Centrifuge modelling and dynamic testing of Municipal Solid Waste (MSW) landfills

N. I. Thusyanthan & S. P. G. Madabhushi
Department of Engineering, University of Cambridge, United Kingdom

ABSTRACT: An investigation into the seismic behaviour of municipal solid waste (MSW) landfills by dynamic centrifuge testing was undertaken. This paper presents physical modelling of MSW landfills for dynamic centrifuge testing, with regard to the following research areas: 1. amplification characteristics of municipal solid waste; 2. tension induced in geomembranes placed on landfill slopes due to earthquake loading; 3. damage to landfill liners due to liquefaction of foundation soil. A model waste, that has engineering properties similar to MSW, is presented. A model geomembrane that can be used in centrifuge tests is also presented. Results of dynamic centrifuge tests with the model geomembrane showed that an earthquake loading induces additional permanent tension (~25%) in the geomembrane.

1 INTRODUCTION

1.1 *Landfills*

Every year, countries all over the world deal with the disposal of millions of tons of different kinds of waste. The classification and management of waste differ slightly from country to country. Municipal Solid Waste (MSW) is mainly waste from households and industry. Nearly 50 million tons of MSW is produced by households in Japan every year of which around 15 million tons of waste is landfilled. The United States generates over 230 million tons of MSW, and about 55% of it is landfilled. Both Japan and United states have thousands of landfills located in seismic regions. Hence it is important to understand the effects of an earthquake on landfills. Landfill failures can lead to ground water contamination and other geo-environmental disasters. Better understanding of the seismic behaviour of landfills will lead to improved design for new landfills in earthquake prone areas.

This study presents research into the seismic behaviour of municipal solid waste (MSW) landfills by dynamic centrifuge testing (Thusyanthan et al. 2004a, 2005a). This paper presents physical modelling of MSW landfills for dynamic centrifuge testing, with regard to the following three research areas; 1. amplification characteristics of municipal solid waste; 2. tension induced in geomembranes placed on landfill slopes due to earthquake loading; 3. damage to landfills due to liquefaction of foundation soil. All the dynamic centrifuge tests were carried out at 50 times earth's gravity and model earthquakes were applied to the landfill model using the Stored Angular Momentum (SAM) earthquake actuator developed at Cambridge.

This paper will conclude that dynamic centrifuge modelling and testing of landfills can provide valuable insight into the seismic behaviour of landfills and improve future landfill designs.

2 MODELLING LANDFILL COMPONENTS

2.1 *MSW*

Experimental work in seismic behaviour of MSW landfill has often been limited to numerical analyses due to the difficulties in using real waste. MSW is usually highly heterogeneous and variable in its content. Thus the use of real MSW in experiments raise 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 (Fig. 1) using a mixture of peat, E-grade kaolin clay and fraction-E fine sand (Thusyanthan et al. 2004a) and was used in the centrifuge tests. Shear modulus reduction and damping data of the model MSW (Fig. 2, 3) were obtained from the centrifuge data (Brennan et al. 2005) and shown to match with that reported for MSW. This validates the use of the model waste to study the seismic behaviour of MSW landfills.

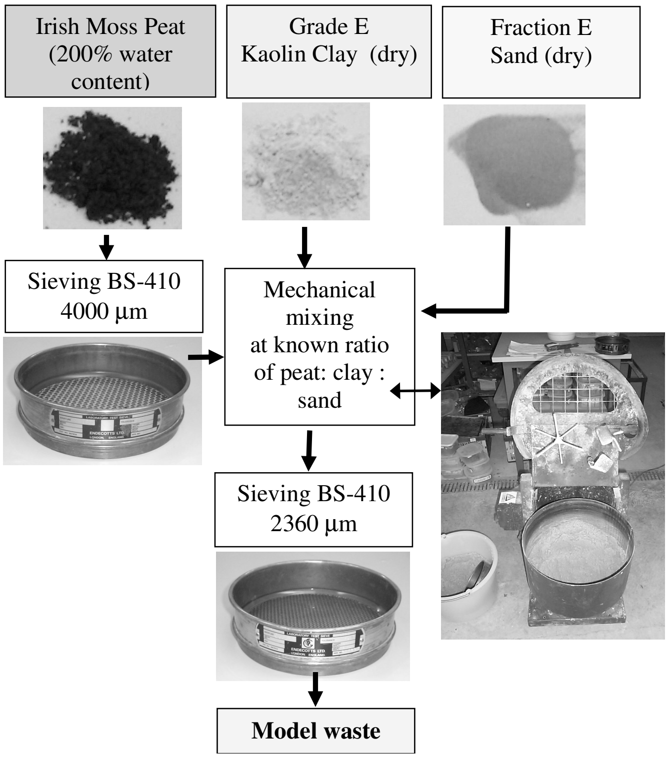


Figure 1. Preparation of model MSW.

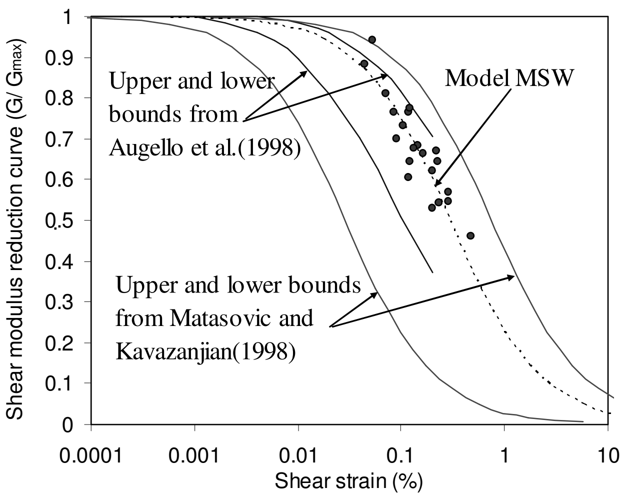


Figure 2. Shear modulus reduction curve of model waste.

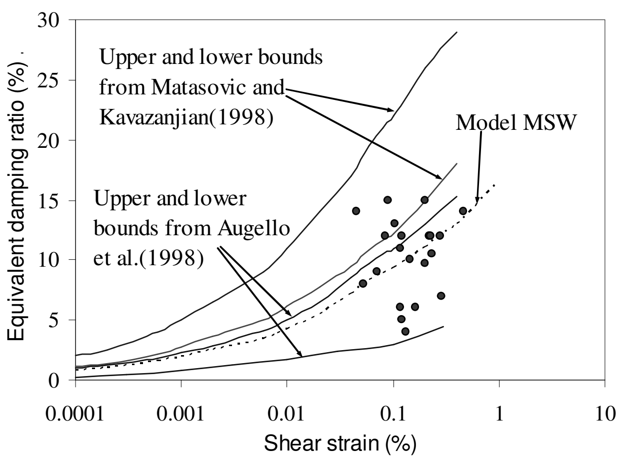


Figure 3. Damping curve of model waste.

2.2 *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%.

2.3 *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 specimens cannot be used in centrifuge testing because the forces developed in the centrifuge model are N^2 times smaller, where N×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 behaviour and interface frictional angles as the real geomembrane was produced from thin (0.1 mm) HDPE for centrifuge testing (Thusyanthan, 2005). Figure 4 shows the models geomembrane's stress-strain characteristics, obtained from wide-strip test, compared with other geomembranes reported by Koerner (1998).

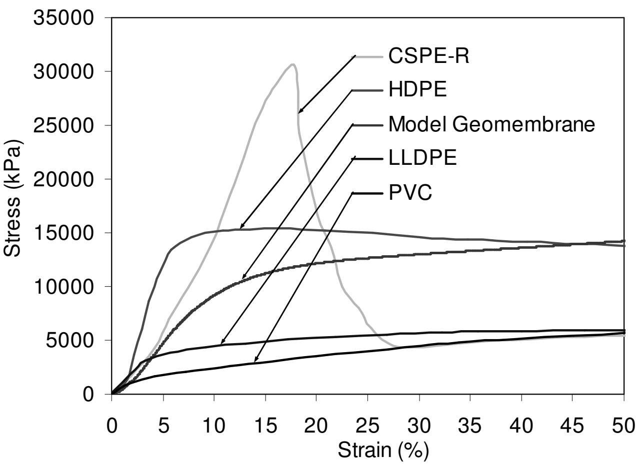


Figure 4. Stress-strain characteristics of model geomembrane.

3 MODEL PREPARATION AND CENTRIFUGE TESTING

All the dynamic centrifuge tests were performed in a equivalent shear beam box (ESB) of internal dimensions 235 mm × 560 mm × 222 mm, whose design and performance is described by Zeng and Schofield (1996).

Three centrifuge models (IT02, IT04 and IT07) are described in this paper. Test data from model IT02 was used to understand the amplification of model waste. Model IT04 was aimed at studying the tension induced in geomembranes placed on landfill slopes due to earthquake loading and model IT07 was used to study the damage to landfill liners due to liquefaction of foundation soil.

3.1 *Model preparation*

A schematic cross section of centrifuge test IT02 is shown in Figure 5. The model waste was placed into the ESB container in layers of 25 mm thick and each layer was compacted by static load to give a compacted unit weight of 9 kN/m^3. Accelerometers (Acc's) were placed in each layer. The total depth of the model waste was 200 mm (Fig. 5).

Centrifuge model IT04 incorporated the model geomembrane as shown in Figure 6. The model was prepared in stages. Firstly, fraction-E dry silica sand was air pluviated to a depth of 200 mm in the ESB container. Accelerometers were placed at the locations shown in Figure 6 during sand pouring. Sand was poured from a hopper elevated above the model container. 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 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. 6. 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 and compacted by a static load to obtain a uniform unit weight of 9 kN/m^3. Linearly variable displacement transducers (LVDT) were mounted as shown in Fig. 6 to measure the model waste settlement during swing up (increasing gravity) and during earthquake loadings.

Figure 7 shows the schematic cross section of the centrifuge model IT07. Surcharge on the model was 19.4 kg. This surcharge was chosen so that the vertical stress level on the clay liner at 50g is equal to the vertical stress from a 20 m deep landfill (with unit weight of waste ~ 10kN/m^3). The model preparation of model IT07 was identical to that of IT04 except that the sand was saturated with methyl cellulose fluid of viscosity 50 centistoke (to satisfy the scaling law for time in dynamic event at 50g) under vacuum. The side gaps in between the ESB container and the clay liner were sealed by a flexible aqua-seal. The model waste was placed into the landfill model in layers (unit weight of 9 kN/m^3). Lead shots were placed on the top of model waste to act as surcharge.

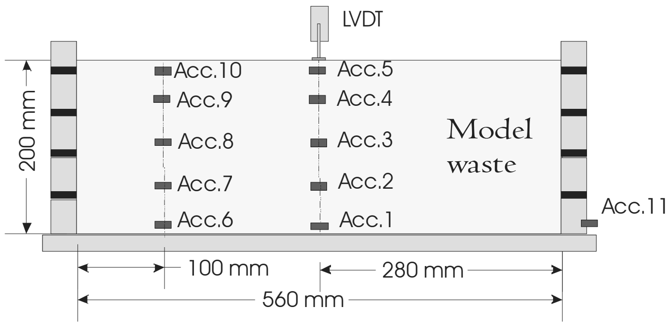


Figure 5. Schematic cross section of model IT02.

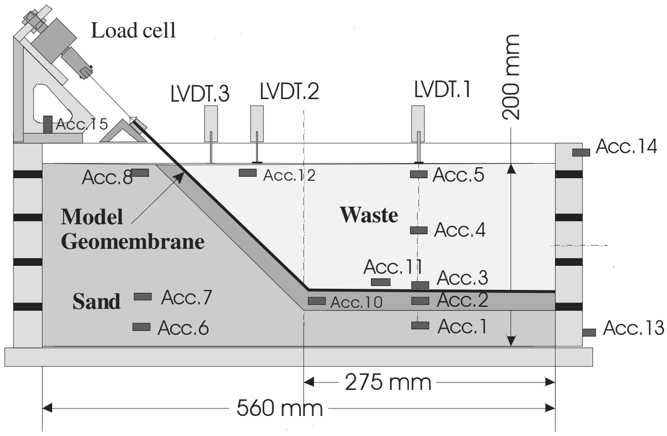


Figure 6. Schematic cross section of model IT04.

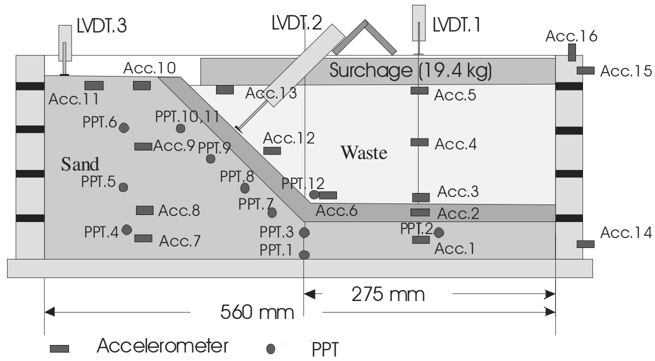
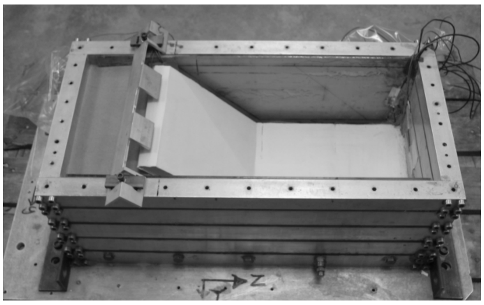
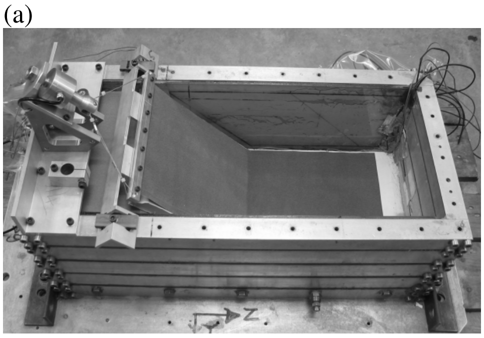


Figure 7. Schematic cross section of model IT07.

The model was then re-saturated with methyl cellulose fluid to a level of 40mm below the top sand surface. A small video camera, viewing the clay liner, was mounted on the ESB box to monitor the movement of the clay liner during the test. Figures 8, 9 & 10 show the model preparation sequence and completed models IT04 and IT07.



(a)



(b)

Figure 8. Model preparation of IT04 (a) Clay liner placed in the model; (b) Model geomembrane placed on the clay liner.

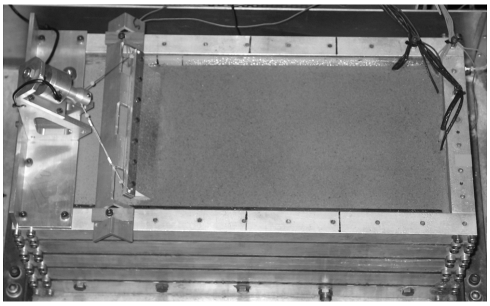


Figure 9. Model IT04 before fixing LVDTs

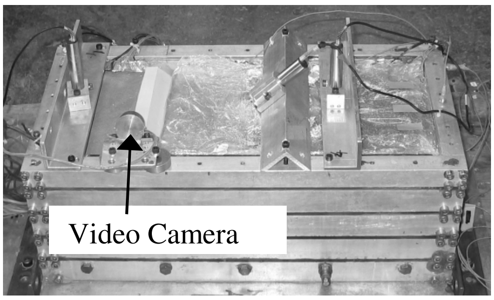


Figure 10. Model IT07

3.2 *Centrifuge Testing*

All the centrifuge tests were performed at 50g on the 10m-diameter beam centrifuge at Schofield Centre, University of Cambridge, UK. At 50g, earthquakes of varying magnitude and duration were applied to the model using the stored angular momentum earthquake actuator. Tables 1, 2 & 3 provides the details of the applied earthquakes in tests IT02, IT04 and IT07 respectively. Enough time (10 to 20 minutes) was allowed between the earthquakes for the model and instruments to reach equilibrium.

Table 1. Earthquakes in test IT02 prototype [model] scale

Earthquake	Frequency (Hz)	Duration (s)	Maximum base acceleration (g)
E.1	0.6 [30]	15 [0.3]	0.075 [3.76]
E.2	0.8 [40]	15 [0.3]	0.123 [6.13]
E.3	1 [50]	15 [0.3]	0.178 [8.90]
E.4	1 [50]	15 [0.3]	0.135 [6.79]
E.5	1 [50]	15 [0.3]	0.236 [11.80]
E.6	1 [50]	15 [0.3]	0.284 [14.20]
E.7	1 [50]	25 [0.5]	0.148 [7.41]

Table 2. Earthquakes in test IT04 prototype [model] scale

Earthquake	Frequency (Hz)	Duration (s)	Maximum base acceleration (g)
E.1	0.6 [30]	15 [0.3]	0.091 [4.55]
E.2	0.8 [40]	15 [0.3]	0.126 [6.30]
E.3	1 [50]	15 [0.3]	0.214 [10.70]
E.4	1 [50]	15 [0.3]	0.184 [9.20]
E.5	1 [50]	15 [0.3]	0.252 [12.60]
E.6	1 [50]	25 [0.5]	0.310 [15.50]
E.7	1 [50]	15 [0.3]	0.320 [16.00]

Table 3. Earthquakes in test IT07 prototype [model] scale

Earthquake	Frequency (Hz)	Duration (s)	Maximum base acceleration (g)
E.1	1 [50]	15 [0.3]	0.163 [8.15]
E.2	1 [50]	15 [0.3]	0.249 [12.45]

4 RESULTS

4.1 *Amplification of model MSW (Test IT02)*

A settlement of 19.2 mm was recorded by the LVDT at 50g before the earthquakes were fired. Hence the prototype depth of the model waste is 9.1 m. The peak prototype accelerations of Acc.5 in every cycle, in all seven earthquakes, were plotted against the peak acceleration levels of Acc.6 in Fig. 11 (Acc.1 failed to work in the experiment). Amplification data for MSW from Singh and Sun (1995) is also shown in Figure 11.

Since the shear wave velocity of MSW appears to be mainly between that of soft and medium stiff soil, Kavazajian and Matasovic (1995) suggested that the soft soil curve of Idriss (1990) can be used to evaluate the peak acceleration at the top of a landfill. The dynamic centrifuge test data of model waste agrees well with the soft soil site amplification curve and also fall within the range of results obtained by non-linear analyses of landfills (Kavazajian and Matasovic, 1995). Hence, it can be concluded that the model waste seems to model the amplification characteristics of MSW well. Figures 2 & 3 show the shear modulus reduction and damping curves of model waste from test data of IT02.

Results show that the dynamic characteristics of real waste is captured well by the model waste.

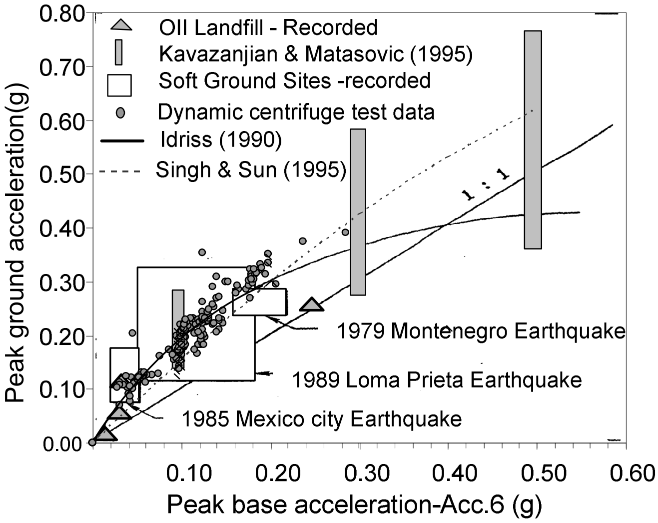


Figure 11. Amplification of model waste compared with data from literature.

4.2 *Tension in geomembrane (Test IT04)*

The geomembrane tension prior to applying earthquake loadings was 12.35 kN/m (prototype scale), which was caused by the static loading of the model waste. Figure 12 shows the increase in geomembrane tension due to earthquake loading E.1. This measured tension is a realistic value that would be experienced by a geomembrane at anchor level in a real landfill during an earthquake. This is because 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.

Figure 13 summaries the geomembrane tension before and after each earthquake loading. Earthquake E.1 of magnitude 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. E.1 can be associated with a new landfill experiencing an earthquake loading for the first time while E.2 to E.7 can be associated with a landfill experiencing multiple earthquake landings (aftershocks).

All earthquakes show that the 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. Figure 8 shows that an earthquake loading induces additional tension in the geomembrane even if it has previously experienced earthquake loading and higher tensions (E.3 & E.4). 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 MSW/ geomembrane, clay/geomembrane and in the geomembrane itself. This is a realistic behaviour present in real geomembranes as well.

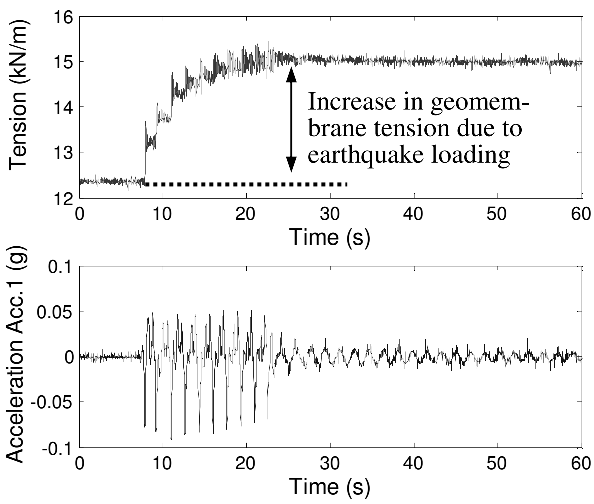


Figure 12. Tension induced by earthquake loading on side-slope geomembrane due to E.1 in test IT04.

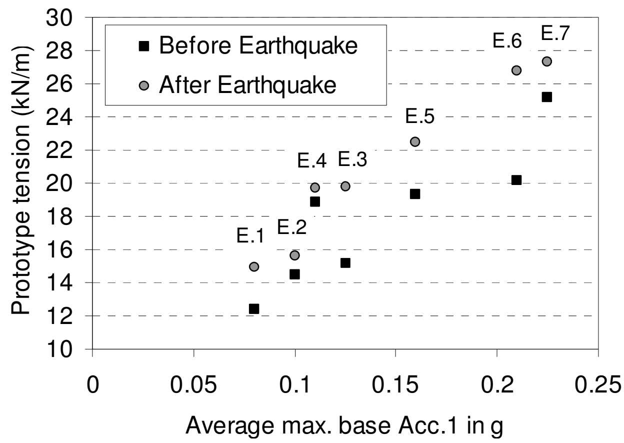


Figure 13. Geomembrane tension from test IT04.

4.3 *Liner damage due to liquefaction of foundation (Test IT07)*

Figures 14a, b & c show the picture of the clay liner recorded by the video camera before and after each earthquake loading. A small movement of the clay liner away from the landfill occurred due to E.1 (Fig. 14b). Figure 14c, which was taken just after E.2, shows further clay liner movement and cracks on the top soil surface. Soon after the end of E.2, it was possible to observe cracks opening up on the soil surface and the pore fluid emerging from those cracks. It was also possible to see the pore fluid filling inside the landfill through the failed connection between clay liner and ESB side walls.

Figure 15 shows the post test cross section of the side clay liner. The movement of the side-slope clay liner from its original position is apparent from Figure 15. This deformation may damage the leachate collection pipes that may run along the side-slopes. The maximum radius of curvature of the side clay liner after test IT07 was measured to be 80 cm (model scale). Hence, the corresponding maximum tensile strains experienced by clay liner is 1.25%. It should be noted that the clay liners in the field are made with compacted clay (lifts of 150 mm), thus cracking could occur at much lower strains than in consolidated clay. Furthermore, if the soil beside the side-slope clay liner had been unrestrained by the ESB box, as would be in real landfills, soil could have moved laterally and the clay liner could have moved outwards further. Therefore landfill liners in the field could sustain much more damage than the centrifuge model liners for similar earthquake induced liquefaction and strains.

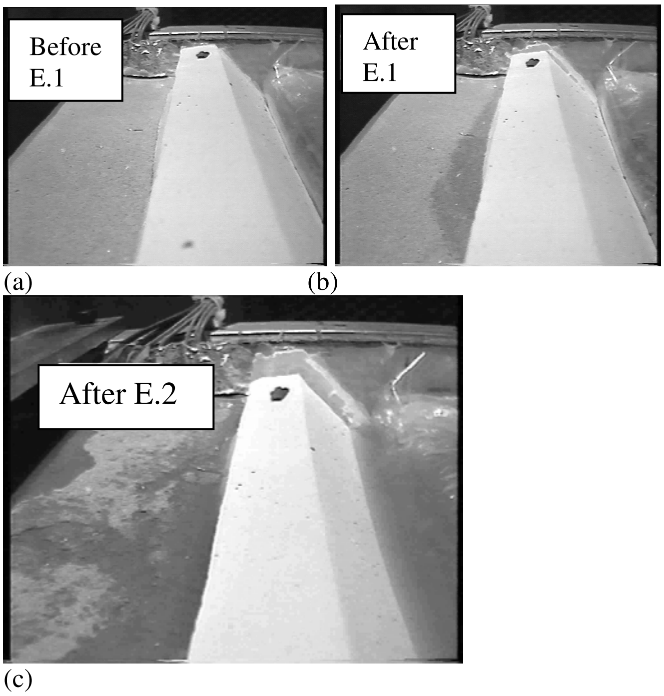


Figure 14. Clay liner failure in test IT07

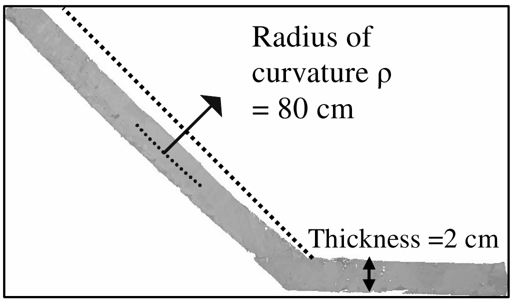


Figure 15. Post test cross section of side clay liner.

5 CONCLUSIONS

The centrifuge modelling of MSW, clay liner and geomembrane and model preparation techniques required for centrifuge testing of MSW landfills were presented in this paper.

Dynamic centrifuge tests showed that an earthquake loading induces additional permanent tension in the side-slope geomembrane. For earthquake loading of intensity, 0.2g to 0.3g at the foundation level, the tension in the geomembrane (slope angle 45° and slope length ~10 m) can increase by up to 25% of pre-earthquake value.

Centrifuge test of a landfill model on liquefiable foundation showed that the clay liner is susceptible to damage due to earthquake loading.

This study showed that dynamic centrifuge testing can be an effective tool to investigate the effects of earthquake loading on landfills. Further work in dynamic centrifuge testing of landfills can provide useful data that can be used to validate numerical codes and provide design guidelines for landfills in seismic regions.

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