waste landfill systems—part 1: development of a model municipal solid waste. ASTM Geotechnical Testing Journal 29 (3), 217–222.
- Thusyanthan, N.I., Madabhushi, S.P.G., Singh, S., 2006b. Centrifuge modeling of solid waste landfill systems—part 2: centrifuge testing of model waste. ASTM Geotechnical Testing Journal 29 (3), 223–229.

- Taylor, R.N., 1995. Geotechnical Centrifuge Technology. Blackie academic and Professional.
- Villard, P., Gourc, J.P., Feri, N., 1999. Analysis of geosynthetic lining systems (GLS) undergoing large deformations. Geotextiles and Geomembranes 17, 17–32.
- Wesseloo, J., Visser, A.T., Rust, E., 2004. A mathematical model for the strain rate dependent stress–strain response of HDPE geomembranes. Geotextiles and Geomembranes 22 (4), 273–295.
- Xu, S., Imaizumi, S., Doi, Y., 2002. Centrifuge model tests to determine the tensile force of geotextile and geomembrane used on the side slope of a waste landfill. In: Proceedings of the Seventh International Conference on Geosynthetics, 7 ICG-NICE 2002, Balkema, vol. 2, pp. 699–702.