Centrifuge modelling of municipal solid waste landfills under earthquake loading

N.I. Thusyanthan
Ph.D research student, Schofield Centre, University of Cambridge, Cambridge, CB3 0EL, UK.
Email: it206@cam.ac.uk
S.P.G. Madabhushi
Senior Lecturer, Department of Engineering, University of Cambridge, Cambridge, CB2 1PZ,UK.
Email: mspg1@cam.ac.uk
S. Singh
Nicholson Family Professor and Head of Civil Engineering, Santa Clara University, California 95053, USA.
Email: ssingh@scu.edu

ABSTRACT – Landfills located in seismic regions can experience earthquake loadings during its lifetime, hence it is important to understand the integrity of landfills under earthquake loading as landfill failures can lead to ground water contamination and other geo-environmental disasters. This paper presents data from dynamic centrifuge testing in which a municipal solid waste (MSW) landfill with a single clay liner and 45° side-slope founded on liquefiable soil is modelled and tested. Dynamic centrifuge testing was carried out at 50g. The results show that the liquefaction of soil below the side-slope clay liner results in clay liner deformation during and after earthquake loading.

1 INTRODUCTION

Every year, countries all over the world deal with the disposal of millions of tons of different kinds of waste. Landfilling is the most common and cheapest form of municipal solid waste (MSW) disposal in the world. Nearly 50 million tons of waste is produced by households in Japan every year of which around 15 million ton of waste is landfilled. United States generates over 230 million ton of MSW and about 55 % of it is landfilled.

Thousands of landfills are located in seismic regions in the world. Hence it is important to understand the integrity of landfills under earthquake loading as landfill failures can lead to ground water contamination and other geo-environmental disasters. The concern of landfill liner integrity is greatest for landfills which have liquefiable soil near its side-slopes or foundation. Unlike the traditional landfill designs where the water level was well below the landfill base, new landfills are allowed to be built below ground water level (for example: Virginia landfill, Southeastern Public Service Authority landfill's fifth cell, US). Even when landfills have been built well above water table, over the years ground water levels in the landfill vicinity may rise. This can result in liquefiable soil near the landfill.

This study investigates the integrity of single clay liner landfills founded on saturated soil under earthquake loading by dynamic centrifuge testing. The test was done in the 10m diameter beam centrifuge of Schofield centre, University of Cambridge, UK.

2 MODELLING LANDFILL COMPONENTS

The main difficulty associated with centrifuge modelling of landfills is the physical modelling of landfill components, such as 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 et al., 1996).

2.1 Clay liner

The present study uses a strip of consolidated kaolin clay to model the compacted clay liner. 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 thickness strips. A 2 cm thickness layer would represent a 1m clay liner at 50g centrifuge test. The final water content of consolidated clay was 36%.

2.2 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 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. The foundation soil of landfill was modelled by fraction-E silica sand. The properties of fraction-E sand are given in Table 1.

Table1. Properties of fraction E sand

Property	Value
Minimum voids ratio e_{min}	0.613
Maximum voids ratio e_{max}	1.014
Permeability at e = 0.72	0.98×10^{-4} m/s
Critical state friction angle φ_{crit}	32°
Minimum voids ratio e_{min}	0.613

3 CENTRIFUGE TESING

3.1 Model preparation

Figure 1 shows the schematic cross section of the centrifuge model used in the study. Surcharge on 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 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).

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 (Accs) and pore pressure transducers (PPTs) were placed at the locations shown in Fig. 1 during sand pouring. The rate of pouring and the height of drop were selected to obtain a relative density of 45%. The sand was then saturated, through drainage holes near the base of the box, by the upward percolation of methyl cellulose fluid (viscosity 50 cSt) under vacuum. Once the sand was fully saturated, methyl cellulose 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 a depth of 140 mm with a side slope of 45°. The 2 cm thickness clay liner strips, which were trimmed from one-dimensional consolidated clay, were placed on both the excavated bottom surface and the side slope. The corner joint of bottom and side clay liner was carefully sealed by applying small pressure. The slope length in prototype scale is 9.9 m.

The accelerometers were placed near the clay liner as shown in Fig.1. The model waste was then placed into the landfill model in layers. Each layer was compacted by static load to produce a unit weight of 10 kN/m^3. Once the model waste had been placed, lead shots were placed on the top to act as surcharge weight. Linearly variable displacement transducers (LVDT) were mounted as shown in Fig.1 to measure the model waste settlement and clay liner movement both while the centrifuge was being accelerated, and during the earthquakes.

The model was then re-saturated with methyl cellulose fluid to a level of 40mm below the top sand surface. Fig. 2a to 2d shows the model preparation sequence. 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.

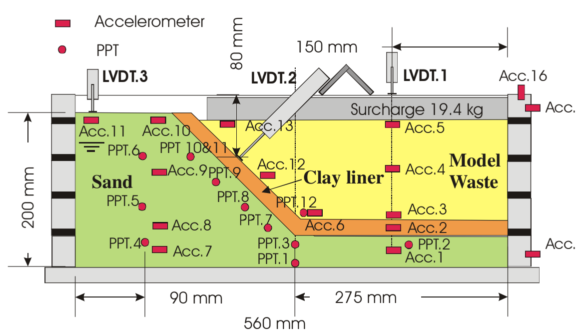

Fig. 1. Centrifuge Model IT07

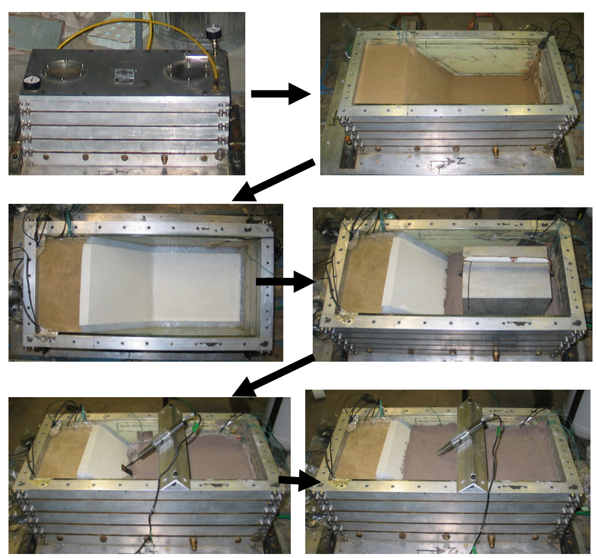

Fig. 2. Model preparation sequence

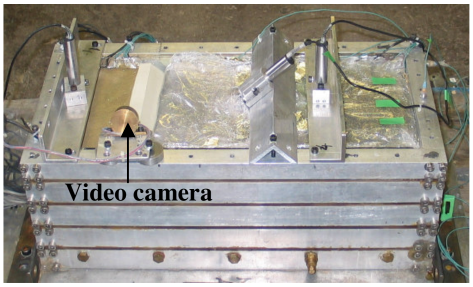

Fig. 3. Completed model

3.2 Testing procedure

The centrifuge test was performed at 50g on the 10m-diameter beam centrifuge at Schofield Centre, University of Cambridge (Schofield, 1980), UK. The landfill model was loaded into the centrifuge (Figure.3) and was swung-up to 50g in stages of 10g to 50g. At 50g, earthquakes of varying magnitude were applied to the model using the stored angular momentum earthquake actuator (Madabhushi et al., 1998). Table 2 provides the details of the applied earthquakes.

Table 2. Earthquakes applied to the model.

Earthquake	Frequency (Hz)	Duration (s)	Acceleration max. Acc.1(g)
EQ.1	1	15	0.163
EQ.2	1	15	0.249

4 RESULTS

The following section presents results from the dynamic centrifuge test. During the swing-up to 50g, LVDT 1, 2 and 3 recorded movements of 25 mm, 1.42 mm and 0.23 mm respectively. All the data in the following section is presented in prototype scale. The centrifuge model at 50g represents a 20 m deep MSW landfill with 8 m below ground level, 1m-thickness clay liner and with water level 2 m below ground level.

4.1 Accelerations

Fig. 4a and 4b show the accelerations recorded during earthquakes 1 & 2 respectively. A small amplification (5%-10%) in acceleration can be observed between Acc.1 and Acc.5 in both earthquake loadings. Initially, amplification (15%) of acceleration is also observed between Acc.1 and Acc.10. However, excess pore pressure generation in the saturated soil (Fig. 5a&5b) causes accelerations to attenuate towards the end of the earthquake as shown in Fig. 4a. Acc.10 of EQ.2 (Fig. 4b) does not show this trend. This is due to the considerable oscillatory motion of the side-slope clay liner that failed during EQ.2

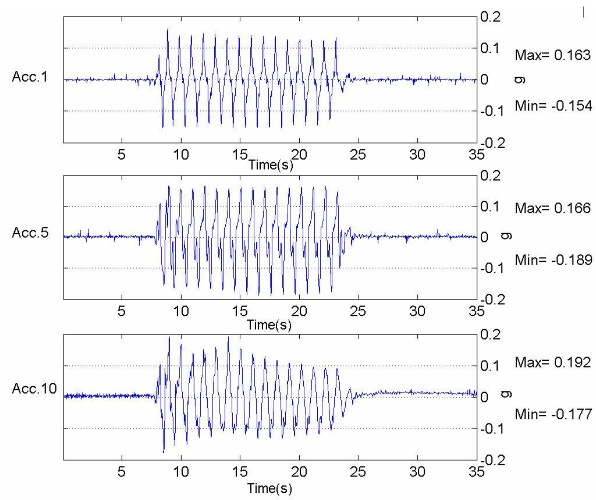

Fig. 4a. Accelerations during EQ.1

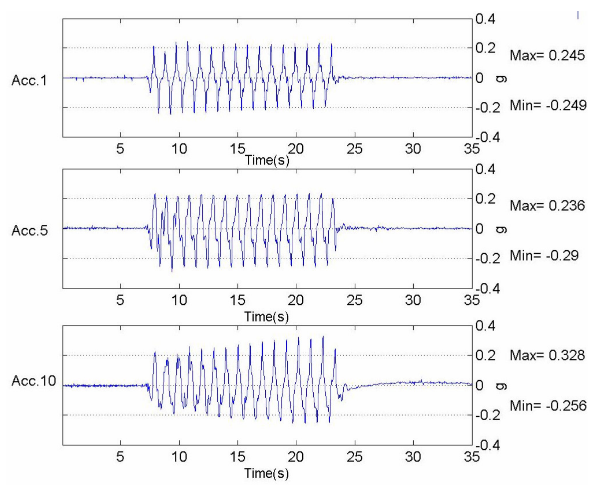

Fig. 4b. Accelerations during EQ.2

4.2 Pore pressure generation and dissipation

Fig. 5a and 5b show the pore pressures recorded during and after EQ.1 & EQ.2 respectively. Fig. 5a shows that the EQ.1 generated excess pore pressures of 59 kPa in PPT.2 and 82 kPa in PPT.4. The excess pore pressure of PPT.2 started to dissipated immediately after the end of earthquake loading while that of PPT.4 took about 20s after the end of earthquake loading to start dissipation. This suggests that earthquake loading had liquefied the soil near PPT.4 but not the soil near PPT.2. This is expected as soil region near PPT.2 has a higher effective stress than soil region near PPT.4. Hence liquefaction is expected at PPT.4 first.

Pore pressure generation and dissipation of PPT.2 and PPT.4 in EQ.2 (Fig. 5b) are similar to that from EQ.1. The

PPT. 2 and PPT.4 generated excess pore pressures of 63 kPa and 83 kPa respectively. Dissipation in PPT.2 started immediately after the end of earthquake loading while that in PPT.4 started about 30s after the end of earthquake loading. The PPT.10 in EQ.2 shows that the excess pore pressure drops by about 5 kPa between 150s and 200s. This indicates the point where the clay liner had moved enough to allow the dissipating pore fluid to flow between the ESB box walls and the clay liner into the model waste.

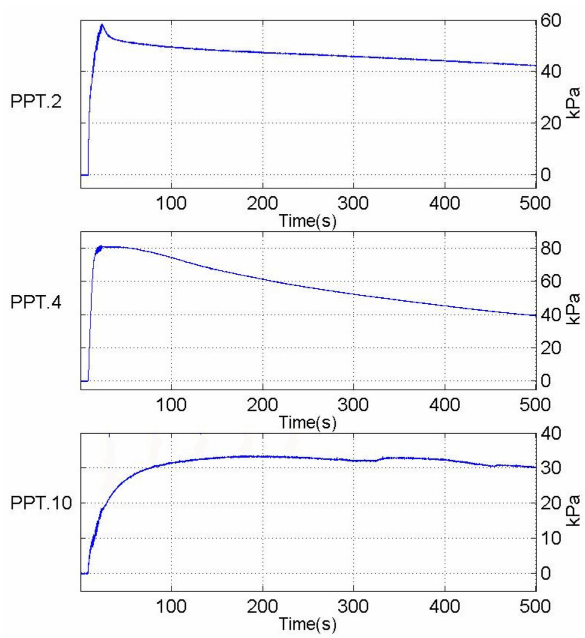

Fig. 5a. Excess pore pressures during EQ.1

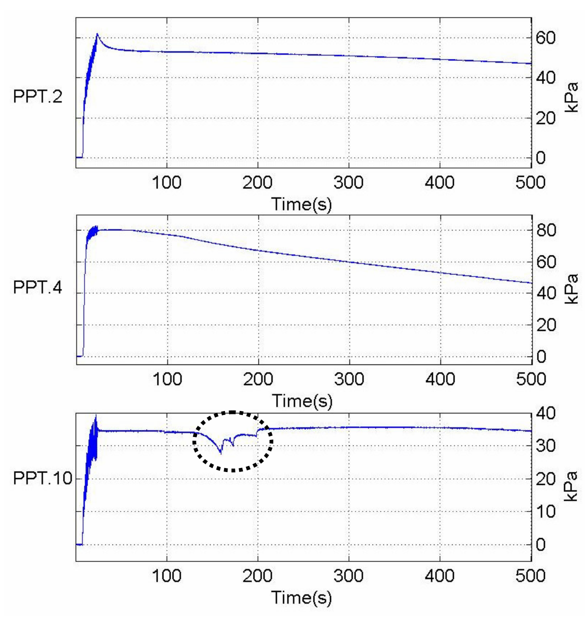

Fig. 5b. Excess pore pressures during EQ.2

4.3 Surface soil and clay liner movements

Fig. 6a and 6b show the movement of side-slope clay liner and the surface soil during earthquake loading EQ.1 and EQ.2. During earthquake loading EQ.1 and EQ.2, the side-slope clay liner moved outwards by 70 mm and 150 mm, while the soil surface moved up by 80 mm and 100 mm respectively. The motion of the clay liner and the top soil during the earthquake loading are in anti-phase (i.e the soils moves up when the clay liner moves outwards and the top soil moves down when the clay liner moves inwards). This suggests that the behaviour of the soil in-between the side-slope and the ESB box during earthquake loading was undrained.

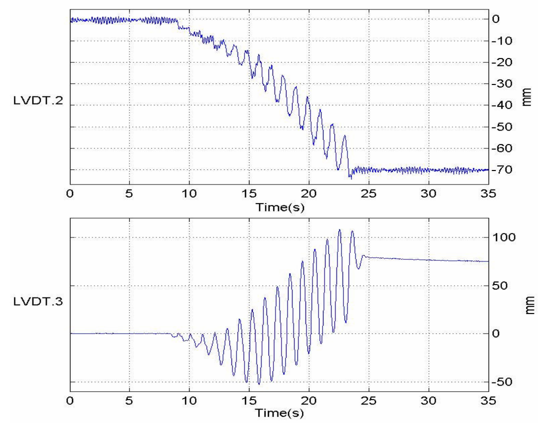

Fig. 6a. Clay liner & soil surface motion during EQ.1

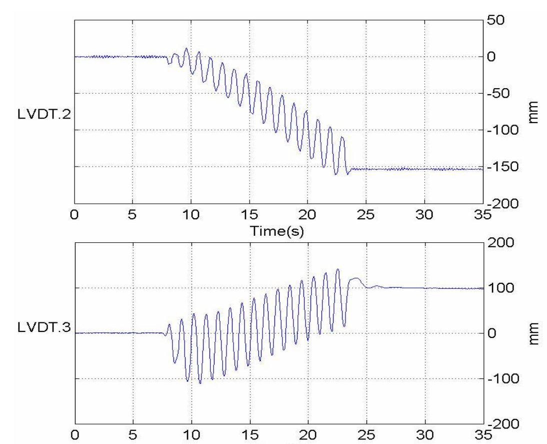

Fig. 6b. Clay liner & soil surface motion during EQ.2

Long term movements of the side-slope clay liner and the tops soil surface during EQ.1 and EQ.2 are shown in Fig. 7a & 7b. The total movement of the clay liner due to EQ.1 and EQ.2 are 82 mm and 165 mm respectively. Hence, 85% to 90% of the total movement of the clay liner occurred during earthquake loading. It is clear from the Fig. 7a & 7b, that the soil moves upwards during the earthquake and consolidates after the end of earthquake. As the clay liner moves outwards, the soil is forced to move upwards as the ESB box constrains the soil from moving laterally. If the soil beside the side-slope clay liner had been unrestrained by the ESB box, as would be in real life landfills, soil could have moved laterally and the clay liner could have moved outwards further, as shown in Fig. 7c. Hence the recorded movements of the clay liner in this test are lower than the movements that may occur in the field. This area needs further research.

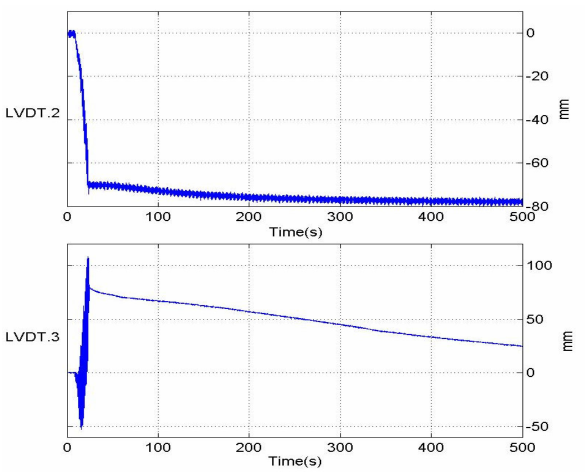

Fig. 7a. Clay liner & soil surface motion after EQ.1

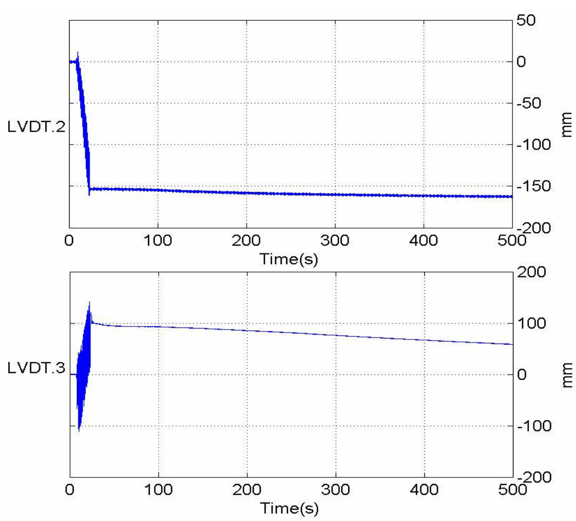

Fig. 7b. Clay liner & soil surface motion after EQ.2

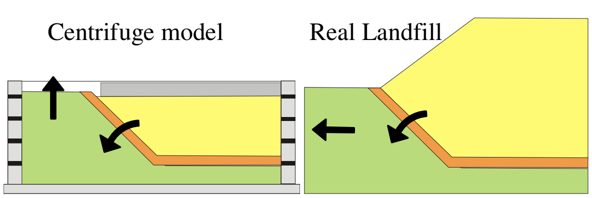

Fig. 7c.Clay liner motion in model vs in real landfills

6 OBSERVATIONS DURING THE TEST

Fig. 8a to 8d show the picture of the clay liner recorded by the video camera before, immediately after and long time after each earthquake. Fig 8a shows the clay liner and the top surface of the soil before the earthquake loading was applied to the model. Fig. 8b shows that clay liner just after EQ.1. A small movement of the clay liner away from the landfill can be seen in Fig 8b. Fig. 8c shows that the dissipating pore fluid had wet the region near the clay liner. Fig. 8d, which was taken just after EQ.2, shows further clay liner movement and cracks on the top soil surface. Soon after the end of EQ.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.

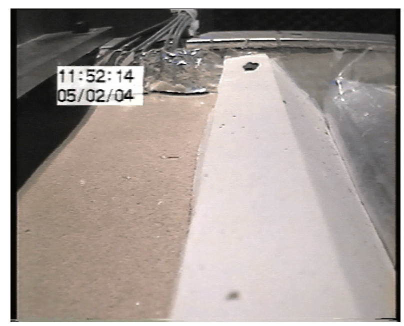

Fig. 8a. Before Earthquake 1

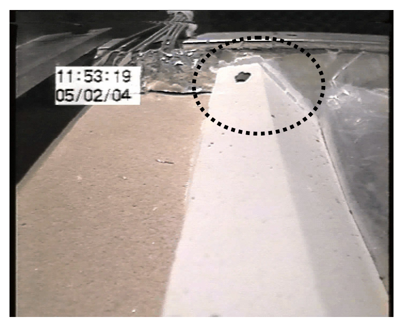

Fig. 8b. Immediately after Earthquake 1

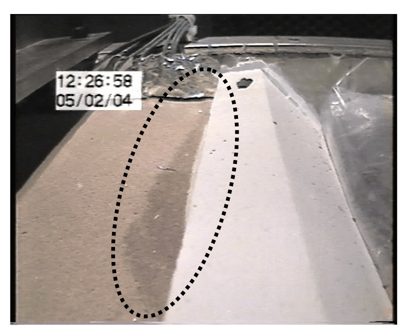

Fig. 8c. Long time after Earthquake 1

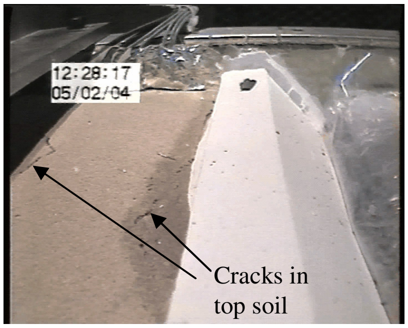

Fig. 8d. Immediately after Earthquake 2

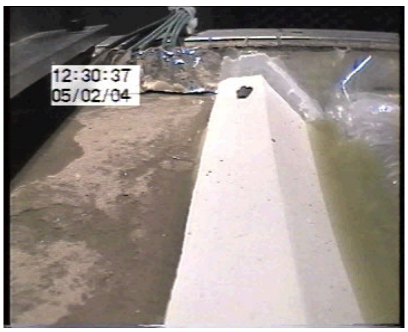

Fig. 8d. Long time after Earthquake 2

Fig. 8d shows the pore fluid inside the landfill and on top of the soil surface. Fig. 9 shows the cross section of the clay liner obtained after the test. The movement of the side-slope clay liner from its original position is apparent from Fig. 9. This deformation may damage the leachate collection pipes that may run along the side-slopes.

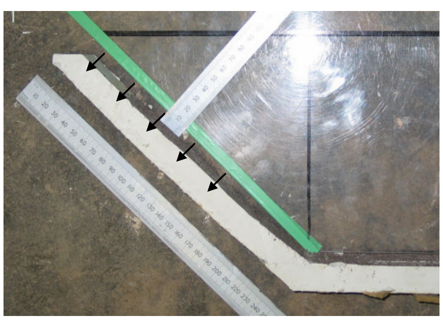

Fig. 9. Post-test cross section of the clay liner.

5 CONCLUSIONS

Dynamic centrifuge testing was carried out to study the effects of earthquake loading on a MSW landfill founded on liquefiable soil. The test results show that,

- The clay liner system of a landfill founded on liquefiable soil is susceptible to damage due to earthquake loading.
- The side-slope clay liner undergoes settlement and sideway movement during and after earthquake loading. 85%-90% of the clay liner movement occurred during the 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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