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Tension in geomembranes placed on landfill slopes under static and dynamic loading

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Abstract: Geomembranes placed on side slopes of a landfill experience tension as the settling waste induces down-drag. During the lifetime of a landfill, dynamic loading such as an earthquake may also induce additional tension on the geomembrane. Tension in the geomembranes determines the long-term performance of the liner system. It may also result in the failure of geomembranes leading to ground water contamination and other geo-environmental disasters. Hence it is important to be able to evaluate the tension in geomembranes under static and dynamic loading. This paper presents results from a centrifuge test carried out at 50 times earth-gravities, in which the tension in model geomembrane placed on landfill slope under static and dynamic loading was measured. The landfill modeled in the centrifuge test was a municipal solid waste (MSW) landfill with a single geomembrane and clay liner with a 1:1 side slope.

Keywords: Landfills; Geomembrane; Tension; Centrifuge testing

Introduction

Geomembranes are commonly used in landfill liner systems to retain the leachate produced by the waste and to prevent the leachate from entering ground water. Geomembranes placed on side slopes of a landfill can experience tension due to various factors. For example, shrinkage due to low temperature, wind up-lift on uncovered areas, movement of heavy vehicles such as bulldozers, frictional forces of cover soil or waste and down-drag caused by settling waste can all cause tension in the geomembrane. During the lifetime of a landfill, dynamic loading such as an earthquake may also induce additional tension on the geomembrane. Tension in the geomembranes determines the long-term performance of the liner system. It may also result in the failure of geomembranes leading to ground water contamination and other geo-environmental disasters. Hence it is important to be able to evaluate the tension in geomembranes under static and dynamic loading.

The limit equilibrium method was used in the early work on evaluating the tension on geomembranes on landfill fill side slopes (Giroud and Beech, 1989; Koerner and Hwu, 1991). Kodikara (2000) presented analytic solutions for the tension developed on geomembranes on landfill slopes. Kanou et al. (1997) performed field tests on the tension developed on geomembranes on side slopes 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 determine the tension induced by settling ash.

This paper presents the modeling of landfill components, such as geomembrane and MSW, and the results from a centrifuge test carried out at 50 time earth-gravities, in which the tension in a model geomembrane placed on landfill slope under static and dynamic loading was measured. The centrifuge experiment was performed in the 10m beam centrifuge of Schofield Centre, Cambridge,UK. The landfill modeled in the centrifuge test was a municipal solid waste (MSW) landfill with a single geomembrane-clay liner with a 1:1 side slope.

Centrifuge Modeling Technique

The Centrifuge modeling technique has been used successfully in many geotechnical studies in the past. The technique allows experiments on reduced scale models to be carried out at prototypes stresses, which is vital in modeling the non-linear stress-strain behavior of the soil, (Schofield, 1980, 1981). The prototype stresses are recreated in the model by performing the experiment in enhanced gravity in a geotechnical centrifuge. Over the years, the use of centrifuge modeling has increased vastly and is applied for various studies from embankment stability to underground construction.

Table 1- Scaling laws for centrifuge modeling.

Parameter	Model	Prototype
Length	1/N	N
Acceleration	N	N
Velocity	1	1
Force	1	N^2
Strain	1	1
Stress	1	1
Mass	1	N^3
Time(dynamic)	1	N

The technique of dynamic centrifuge modeling has also been established as a powerful tool to study the behavior of various geotechnical structures subjected to earthquakes. In dynamic centrifuge modeling the model has to be subjected to lateral shaking in-flight, to simulate the earthquake while the centrifuge is spinning. At Cambridge University, a new Stored Angular Momentum (SAM) based earthquake actuator was developed for use on the 10 m beam centrifuge, Madabhushi et al (1998). This new actuator is currently being used successfully to study a wide variety of earthquake problems, for example, behavior of rock-fill dams and gravel embankments on liquefiable foundations, Madabhushi et al (1996). The scaling laws involved in centrifuge modeling is given in Table. 1.

Centrifuge modeling of landfill components

The main difficulty associated with centrifuge modeling of landfills is the physical modeling 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 MSW (Syllwasschy and Jessberger, 1998). The following sections explain how the geomembrane, clay liner and MSW are modeled in the performed centrifuge test.

Municipal Solid Waste (MSW)

MSW is usually highly heterogeneous and variable in its content. Thus the use of real MSW in experiments has many concerns such as the dependence of test results on the source and age of the MSW and hence the question of repeatability, 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 properties closely match those of real MSW.

A model waste, whose mechanical properties closely match to those of a typical MSW, was developed using a mixture of peat, E-grade kaolin clay and fraction-E fine sand (Fig. 2). Preliminary development involved producing 3 mixtures (A, B & C) . The ratio of peat : clay : sand by weight in mixtures A, B and C were 2:1:1, 1:1:1 and 1:2:1 respectively. Unit weight, compressibility and shear strength characteristics of the model waste were experimentally determined and shown to match well with those of a typical MSW (Thusyanthan et al. 2004). Even though all three mixtures have the potential to be used as model MSW, mixture B was chosen as the most suitable model MSW due to ease of handling and consistency

Clay liner

In practice, compacted clay liners are constructed by compacting clay in lifts of 150 mm to form a minimum of 0.6 m (2 foot) 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. This clay has a liquid limit of 51 % and plastic limit of 30 % and permeability of the order of 10-9 m/s. 100 % water content kaolin slurry was one-dimensionally consolidated to an effective stress of 500 kPa in a consolidation unit. The water content of consolidated clay was 36 %. The consolidated clay was trimmed into 2 cm thickness strips. Such a 2 cm thickness layer would represent a 1 m clay liner at 50g.

Geomembrane

Geomembranes are one of the most commonly used geosynthetics in landfill liner systems. There are many different geomembranes in use today, most widely used one being High Density Polyethylene (HDPE) and others include Liner low-density polyethylene (LLDPE), flexible polypropylene (FPP), polyvinyl cholide (PVC) and chlorosulphonated polyethylene (CSPE).

Real geomembranes cannot be used in centrifuge testing because the forces developed in the centrifuge model is N^2 times smaller hence geomembranes will not experience the same strains as in a real landfill. Thus a model geomembrane, which is smaller in thickness but exhibits similar stress-strain behavior as the real geomembrane, is required for centrifuge testing.

200mm wide specimen tensile testing was performed on several thin HDPE sheets and a 0.1mm thickness HDPE sheet was identified as a suitable model geomembrane. Stress-strain behavior of the model geomembrane is compared with that of real geomembranes given by Koerner (1998). It can be seen that the model geomembrane compares well up to a strain of 10%. This is considered satisfactory as the centrifuge tests will not lead to geomembranes strains larger than this value of strain.

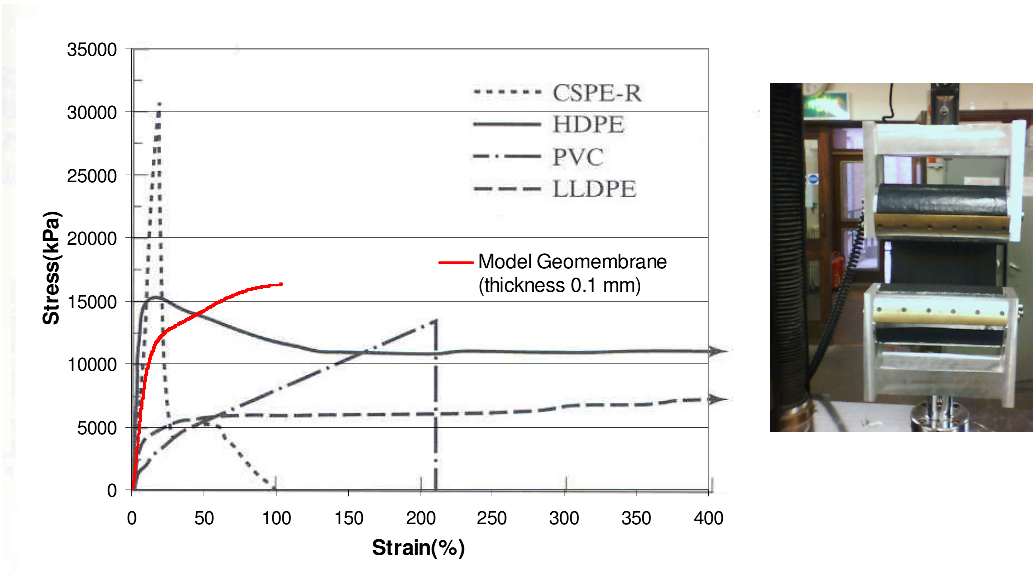


Figure 1.Stress-strain behavior of Geomembarne (200mm width specimen test)- modified from Koerner 1998)

Friction angle of Geomembrane/MSW and Geomembrane/Clay liner

Fraction E sand was pasted on the upper side of the model geomembrane to increase its friction with the model waste. A modified shear box (100mm x 100mm x 50mm) was used to test the interface friction angles between model geomembrane/model waste (24.9°) and model geomembrane(sand pasted side)/clay (peak-7.26°).Model waste has a friction angle of 45°.

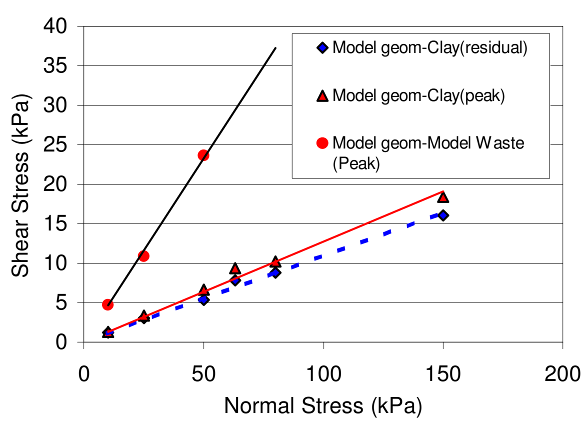


Figure 2:- Interface friction between model geomembrane/waste and model geomembrane/clay

Tensile measurement in geomembrane

The model geomembrane is very thin 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 of the geomembrane. This is similar to Heisenberg's uncertainty principle, as the act of measuring forces in the geomembrane will change the tensile forces we wish to measure. As a result, a new tension measuring setup, with a load cell, is developed. In this setup, the model geomembrane is clamped by two aluminum strips and attached to a load cell as shown in Fig. 7 & 8. Proof test were done at 50g on the tension measuring setup to calibrate and validate the measurements. The setup is capable of measuring up to 400N with an accuracy of ± 0.2N.

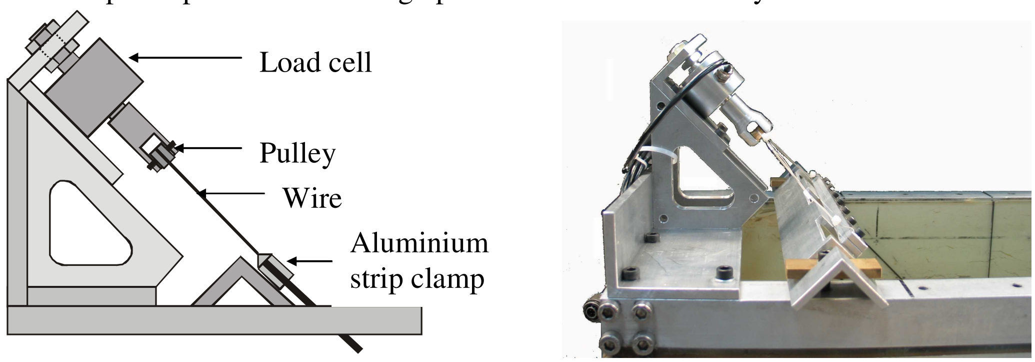


Figure 3- Load cell setup to measure tension in model geomembrane

Centrifuge experiment setup

The centrifuge model is shown in fig.The model was prepared in stages. Firstly fraction-E dry silica sand was air pulviarised to a 200 mm. Accelerometers were placed at the locations shown in Fig. 4 during sand pouring stage. The rate of pouring and the height of drop were selected to obtain a relative density of 45%. The sand was then saturated by the upward percolation of water through drainage holes near the base of the box. Once the sand was fully saturated, water was allowed to drain under gravity. The suction created by this process in sand allowed the subsequent excavation of the sand to obtain the required bottom profile of the landfill. The sand was carefully excavated to obtain a side slope of 45°. The 2 cm clay liner strips, which were trimmed from one-dimensional consolidated clay, were placed on both the excavated bottom surface and the side slope. Accelerometers were placed at the bottom and side liners. The model waste was then placed into the landfill in layers; each layer was compacted by static load to produce a unit weight of 9 kN/m^3. Linearly variable displacement transducers (LVDT) were mounted on the top of the container to measure the model waste settlement during the swing up and during the test.

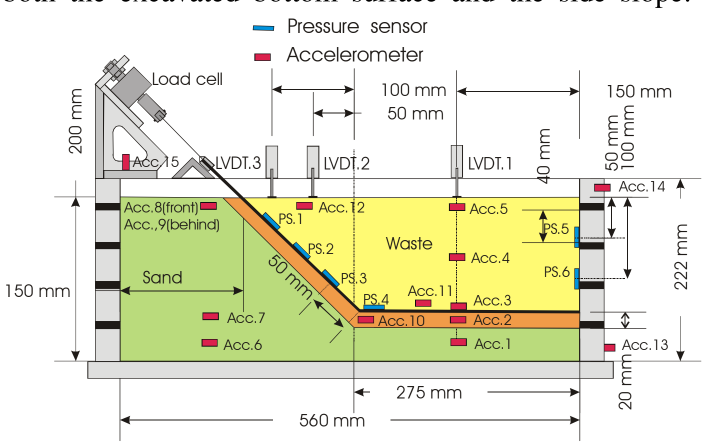


Figure 4- Cross section of centrifuge model in Equivalent Shear-Beam box (ESB box).

Test procedure

Completed model was loaded into the centrifuge. A pre-tension of about 10N was applied to the model geomembrane by tightening the load cell fitting. This pretension is required to remove any slag in the geomembrane and clap attachment to load cell. The model was swung up to 50g in stages of 10g (i.e. 10g, 20g, 30g, 40g and 50g). Load cell, LVDT and pressure cell measurements were all recorded throughout. Once the consolidation of waste had finished at 50g, earthquakes of varying intensity and magnitude were fired using the stored angular momentum earthquake actuator. Table 1 provides the details of the fired earthquakes in prototype scale. Enough time (10 to 20 minutes) was allowed in-between the earthquakes for the geomembrane and instruments to reach equilibrium. All dynamic data was recorded at 4 kHz.

Table 2. Earthquakes applied in the test. Prototype scale[model scale]

Earthquake Number	Frequency (Hz)	Duration (s)	Maximum base acceleration-Acc.1(g)
EQ.1	0.6 [30]	15 [0.3]	0.091[ ]
EQ.2	0.8 [40]	15 [0.3]	0.126
EQ.3	1 [50]	15 [0.3]	0.214
EQ.4	1 [50]	15 [0.3]	0.184
EQ.5	1 [50]	15 [0.3]	0.252
EQ.6	1 [50]	25 [0.5]	0.310
EQ.7	1 [50]	15 [0.3]	0.320

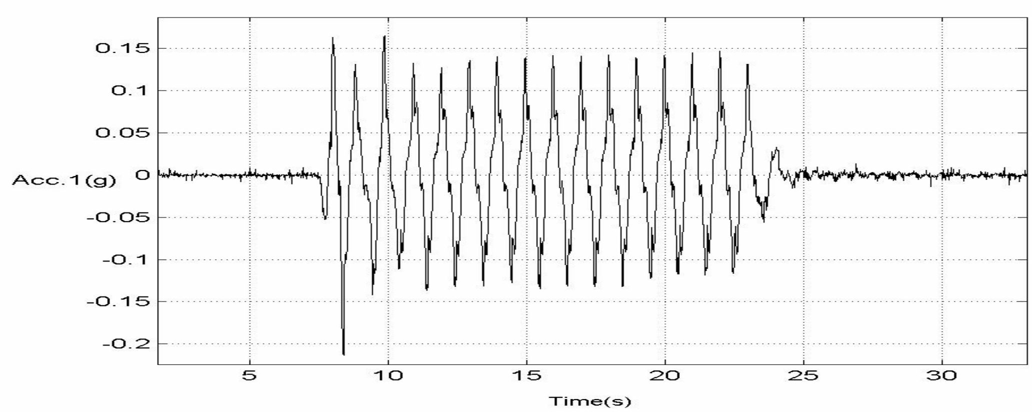


Figure 5- Typical input acceleration:- Acc.1 in EQ.3

Results

Due to the limitation in page, only the tension measurements are presented in this paper. Results are presented in two sections; tension in geomembrane during static loading (i.e as model waste settles during swingup- increasing gravity to 50g in 10g steps), tension in geomembrane during earthquake loading.

Tension in geomembrane during static loading (swingup)

Fig.6 shows the tension measurement of the geomembrane during the swingup (i.e when gravity is increased from 1g to 50g). The load cell readings due to mounting weights (clamp, wire etc..) is also shown in Fig.6 (obtained in a separate swingup). The load cell reading due to the weight of mountings was obtained by swinging up the load cell setup without the geomembrane to 50g at 10g steps. Hence the difference in the readings is the actual tension in the geomembrane.

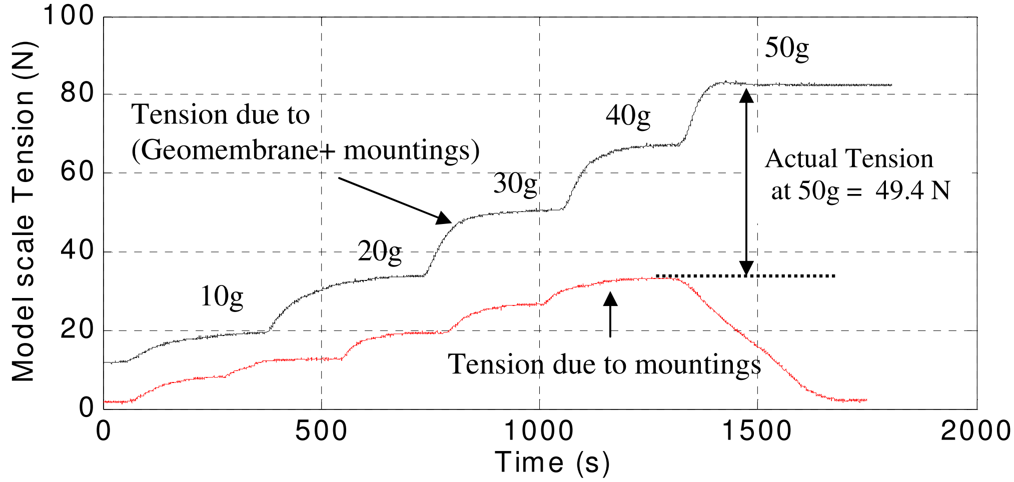
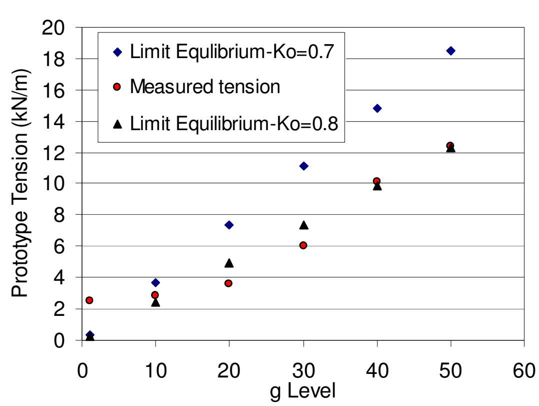
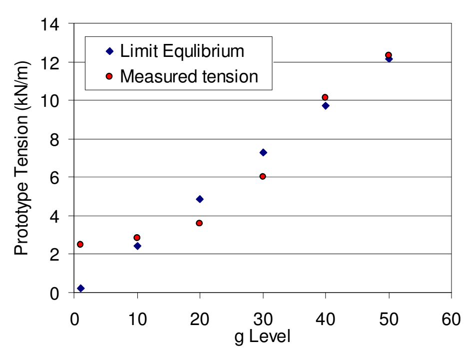


Figure 6- Tension measurements during 2 swing ups (Gomembrane and mountings, mountings alone)
Note:- measurements in model scale

Table 3. ***Tension in geomembrane at different g levels***

g Level	LVDT. 1 (mm)	LVDT. 2 (mm)	LVDT. 3 (mm)	Tension in model geoemembrane (width 0.2m)	Tension in model geoemembrane (N/m)	Tension (kN/m-Prototype scale)
1g	0	0	0	10	50	2.500
10g	1.1	0.7	0.4	11.4	57	2.850
20g	3.5	2	1	14.4	72	3.600
30g	6.1	3.2	1.7	24.1	120.5	6.025
40g	8.7	4.5	2.5	40.6	203	10.150
50g	11.2	5.8	3.2	49.4	247	12.350





equilibrium

Figure 7- Measured and calculation tension in the model geomembrane

Tension in geoemembrane during earthquake loading

Fig.8 shows the tension measured during each of the applied model earthquakes. The tension is given in prototype scale. This measured tension is a realistic value that would be experienced by the geomembrane at anchor level in a real landfill. This is because the base of the load cell is attached to the top ring of the ESB box that experience similar acceleration as the top soil surface.

Earthquake.1 (EQ.1) of magnitude 0.091g induced about 25% increase in the maximum tension and 20% increase in permanent tension in the geomembrane. Information from EQ.1 can be associated with a new landfill experiencing an earthquake for the first time. Information from EQ.2 to EQ.7 can be associated with old landfills that can experience several earthquakes of increasing magnitude.

All earthquakes show that the tension induced on the geomembrane increases with the duration of the earthquake loading. This is confirmed by EQ.6 which is of longer duration than the rest of the earthquakes.

Fig. 8 shows that an earthquake loading induces additional tension in the geomembrane even if it has previously experienced earthquake loading and higher tensions.

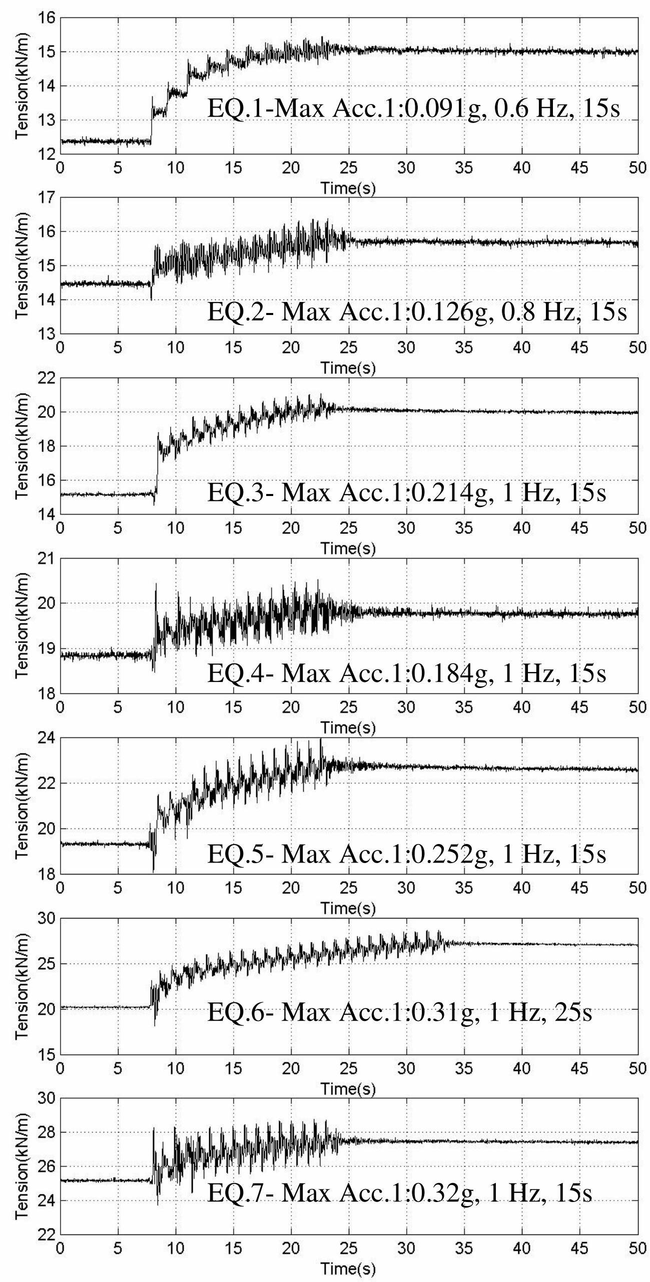


Figure 8- Tension in model geomembrane during earthquake. (prototype scale)

The drop in tension between the final and initial values of consecutive earthquakes is due to the creeping of the model geomembrane. This is a realistic behavior present in real geomembranes as well.

Fig.9 summaries the prototype tension in the geomembrane as measured in the centrifuge test.

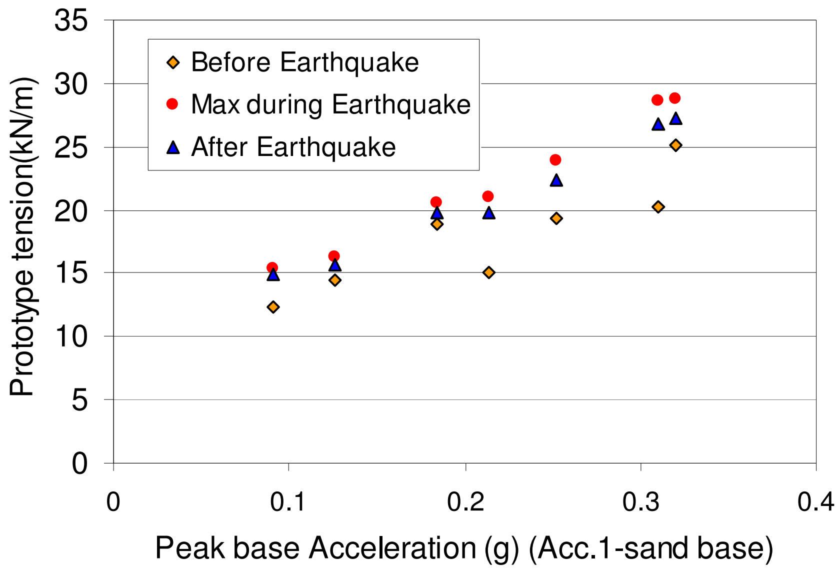


Figure 9- Tension in geomembrane during earthquake loading

Conclusions

The physical modeling required for centrifuge testing of MSW landfills has been presented in this paper. A tension measuring setup has been designed and calibrated to measure the tension developed in a model geomembrane placed on the side slope in a centrifuge model.

Tension in a model geomembrane under static and dynamic loading was measured at 50 earth gravities. Tension experienced by the model geomembrane under static loading was predicted well by the Limit-equilibrium method. Tension measured in the model geomembrane during model earthquakes of varying intensity and duration showed that;

- For an earthquake loading of 0.09g and 15s duration at the foundation level, the tension in the geomembrane can increase up to 25% of the pre-earthquake value during the earthquake loading and have a permanent increase of 20% of pre-earthquake value (Fig.7 and Fig.8, EQ.1).
- For earthquake loadings of higher intensity 0.2g to 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 30% of pre-earthquake value(Fig.7 and Fig.8).
- Maximum and permanent tension developed in the geomembrane directly increases with the duration of the earthquake loading (Fig.8, EQ.6 and EQ.8)
- Earthquake loading induces additional tension in the side-slope geomembrane even if the landfill has previously experienced earthquake loadings (Fig.8, EQ.2 to EQ.7).

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