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SEISMIC BEHAVIOUR OF MUNICIPAL SOLID WASTE (MSW) LANDFILLS

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SUMMARY

A pioneering study into the seismic behaviour of municipal solid waste (MSW) landfill has been carried out by dynamic centrifuge testing. The study investigates the amplification characteristics of a MSW landfill. This paper presents experimental results from dynamic centrifuge testing of a MSW landfill model and compares the experimental results with one-dimensional numerical predictions. The landfill modelled was a single clay liner MSW landfill with 1H:1V side slope founded on a sand foundation. The MSW was modelled by mechanically representative model waste and the clay liner by a strip of normally consolidated E-grade kaolin clay. The accelerations experienced by the clay liner, the top surface of sand and the model waste, when the foundation soil was subjected to seven model earthquakes of varying frequency and intensity, were recorded and have been analysed in this paper. Results from this study provide valuable experimental results to show that a simplified site response chart can be used to obtain the amplification of accelerations through MSW landfills.

INTRODUCTION

Every year, countries all over the world deal with the disposal of millions of tons of MSW. MSW consists of house-hold waste and some industrial waste. The most common and one of the cheapest solutions for disposal of MSW has been a landfill. The United States generates over 230 million ton of MSW every year and about 130 million ton of it is landfilled. Japan produces nearly 50 million ton of MSW every year of which around 15 million ton of waste is landfilled. Both Japan and the United states have thousands of landfills located in seismic regions. Therefore, it is important to understand the behaviour of MSW landfills under earthquake loading as earthquake loading can induce landfill failures and lead to ground water contamination or other geo-environmental disasters. The Federal Resource Conservation and Recovery Act (RCRA 1993)[1] of the United States Environment Protection Agency was one of the first regulatory legislations that has addressed the concern of seismic loading on MSW landfills. RCRA states that all components of a landfill located in a seismic impact zone must be

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designed to resist the maximum horizontal acceleration (seismic impact zone is defined as the area with 10 % or greater probability that the maximum horizontal acceleration in lithified earth material exceeds 0.1g in 250 years). Better understanding of seismic behaviour of MSW landfills can be used both for the design of new landfills and for risk assessing old landfills located in seismic regions.

Case histories reporting the performance of MSW landfills in the past earthquakes suggest that overall performance of landfills has been reasonably good, as shown in Augello et al. [2] and Anderson and Kavazanjian [3]. However, significant damage in the form of cover cracking and geomembrane tears was experienced by several landfills during the 1994 Northridge earthquake. While case histories provide valuable information about the seismic behaviour of MSW landfills, seismic design and analysis procedures should not be validated solely based on case histories as there are many uncertainties involved in case histories. Research into the seismic behaviour of MSW landfills has been limited to numerical analyses due to the difficulties associated in dealing with MSW in experiments. Hence, present understanding of seismic behaviour of landfills is mainly based on parametric studies carried out using various numerical packages such as SHAKE91(Idriss and Sun [4]), D-MOD (Matasovic [5]) and QUAD4M (Hudson et al. [6]). The results from numerical simulations have been compared with available case histories for validation. However, case histories provide only limited validation for the numerical procedures used in the seismic analysis of MSW landfills. Thus experimental results, such as from dynamic centrifuge testing, can provide better validation for the numerical procedures and enhance the understanding of seismic behaviour of MSW landfills.

The centrifuge modelling principle (Schofield [7]) has been used in the past by many researchers to study various aspects of landfills, for example Syllwasschy and Jessberger [8] investigated the horizontal earth pressures developed in solid waste landfills and Madabhushi and Singh [9] tested the integrity of landfill liners following earthquake loading. This study investigates the seismic behaviour of a MSW landfill experimentally by dynamic centrifuge testing at 50 times earth's gravity (50g). The landfill modelled was a single clay liner MSW landfill with 1H:1V side slope founded on sand deposit.

CENTRIFUGE MODELLING OF MSW LANDFILL

Modelling MSW landfill components

The main difficulty associated with centrifuge modelling of landfills is the physical modelling of landfill components, mainly the clay liner and the MSW. Researchers in the past have used consolidated clay to model the compacted clay liners (Jessberger and Stone [10]) and processed real MSW as model MSW (Syllwasschy et al. [11]).

Modelling 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 (Thusyanthan et al. [12]). This model waste was used in the centrifuge test. Properties of the model waste are given in Table 1.

Modelling the 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 10^{-9} m/s. In the present study, the compacted clay liner was modelled using a strip of consolidated kaolin clay. The clay was produced using one-dimensionally consolidated E-grade kaolin clay. This clay has a liquid limit of 51%, 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 thick layer would represent a 1 m clay liner at 50g.

Modelling foundation soil

Foundation soil was modelled by fraction-E silica sand, whose properties are shown in Table 1.

Table.1-Properties of Model waste and fraction E silica sand

Properties of Model waste		**Properties of fraction E silica sand**	
Property	**Value**	**Property**	**Value**
Friction angle	45º	Minimum voids ratio e_{min}	0.613
Coefficient of compressibility C_{ce}	0.25	Maximum voids ratio e_{max}	1.014
Unit weight	10 kN/m^3	Permeability at e = 0.72	0.98×10^{-4} m/s
Shear wave velocity	70 m/s	Critical state friction angle φ_{crit}	32º

CENTRIFUGE MODEL PREPARATION

The dynamic centrifuge test was performed in an equivalent shear beam (ESB) box of internal dimensions 235 × 560 × 222 mm. The design and performance of the ESB box was described by Zeng and Schofield [13]. The schematic layout of the landfill model and instruments is shown in Figure 1. The centrifuge model was prepared in stages. Firstly, dry fraction-E silica sand was air-pluviated to a depth of 200 mm in the ESB container. Accelerometers were placed at the locations shown in Figure.1 during the sand pouring stage. The rate of pouring and the height of drop to the sand surface were fixed to obtain a uniform relative density of 45%. The sand was then saturated by the upward percolation of water through drainage holes near the base of the ESB box. Once the sand was fully saturated, water was allowed to drain under gravity. The suction created 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 160 mm with a side slope of 45°. The 20 mm thick clay liner strips, trimmed from one-dimensionally consolidated clay, were placed on both the excavated bottom surface and the side slope. The accelerometers were placed at the bottom and side of the clay liners. The model waste was then placed into the landfill model in layers. Each layer was compressed by a static load to obtain a unit weight in each layer of 9 kN/m^3, which is a common compaction density for MSW. A linearly varying differential transformer (LVDT) was mounted on the top of the container to measure the model waste settlement during swing-up (increase of centrifuge acceleration) and during the earthquake loading. Figure 2a. to 2e. shows the model preparation steps.

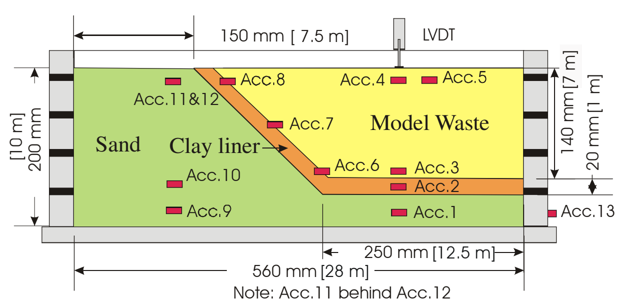
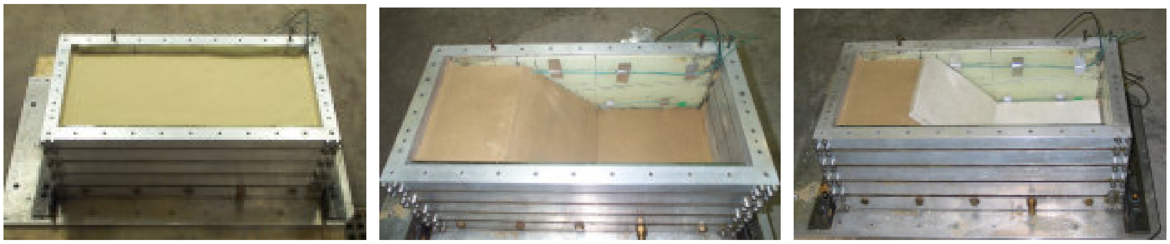


Figure 1 Schematic cross section of the Centrifuge model [prototype dimensions]



2a.Model ready for saturation *2b.Side-slope excavated* *2c.Clay liner placed*

2d. Accelerometers placed on clay liner *2e. Completed model* *2f. Model loaded in centrifuge*

Figure 2. Model preparation sequence

TESTING PROCEDURE

The dynamic centrifuge test was performed at 50 times earth's gravity (50g) on the 10m beam centrifuge at the Schofield Centre, University of Cambridge, UK. The landfill model was loaded into the centrifuge (Figure.2f) and was swung-up to 50g in stages of 10g, 20g and 40g. At 50g, seven earthquakes of varying intensity and magnitude were applied to the model by the stored angular momentum actuator, whose design and performance is described by Madabhushi et al. [14]. Table 2 provides the details of the applied earthquakes. The readings of the accelerometers and the LVDT during the earthquake loading were recorded at 4 kHz.

Table 2. Model earthquakes applied in the test (prototype scale).

Earthquake	Main Frequency(Hz)	Duration (s)	Maximum acceleration of Acc.9 (g)
E.1	0.6	15	0.098
E.2	0.8	15	0.124
E.3	1	15	0.176
E.4	1	15	0.158
E.5	1	15	0.284
E.6	1	15	0.331
E.7	1	15	0.334

RESULTS

Settlement of the model waste was monitored throughout the test. Total surface settlement of 18.6 mm was recorded by the LVDT after the swing-up to 50g. This settlement corresponds to 13.3% of the original height of the model waste (140 mm). Hence at 50g the depth of model waste is 121.4 mm (prototype depth of 6.07 m) and this increases the unit weight of model waste to roughly 10 kN/m^3. Accelerations recorded by Acc.9 (base), Acc.2 (clay liner), Acc.12 (sand surface) and Acc.4 (waste surface) during model earthquakes 1,2,3 and 7 are given in Figure 3a to 3d. Acc.1 and Acc.3 malfunctioned in the test.

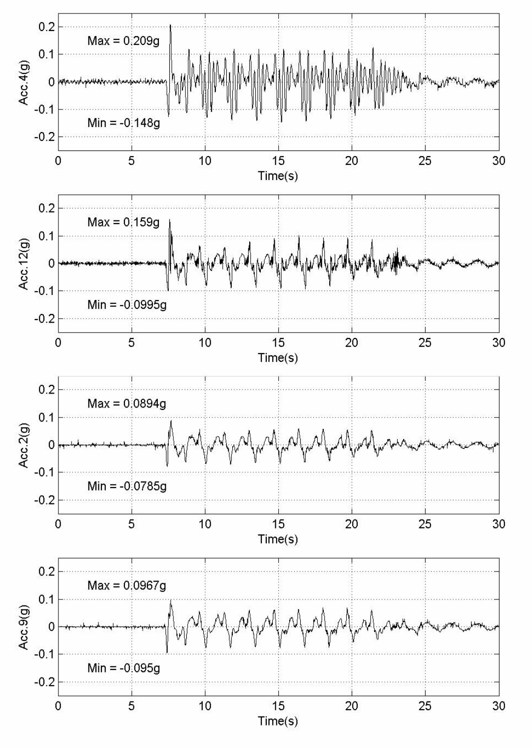


Figure. 3a-Earthquake 1

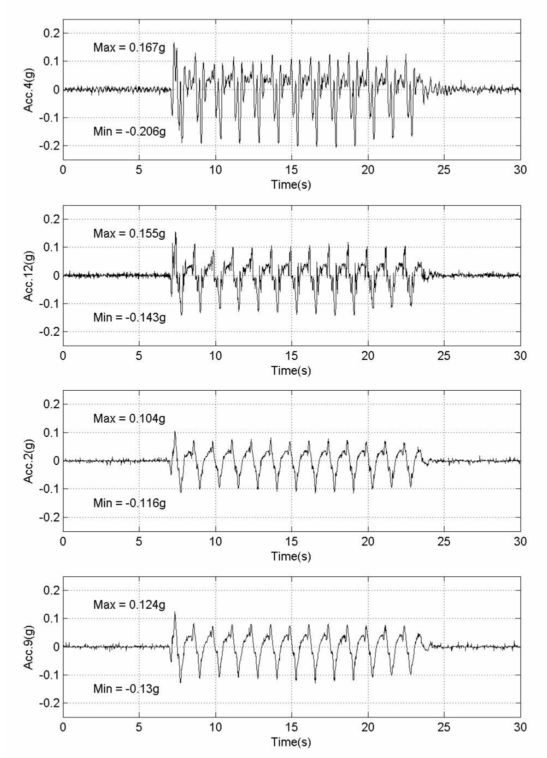


Figure. 3b-Earthquake 2

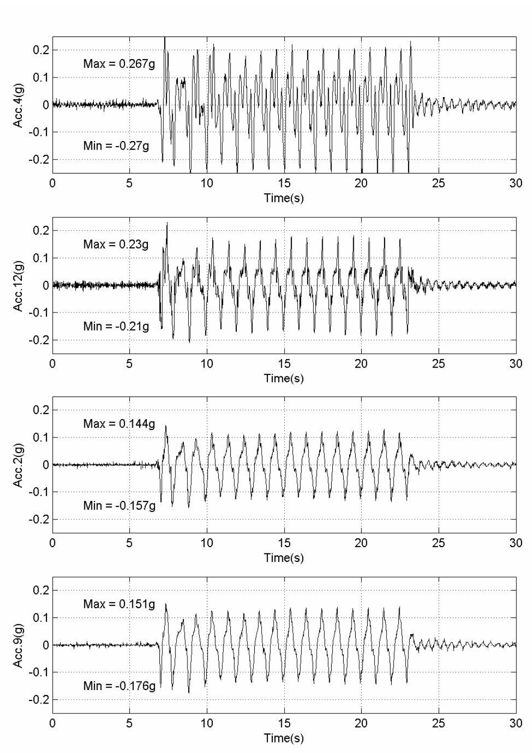


Figure. 3c-Earthquake 3

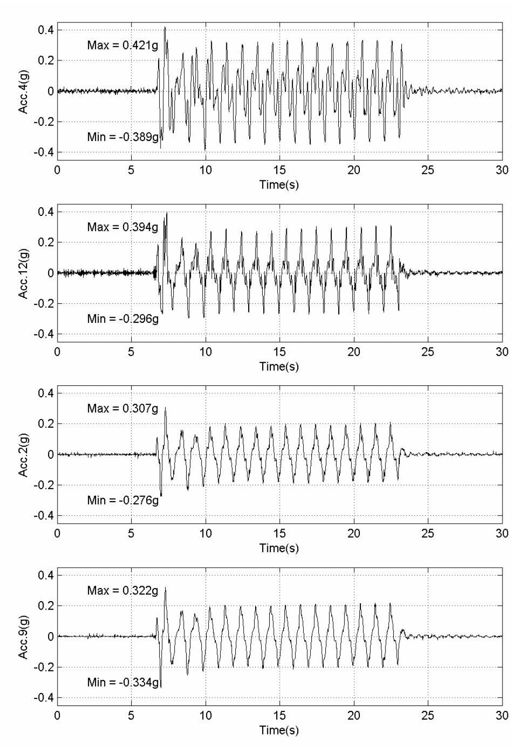


Figure. 3d-Earthquake 7

Post test observations

Post-test observation of the centrifuge model showed a crack in the top surface of the model waste near the clay liner. The cracks were 250 mm to 500 mm wide in prototype scale (5 mm to 10 mm in model scale) running parallel to the clay liner. Since 7 earthquakes were applied to the model, the post-test observation is of accumulated damage. Hence the cracks cannot be associated with any particular magnitude earthquake. However, the observed cracks are similar to those reported by Johnson et al. [15] after Loma Prieta earthquake and by Augello et al. [2] after the Northridge earthquake. In reported cases the most commonly observed damage in the landfills was the surface cracking in the cover soil, mainly near the transition between the waste fill and natural ground. Evidence of similar cracks in the centrifuge model shows that the dynamic centrifuge testing of landfill models can capture the realistic damage that occurs in a landfill under earthquake loading.

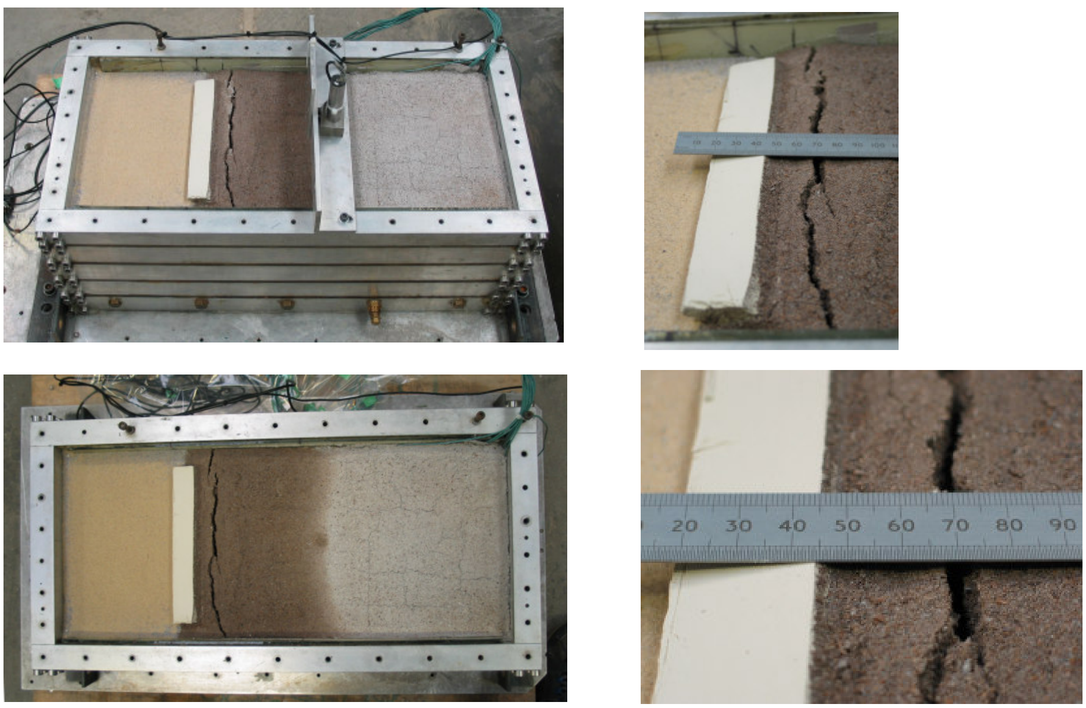


Figure 4. Post Test observations showing the crack in the model waste near the clay liner

ANALYSIS OF RESULTS AND COMPARISON WITH PREVIOUSLY PUBLISHED DATA

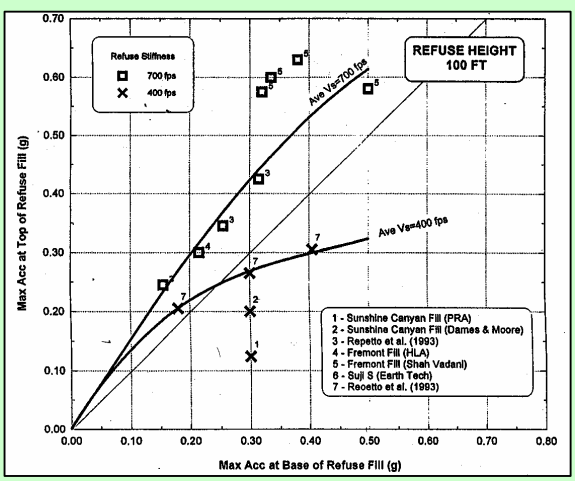
Seismic analysis of landfills involve three main steps:-

1. Characterisation of the seismic ground motion for design or analysis;
2. Evaluation of landfill response to seismic ground motion;
3. Stability and deformation analyses of landfill.

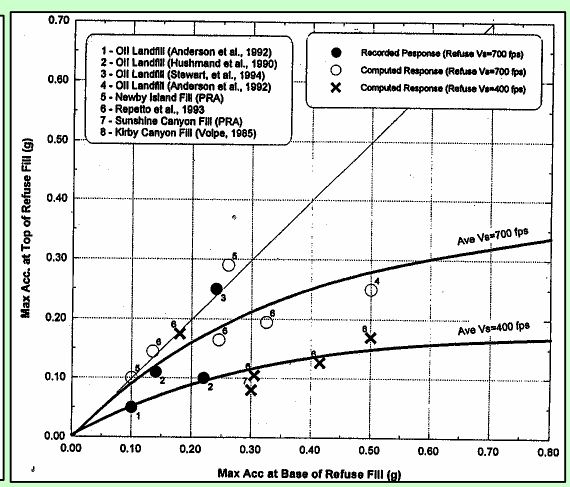
The relevant regulatory bodies govern the first step, characterisation of the seismic ground motion to be used for landfill design. For example, Subtitle D of RCRA (US EPA) provides two alternative ways for evaluating earthquake ground motions; the use of probabilistic acceleration maps (USGS maps), or a site-specific acceleration determination. Simplified response analyses and numerical response analyses are then used in the evaluation of landfill response to the design earthquake. Finally, pseudo-static analyses and Newmark deformation analyses are used to calculate seismic deformations.

The acceleration values obtained either from probabilistic acceleration maps or by site-specific acceleration determination represent the free-field ground motion at a rock outcrop. This does not necessarily represent the free-field soil acceleration at the landfill site. Soil conditions at the landfill site will influence the ground accelerations experienced by the landfill. Simplified and detailed procedures are available for determining the effect of local soil conditions on earthquake ground motions. The simplified approach is mainly based on charts, which were developed from recorded site responses in past earthquakes and analytical studies. The detailed seismic site response analyses are performed by numerical computer codes. The simplified approach for evaluating the influence of soil conditions on the amplification potential of peak ground acceleration (PGA) was first introduced by Seed and Idriss [16].This chart was later modified by Idriss [17] after the 1989 Loma Prieta earthquake. Since the shear wave velocity of MSW appear to be mainly between that of soft and medium stiff soil. Kavazajian and Matasovic [18] suggested that the soft soil curve by Idriss [17] can also be used to evaluate the peak acceleration at the top of a landfill. Singh and Sun [19], using published data, field data and computed response, produced charts of maximum surface acceleration (top or crest of a landfill) against maximum acceleration at the base of a landfill for 30 m (100 feet) and 60 m (200 feet) height waste with shear wave velocities of 122 m/s (700 fps) and 213 m/s (400 fps)-Figure 5.

The acceleration records obtained in the present dynamic centrifuge test can be used to understand the amplification characteristics of MSW landfills. The prototype peak acceleration in the sand (Acc.12) and in the model waste (Acc.4) against the prototype peak acceleration of the base(Acc.9) for each earthquake cycle for all the 7 earthquakes have been plotted along with the results from Kavazanjian and Matasovic [18] and Singh and Sun [19] in Figure.6. The results of Kavazanjian and Matasovic [18] include the soft soil site amplification curve along with the observed response of OII landfill and the results of non-linear site response analyses. Singh and Sun [19] suggested that the amplification developed by Harder [20] for earth dams may be viewed as the upper bound on the amplification of free-field PGA at the top of landfills, which is also included in Figure 6.



100 feet Refuse



200 feet Refuse

Figure 5. Approximate relationship between acceleration at base and crest of a landfill, Singh and Sun [19]

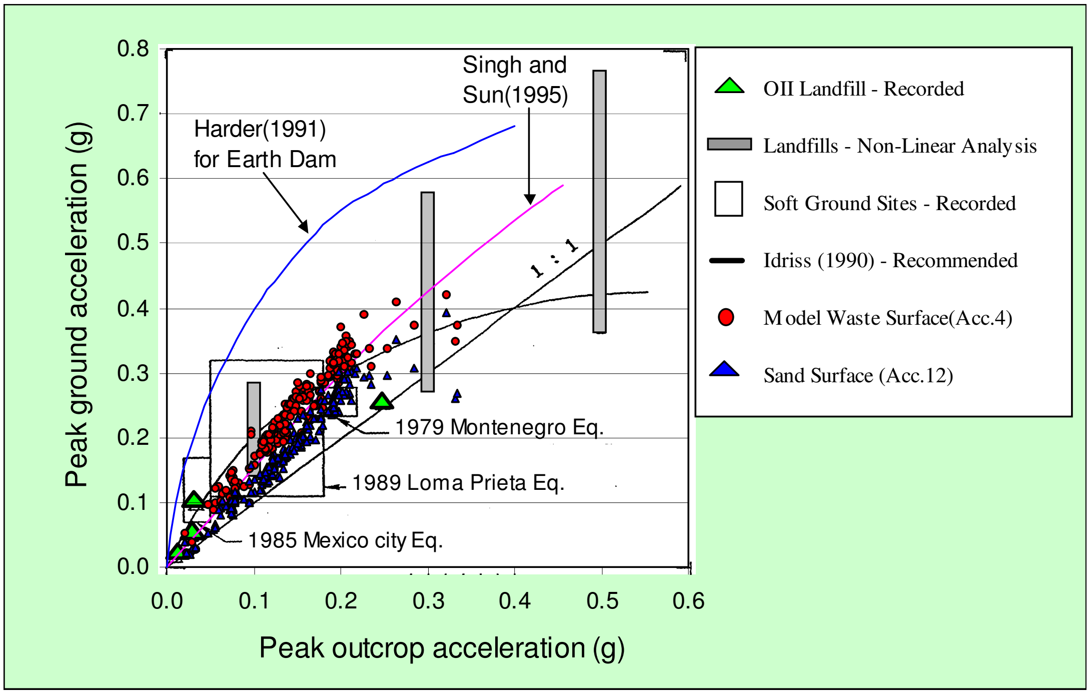


Figure 6. Data from present dynamic centrifuge test and from Kavazanjian and Matasovic [18] and Singh and Sun [19]

As can be seen from Figure. 6, the curve proposed by Singh and Sun for refuse height of 30 m (100 feet) and shear wave velocity of 213 m/s forms almost a lower bound to the dynamic centrifuge test results of the model waste. The relationship between the maximum base acceleration and maximum surface acceleration for both model waste and sand is almost linear. The maximum acceleration at the surface of model waste is about 15 % to 20 % more than that in sand.

It is a well known fact the fundamental frequency (f_0) of the waste fill and the frequency content of the earthquake plays a vital part in the amplification of acceleration through the waste. This is clear from the charts given by Singh and Sun [19] (Figure 5) and in the results of Bray et al. [21,22]. Figure.7 shows the data from the present test and the charts produced by Singh and Sun [19] along with the fundamental frequency (f_0) of the waste fill. The shear wave velocity of the model waste is 70 m/s (Thusyanthan et al. [12]) and the prototype depth at 50g is 6 m, hence its fundamental frequency is 2.9 Hz. Figure 7 shows how the fundamental frequency of the waste fill alters the relationship between the maximum base acceleration and maximum top surface acceleration of a waste fill. In a preliminary assessment for seismic design or analysis of a MSW landfill, Figure 7 can be used to predict the maximum acceleration at the top of a landfill once the fundamental frequency of the landfill is known. The PGA at the top of the landfill estimated from this chart is applicable to seismic cover performance, however the seismic behaviour of the landfill liner requires the peak average acceleration of the entire waste mass above the liner system to be known. Hence the average acceleration of the waste mass, termed the Horizontal Equivalent Acceleration (HEA), is used in seismic analyses of landfill base liner systems by Bray et al. [21].

While these simplified charts provide a quick and easy approach to predict the PGA at landfill sites and of the landfill cover system, the chart should be used with caution as variations in waste properties and landfill topology can result in considerable change in the PGA. Hence a more realistic possible range of the PGA can to be obtained by obtaining an upper and lower bound on the PGA with the possible variations in the waste properties. It should also be noted that the frequency content of an earthquake can also alter this simplified chart (Figure 7). Figure 7 is applicable to common earthquakes whose frequency

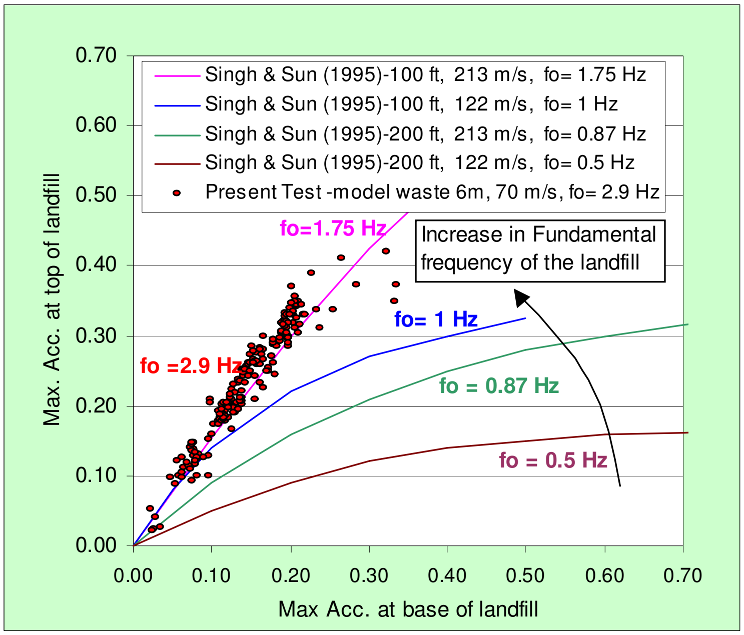


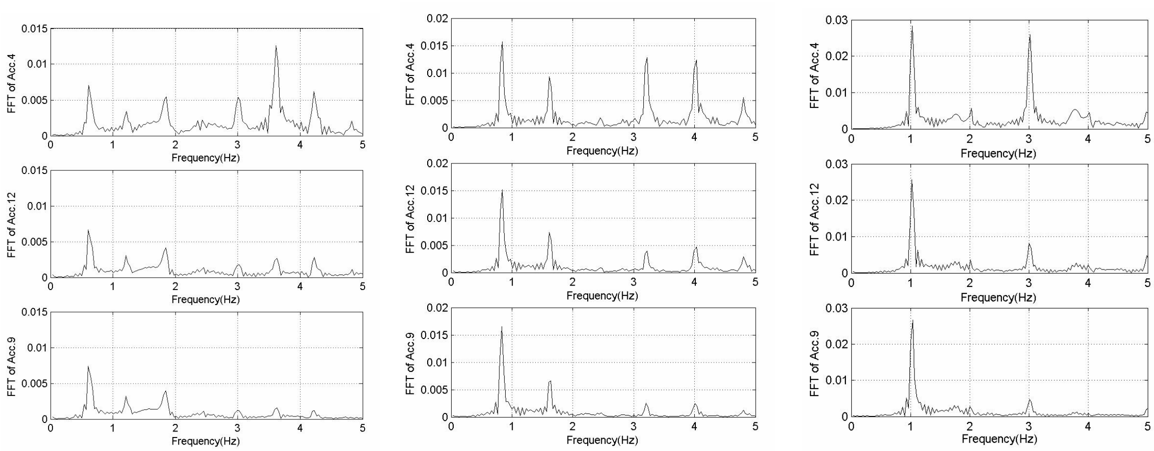
Figure 7. Dynamic centrifuge data and Singh and Sun (1995) proposed curves showing the influence of fundamental frequency (f_o) of the waste fill on the curves.

content is mainly between 1 Hz to 5 Hz. Further centrifuge tests can be used to validate this simplified chart.

This chart provides a good initial estimate of a MSW landfill response. A more formal numerical analysis can be carried out for design purposes.

Frequency analysis

Figure 8 shows the Fast Fourier Transform(FFT) of the acceleration signals Acc.9 (base), Acc.12 (sand surface) and Acc.4 (waste surface) for earthquakes 1, 2 and 3. It is clear from Figure 8 that higher harmonics that are near the fundamental frequency of the waste (2.9 Hz) are amplified in the model waste.



Earthquake 1 (0.6 Hz) **Earthquake 2 (0.8 Hz)** **Earthquake 3 (1 Hz)**

Figure 8. Fast Fourier Transform of acceleration signals from Earthquake 1,2 and 3.

COMPARISON WITH 1D NUMERICAL PREDICTIONS

There are several numerical response analysis programs that can be used to analyse the seismic response of a MSW landfill provided that the appropriate parameters for the MSW is known. SHAKE (Schnabel et al. [23]) was one of the first site response analysis programs and is still commonly used as SHAKE91 (Idriss and Sun [24]). SHAKE91 calculates the seismic site response based on the solution of vertical propagation of shear waves through a one-dimensional column of soil in the frequency domain. It is an elastic total stress analysis and uses an equivalent linear method to model the non-linear dynamic modulus and damping as a function of shear strain. EERA (Equivalent –linear Earthquake Response Analysis, Bardet et al. [25]) is a modern implementation of the SHAKE91 program. Results from EERA have been compared and validated with SHAKE91. EERA's input and output are fully integrated with the spreadsheet program MS Excel, hence it is a very user-friendly piece of software.

EERA was used in the following analyses to predict the top surface acceleration in model waste given that the acceleration to the base of the MSW is known. The acceleration records of Acc.2 (clay liner acceleration) was used as the input base acceleration in the analyses. The MSW was modelled by 6 layers of 1m thickness (same as the prototype thickness of MSW in the experiment) with a shear wave velocity of 70 m/s. A series of analyses were carried out with various shear modulus reduction and damping curves and the top acceleration predicted from the EERA analysis was compared with the experimental acceleration from Acc.4. Figure 9a shows the shear modulus reduction and damping curves that produced an overall best match between predicted and experimental accelerations. These curves are very similar to that reported by Boulanger[26] for Shearman Island peat (Figure 9b). This is not surprising as the model waste consists of 1/3 peat. Hence, the shear modulus reduction and damping curves of model waste can be expected to be similar to that reported for peat. However, it should be noted that the maximum shear strain computed by EERA in the model waste during earthquake 7 (highest magnitude) is 0.52 %. Hence the shear modulus reduction and damping curves given in Figure 9a for model waste are not validated beyond this shear strain.

Figure 10 compares the predicted acceleration time history with the experimental observed acceleration time history. It can be seen form the figure that the EERA analysis predictions are very similar to the experimental values for all seven earthquakes.

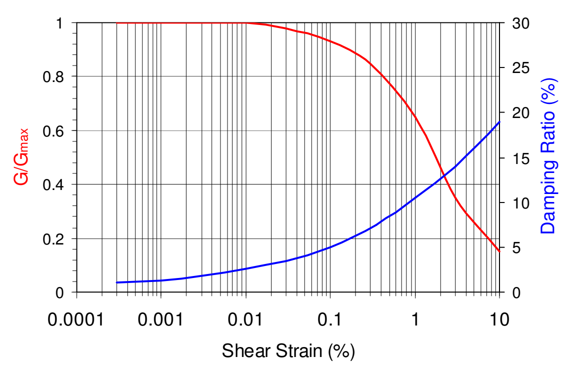


Figure 9a.Shear modulus reduction and damping curves used for model waste

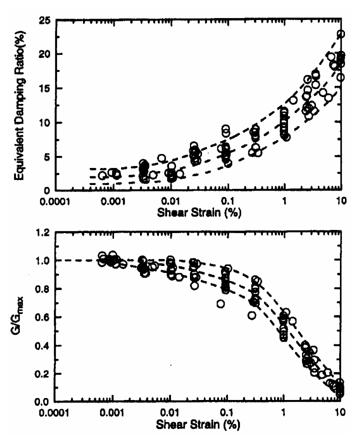
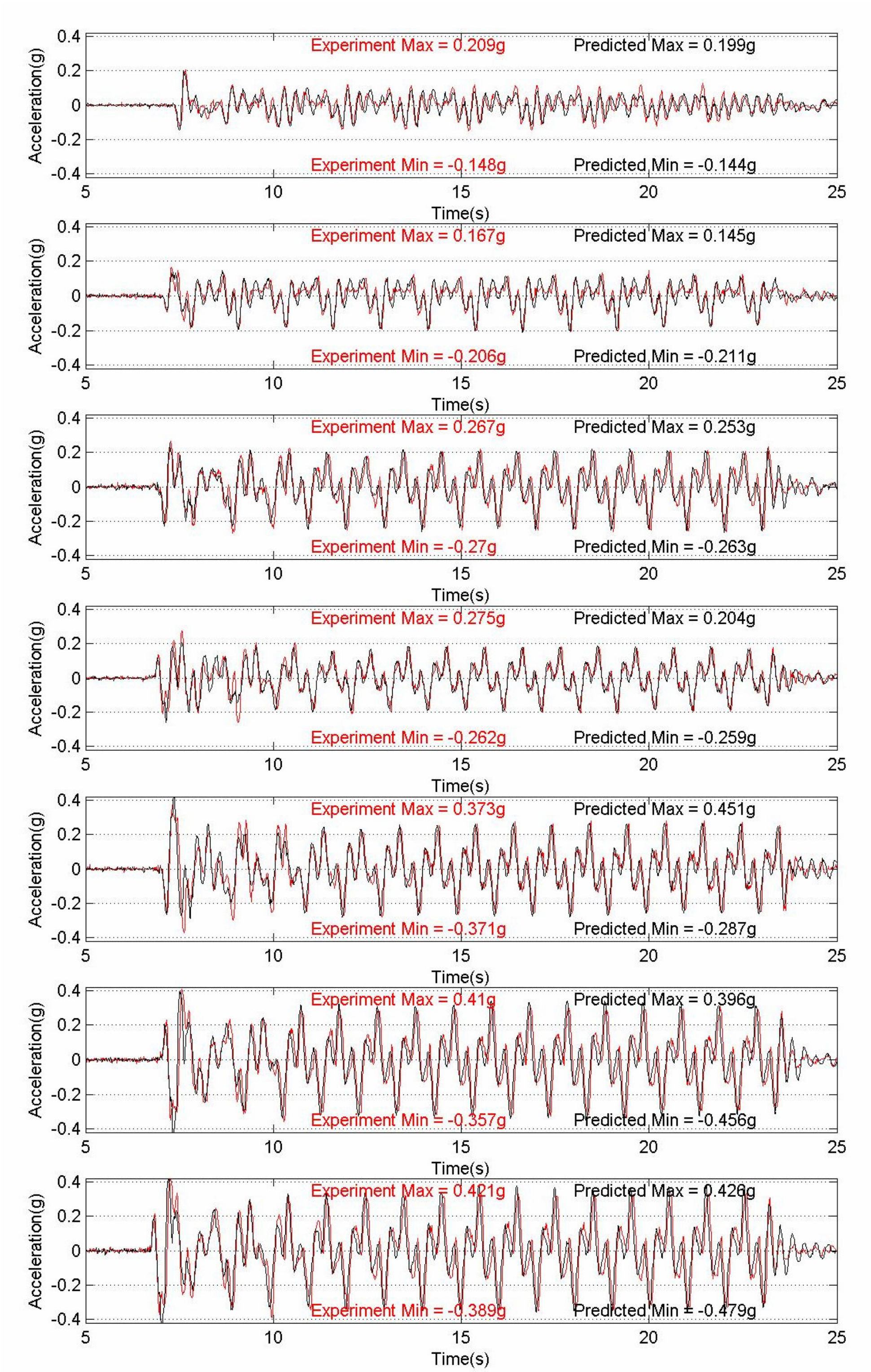


Figure 9b.G/G_{max} and damping ratio versus shear strain for Sherman Island Peat results of Boulanger et al. [26]



Earthquake 1

Earthquake 2

Earthquake 3

Earthquake 4

Earthquake 5

Earthquake 6

Earthquake 7

Figure 10. Comparison between 1D numerical prediction of EERA and experimental results

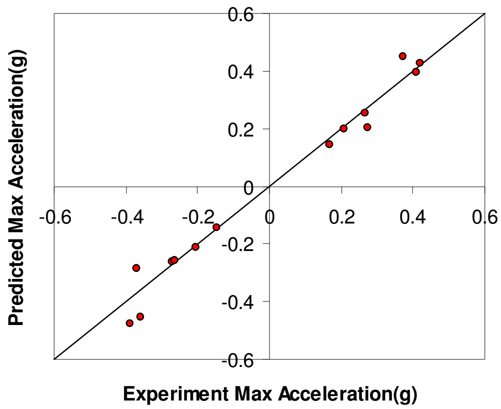


Figure 11 shows the maximum predicted acceleration versus the maximum observed acceleration in the experiment for all seven earthquakes. Again the EERA analysis predictions of maximum accelerations are very similar to the experimental values for all seven earthquakes.

Figure.11- Experimental and predicted maximum accelerations

DISCUSSION

1D time-domain codes and finite element codes can analyse the seismic behaviour of a MSW landfill more accurately than 1D frequency-domain codes. However, 1D frequency-domain analysis (such as SHAKE91) has two main advantages over time-domain and finite element analyses, being much faster and more economical. Results from the analyses in EERA has shown that it is possible to use a 1D frequency-domain numerical code to predict the acceleration response of the model waste well. Since the model waste has similar physical properties as real MSW, it can be inferred that 1D frequency-domain numerical analysis can predict the acceleration response of MSW well provided that the correct shear modulus reduction and damping curves of MSW are used in the analysis.

However care should be taken when using 1D frequency-domain numerical codes such as SHAKE91 for analysis or design of MSW landfills. This is because the accuracy of the results entirely depends on using the correct shear modulus reduction and damping curves. For a given earthquake, the SHAKE91 results will be correct provided that the shear modulus reduction and damping curves are correct up to the maximum shear strain calculated in SHAKE91 for that earthquake. The shear modulus reduction and damping curves for shear strains beyond this maximum shear strain are irrelevant for that particular analysis. Hence in order to obtain reliable results from SHAKE91, the shear modulus reduction and damping curves should have been validated for a slightly higher magnitude earthquake than the one which is to be analysed (this is due to the iterative nature in following the shear modulus reduction and damping curves in SHAKE91 type analysis). In the present analysis carried out in EERA, accelerations predicted for all seven earthquakes agreed well with the experimental results. This validates the shear modulus reduction and damping curves up to the maximum shear strain of 0.52 %, which was calculated in the highest magnitude earthquake (E.7). Hence these curves can be used in EERA or SHAKE91 analysis with confidence for earthquakes that yield calculated shear strains up to 0.52 %.

CONCLUSIONS

Dynamic centrifuge testing was performed to understand the seismic behaviour of a single clay liner MSW landfill founded on sand. The MSW was modelled by a model waste whose physical properties are typical of real MSW and the clay liner was modelled by a strip of normally consolidated clay. Seismic response of the MSW landfill was investigated under seven model earthquakes of varying intensity (0.098g to 0.334g) and frequency (0.6 Hz to 1 Hz). The maximum accelerations experienced by the model waste whilst subjected to the model earthquakes were used to understand the amplification characteristics of MSW landfill. Previously published data along with the present dynamic centrifuge test results were used to produce a simplified acceleration response chart (Figure 7) for MSW. This chart relates the maximum base acceleration to the maximum top surface acceleration of MSW landfill for various fundamental frequencies. It was also shown that 1D frequency-domain numerical analysis can predict the acceleration response of a MSW landfill well provided that correct and validated shear modulus reduction and damping curves are used in the analysis.

This study has shown that dynamic centrifuge testing can be utilised to understand the effects of earthquake loading on MSW landfills, both in understanding physical damage to MSW landfill and in understanding its acceleration response. Hence further dynamic centrifuge testing with the model waste can be used to better understand the seismic response of MSW landfills with different configurations or different foundation conditions.

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