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Seismic Performance of Geomembrane placed on a Slope in a MSW Landfill Cell -A Centrifuge study

by

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Abstract

Geomembranes are one of the most commonly used geosynthetics in landfill liner systems. They retain the leachate produced by the waste and prevent leakage. 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 modeled in the dynamic centrifuge test was a municipal solid waste (MSW) landfill cell with a single geomembrane-clay liner system (45° side slope and 10 m slope length). The paper shows that moderate earthquake loading (base acceleration between 0.1g to 0.2g) can result in transient increases of around 20% in geomembrane tension, with permanent tension increases of around 5%.

Introduction

Every year, countries all over the world deal with the disposal of millions of tons of municipal solid waste (MSW). Landfilling is one of the most common and cheapest options for disposal of waste. Hence there are thousands of landfills across the world. 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. 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, which only had a clay liner, modern landfills have multilayered liner systems with geosysthetics and compacted clay. Geomembranes are one 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 (coarse sand or gravel) as shown in Fig.1a. Geomembranes may experience harsh environmental conditions such as extreme high and low temperatures or excessive loading. Such harsh conditions may result in the failure of the geomembrane and the liner system.

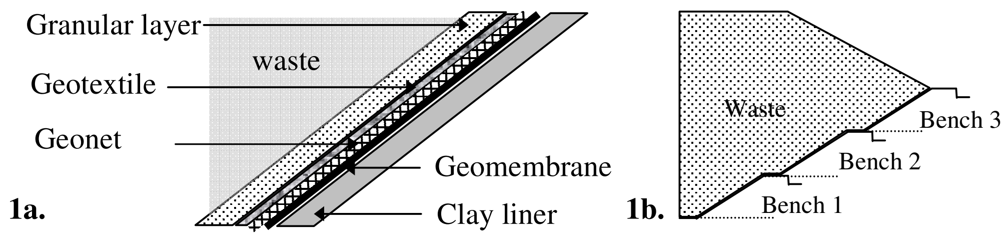


Figure 1a.Typical side liner cross section of a landfill, 1b. Geomembrane anchored at bench levels

Loading on geomembranes can be caused by many 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 also induces tension in the geomembrane. For landfills located in seismic regions, the most critical loading to the liner system and 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. Geomembranes are commonly anchored at the crest level of each bench (Fig.1b), hence an increased geomembrane tension can lead to geomembrane 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 and ground water pollution or a catastrophic failure of landfill. Hence it is important to understand the 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) and Chia Nan Liu (2001) 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.

This study, using dynamic centrifuge testing, investigates the seismic behaviour of a geomembrane on a landfill side slope. The landfill modeled in the dynamic centrifuge test was a municipal solid waste (MSW) landfill cell with a single geomembrane-clay liner system with 45° side slope and 40° waste slope. The prototype slope length was 9.9 m and the height of the landfill was 7 m. The dynamic centrifuge tests were carried out at 50 times earth's gravity on the 10 m diameter beam centrifuge at the Schofield centre (Schofield, 1980), Cambridge University, UK. The tension in the model geomembrane was measured while the landfill model was subjected to six simulated base excitations of varying intensity as described in section 3.

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 the waste (Syllwasschy et al., 1996). The scaling laws of centrifuge modeling are given by Schofield (1980) and Taylor (1995). The following sections explain how the MSW, clay liner and the geomembrane are modeled in the centrifuge test described in this paper.

Modeling Municipal Solid Waste (MSW)

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) and was used in the centrifuge test.

Modeling Clay Liner

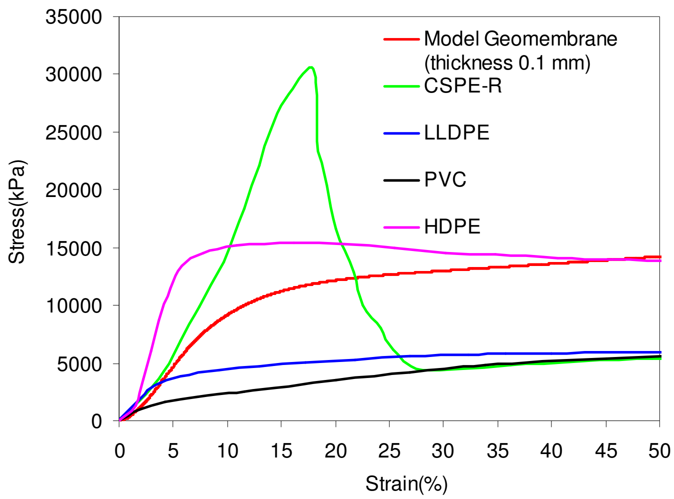
In practice, compacted clay liners are usually constructed by compacting clay in lifts of 150 mm to form a minimum of 0.6 m thick liner with a hydraulic conductivity of less than 1.0×10^{-9} m/s. In the present study, the compacted clay liner was modeled using a strip of consolidated kaolin clay. The 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 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%.

Modeling Geomembrane

Geomembranes are one of the most commonly used geosynthetics in the landfill liner systems. There are many different geomembranes in use today, most widely used one being High Density Polyethylene (HDPE), Others include Linear Low-Density Polyethylene (LLDPE), Flexible Polypropylene (FPP), Polyvinyl Chloride (PVC) and Chlorosulphonated Polyethylene (CSPE). Actual geomembrane specimen cannot be used in centrifuge testing because the forces developed in the centrifuge model are N^2 times smaller, where $N \times g$ is the centrifugal acceleration (here N=50). Hence, in centrifuge test, 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 and interface frictional angles as the real geomembrane is required for centrifuge testing.

Matching stress-strain characteristics of real geomembrane

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. In Fig.2 the stress-strain behaviour of the model geomembrane is compared with that of real geomembranes given by Koerner (1998). Wide-width 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.2 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. Hence, the model geomembrane can be used to model a typical geomembrane. This is considered satisfactory for the present study.



Wide-width strip testing of model geomembrane

Figure 2. Stress-strain behaviour of model geomembrane (200mm width specimen test)- compared with results reported by Koerner (1998)

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 consisting 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 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° to 30° (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. 3).

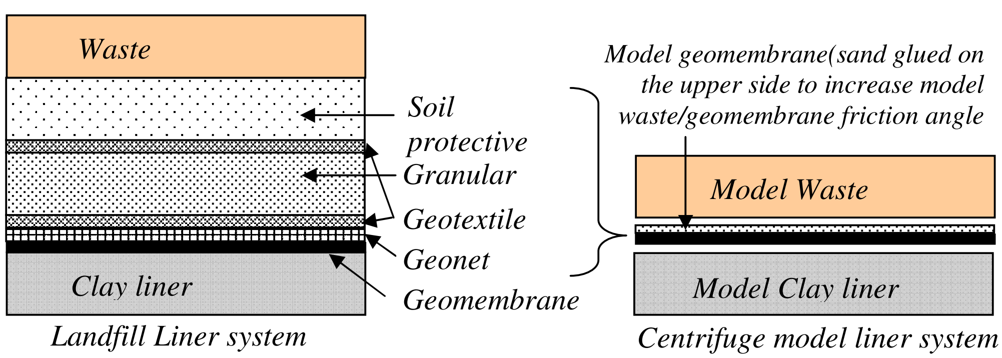


Figure 3. Landfill liner system and centrifuge model liner system

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	29°	Villard et al. (1999)
Geotexile-geonet	20°	Mitchell et al.(1988)
Geonet-geomembrane	7.6° to 9° 11°-18° (dynamic friction)	Mitchell et al.(1988) 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)

The interface friction angles of the model geomembrane with clay and model waste were tested using a modified shear box (100mm × 100mm × 50mm). 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°. This measured friction angle is typical of the values reported for real geomembrane/clay interface (Table 1). The interface friction angle between model geomembrane (glued sand side) and model waste was 24.9°. This higher friction angle represents a realistic worst case scenario for the effective friction angle of a multi layered liner system (Fig.3).

Centrifuge model preparation and testing

A schematic cross section of the centrifuge model is shown in Fig.4. The container is an equivalent shear beam box (ESB) of internal dimensions 235mm × 560mm × 222 mm. The model was prepared in stages. Firstly, fraction-E dry silica sand was air pluviated to a depth of 200 mm. Accelerometers were placed at the locations shown in Fig. 4 during the sand pouring stage. Sand was poured from a hopper elevated above the model container. The height of the hopper above the model and the flow rate can be adjusted. For a given flow rate, increase in the height of drop increases the relative density of the sand. For a given drop height, increase in the flow rate decreased the relative density of the sand. A drop height of 1 m and a flow rate of 50 g/minute resulted in relative density of 45%.

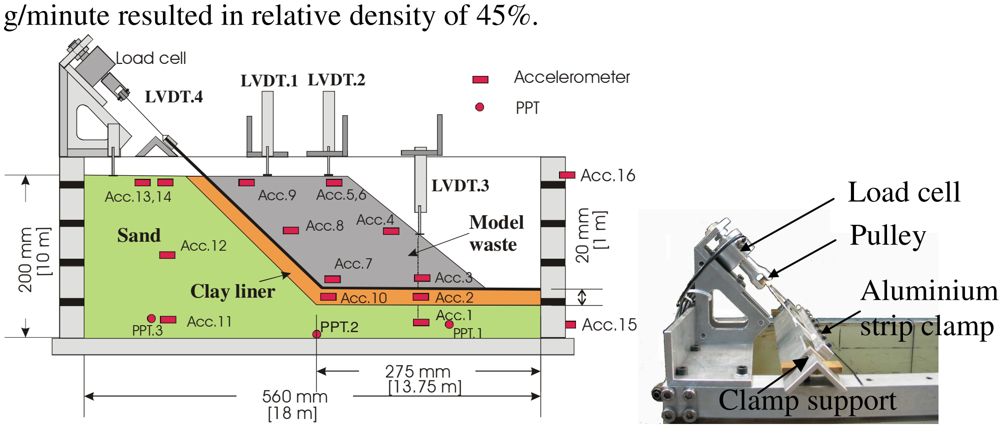


Figure 4. Cross section of the centrifuge model.

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 in the 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 thick clay liner strips, which were trimmed from one-dimensional consolidated clay sample, were placed on both the excavated bottom surface and the side slope. The slope length on prototype scale is 9.9 m. The model geomembrane was then placed on top of the clay liner. The top edge of the model geomembrane was clamped and attached to a load cell as shown in Fig.4. A support was introduced, attached to the container, to restrict geomembrane movement to the plane of the slope. The model waste was then placed into the landfill 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.4 to measure the model waste settlement while the centrifuge was being accelerated, and during earthquake loading. Fig 5a-d Figures 5a to 5d show the model preparation sequence.

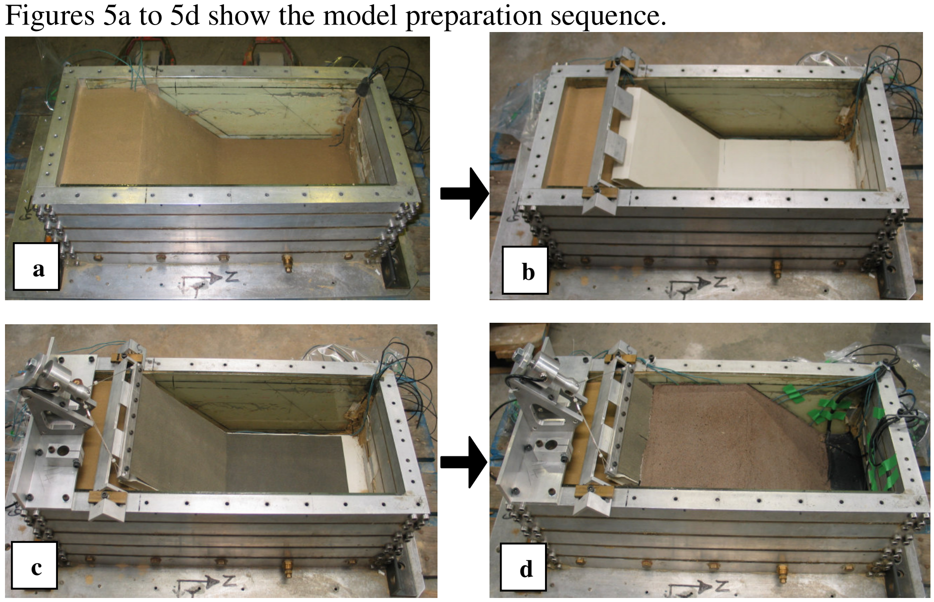


Figure 5. Centrifuge landfill model preparation.

Testing Procedure

After placing the model on 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 slack in the geomembrane and clamp attachment at the load cell. The model was swung up to 50g in increments of 10g. Load cell measurements were recorded throughout the test as shown in Fig. 6. Once the consolidation of waste had finished at 50g, simulated earthquakes of varying intensity were fired using the Stored Angular Momentum (SAM) earthquake actuator, Madabhushi et al. (1998). Table 2 provides the details of the fired earthquakes. Enough time (10 to 20 minutes) was allowed between the earthquakes for the geomembrane and instruments to reach equilibrium.

Table 2. Simulated earthquakes applied in the test–prototype scale [model scale]

Simulated excitation number	Driving frequency (Hz)	Duration (s)	Average of Max. base acceleration at Acc.1(g)
E.1	0.6 [30]	15 [0.3]	0.05 [2.5]
E.2	0.8 [40]	15 [0.3]	0.1 [5]
E.3	1 [50]	15 [0.3]	0.125[6.25]
E.4	1 [50]	15 [0.3]	0.15 [7.5]
E.5	1 [50]	15 [0.3]	0.2 [10]
E.6	1 [50]	25 [0.5]	0.2 [10]

Tension in model geomembrane during swing up

The load cell reading is the sum of geomembrane tension plus mounting weight, both of which increase during swingup. To obtain the component due to mounting alone, a separate test with no geomembrane was carried out. Both total and mounting forces are shown in Fig.6. The actual geomembrane tension is the difference between the two readings. Table 3 summaries the tension measured in the model geomembrane along with prototype tension and depth of landfill. 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 (Fig. 2).

Table 3. Tension in geomembrane during swingup.

g level	Actual tension in model Geomembrane(N)	Prototype Tension (kN/m)	Prototype waste height (m)	Prototype slope length(m)
1g	10.3	0.05	0.14	0.2
10g	18	0.9	1.40	1.98
20g	42.7	4.3	2.80	3.96
30g	79.5	11.9	4.20	5.94
40g	124.7	24.9	5.60	7.92
50g	156.6	39.1	7.00	9.90

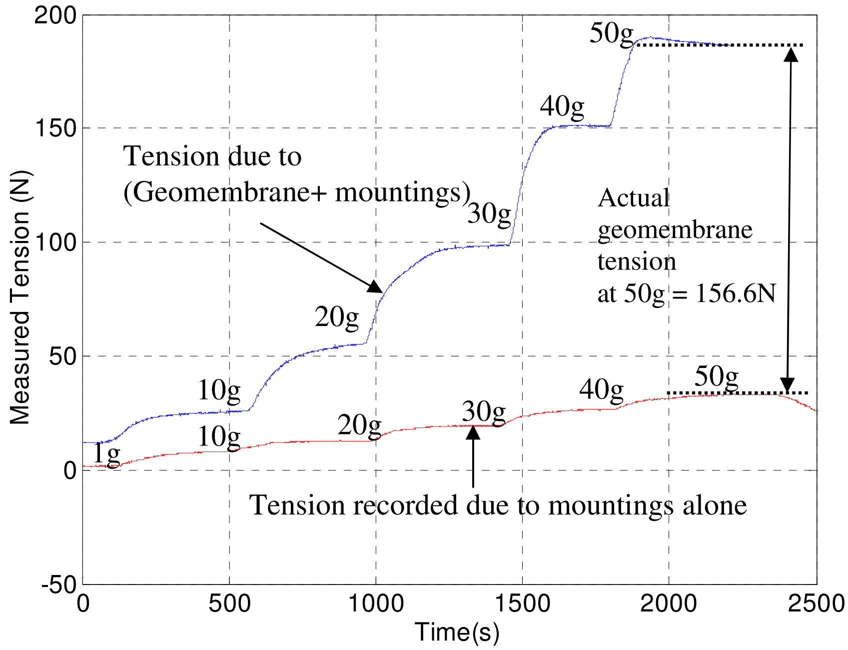


Figure 6. Tension measured during swingup (model scale).

Tension in geomembrane due to earthquake loading

Fig.7 shows the true tension in geomembrane (corrected as described in section 4 to eliminate tension measured due to mounting load) at prototype scale during the model earthquakes. The base of the load cell is attached to the top ring of the ESB box that experienced similar acceleration as the top soil surface. Hence the measured tension is a realistic value that would be experienced by the geomembrane, at anchor level in a real landfill, during an earthquake.

E.1 can be associated with a new landfill cell experiencing an earthquake loading for the first time while E.2 to E.6 can be associated with a landfill cell experiencing multiple earthquake landings (aftershocks). Fig.7 shows that even a small magnitude earthquake loading (0.05g) induces tension in the geomembrane. Permanent increase in the geomembrane tension is observed in all simulated earthquakes. It can also be observed that there is a drop in tension between the final value of one earthquake and initial value of subsequent earthquake. This could be due to creep in interfaces between model waste/geomembrane, clay/geomembrane and in the geomembrane itself.

Fig.8 summaries the earthquake induced tension in the geomembrane as a percentage of pre-earthquake geomembrane tension. Permanent increase in tension was calculated by subtracting the pre-earthquake tension from post-earthquake (after about 10 minutes) tension. Since all 6 model earthquakes were applied to the same centrifuge model, the increase in tension for E.2 to E.6 need to be interpreted as that of a landfill experiencing multiple earthquake loadings. The results (Fig.8) show that an earthquake loading induces additional tension in the geomembrane even if it has previously experienced multiple earthquake loadings. Fig.8 shows that the earthquake loading can induce additional tension up to 20% of pre-earthquake values during the earthquake and a permanent increase of 8%. All 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% permanent tension increase.

Conclusions

This study shows that centrifuge modeling and dynamic centrifuge testing is an effective tool to evaluate the tension developed in a geomembrane placed on a landfill slope. The following conclusions can be drawn from this study;

- Earthquake loading may induce additional permanent tension in the geomembrane on landfill side slopes. For base excitation of earthquake loadings that produce base acceleration magnitudes of 0.05g to 0.2g, 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.
- Earthquake loading induces tension in the geomembrane even if the landfill has previously experienced earthquake loadings (Fig.7, E.2 to E.6).
- Maximum and permanent tension developed in the geomembrane increases with the duration of the earthquake loading (E.5 and E.6 in Fig.8).

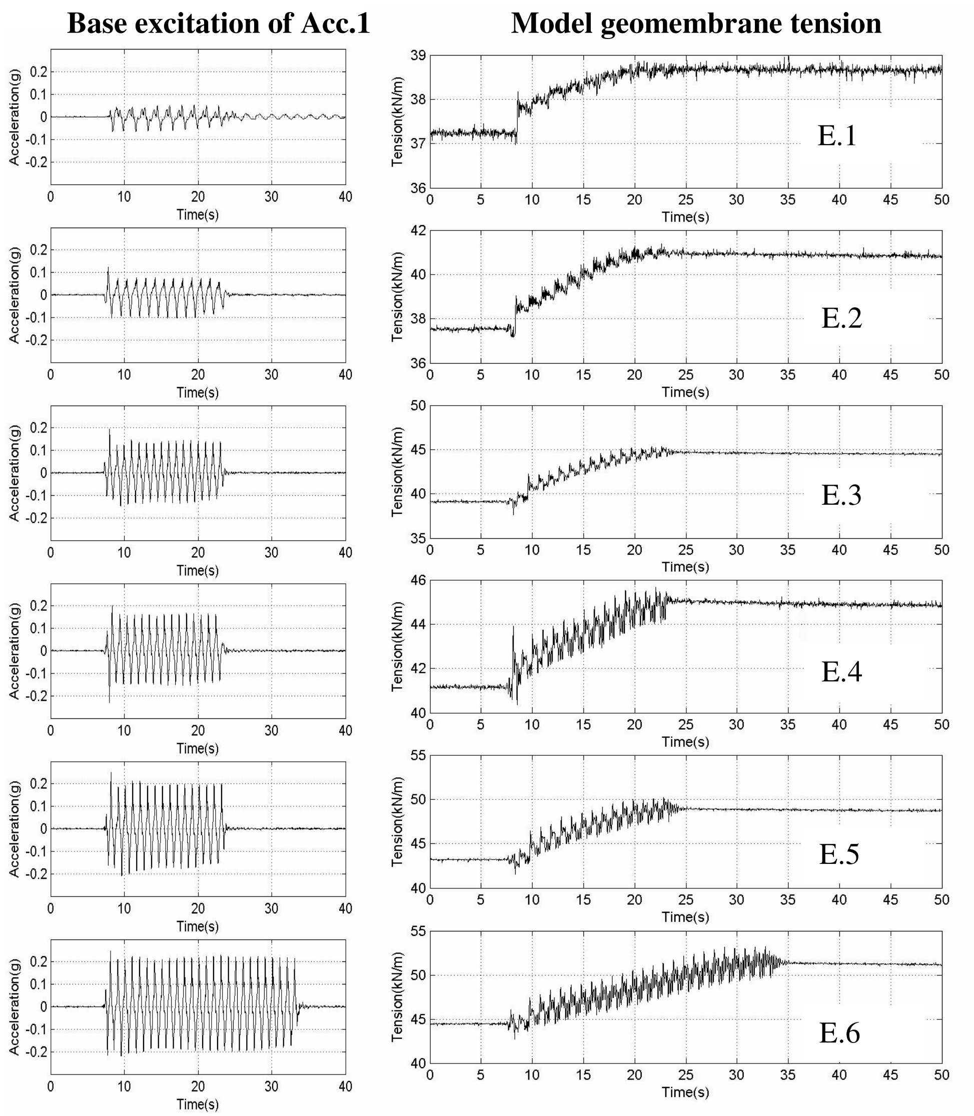


Figure 7. Landfill base excitation records (Acc.1) and tension in model geomembrane during earthquake. (prototype scale)

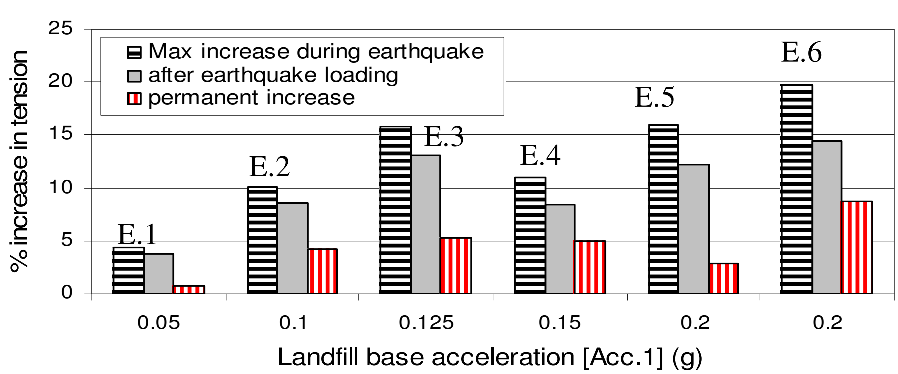


Figure 8. Percentage increase in geomembrane tension versus base acceleration.

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