# Modelling the Seismic Behaviour of Municipal Solid Waste

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Abstract—This study aims to understand the seismic behaviour of Municipal Solid Waste (MSW) by dynamic centrifuge modelling. This paper presents the development of a model waste that has similar physical properties to typical MSW and the results from dynamic centrifuge tests on that model waste. The response of the model waste was measured during model earthquakes of varying intensity and frequency. It will be shown in this paper that the amplification of accelerations within the model waste depends mainly on the earthquake intensity.

*Keywords*—Centrifuge, Municipal Solid Waste, Waste fills, Seismic behaviour

## INTRODUCTION

Seismic behaviour of landfills is a major concern as landfill failures can lead to ground water contamination and other geo-environmental disasters. Study into the seismic behaviour of municipal solid waste (MSW) landfills has often been limited to numerical analysis due to the difficulties associated with dealing with real waste in experiments. Hence present understanding of seismic behaviour of MSW landfills is mainly based on parametric studies carried out using numerical packages (e.g. SHAKE91) and the few recorded earthquakes.

Recorded performance of landfills in past earthquakes have been reasonably good [2], [3] although the 1994 Northridge earthquake raised major concerns over the integrity of many landfills [1]. However much remains to be leant about the seismic behaviour of MSW [4]. Amplification of acceleration through a MSW landfill is one of the main factors which is vital in the seismic design of the cover and gas collection systems. Fourier analysis of recorded accelerations at OII landfill and numerical analysis of other landfills have shown the amplification of low frequency (0.5 to 1 Hz) components [2], [4] & [6] as the natural frequency of these landfills is close to 1 Hz.

Numerical studies have been carried out in the past to understand the influence of the height of waste fill and the characteristics of bedrock motion (intensity, frequency content and duration) on the maximum horizontal acceleration experienced by landfills with different foundation conditions [5]. Results from numerical analysis however depend mainly on the shear modulus reduction and damping curves used for MSW and these curves are not well established and are still being revised. Thus experimental work in this area, such as dynamic centrifuge testing, can be used to validate and enhance the numerical results.

The centrifuge modelling principle has been used in the past by many researchers to study different aspects of MSW landfills [7] & [8]. The main difficulty in centrifuge modelling of MSW landfills is the use of MSW. This paper presents the development of a model waste which can be used in centrifuge experiments to model both the static and dynamic behaviour of MSW. Dynamic centrifuge tests were performed on the model waste and results compared with the available recorded and numerical data.

#### PHYSICAL MODELLING OF MUNICIPAL SOLID WASTE

Municipal solid waste 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. 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 to those of real MSW. Municipal solid waste exhibits physical, chemical and dynamic properties that an ideal model waste would have to match. However, it is both impractical and virtually impossible to create such a model waste without actually using real MSW. If the experimental study in which the model waste is going to be used is aimed at understanding the mechanical behaviour of MSW, it is then sufficient to produce a model waste that has the main physical and dynamic properties of real MSW.

The main physical properties of MSW considered here are unit weight, compressibility, shear strength and moisture content. References [9] and [10] provide a comprehensive summary on these properties published by various researchers. Dynamic properties of the MSW, which are the shear wave velocity and the shear modulus reduction and damping curves, have also been reported by many researchers[11] & [12]. Earlier research on MSW proposed shear modulus and damping curves to be intermediate between those of clay and peat for MSW [13]. Revised curves have been proposed based on backanalyses of past earthquakes and cyclic tests.

## PREPARATION OF MODEL WASTE

Following from the published work, it can be concluded that a mixture of peat and clay can be a starting point for modelling MSW. Since it is a legislatory requirement that all MSW landfills be covered with at least 15 cm of daily cover soil, usually sand, the MSW in a landfill can be expected to contain sand as well. It was reported that 10% to 30% of the recovered material from MSW landfill boreholes to be soils used as daily cover [5]. Hence the modulus and damping curves of MSW might be a combination of those developed for sand, clay and peat. Therefore a mixture of these three materials might produce a reasonable model waste. In order to understand the ratios required to obtain real MSW behaviour, three different mixtures (mixture A,B & C) were produced and their physical properties investigated. Dry fraction E silica sand, dry E-grade kaolin clay and peat were mixed in known ratios to produce the mixtures. Peat, classed as "Irish moss peat", was obtained from a garden centre (Madingley Mulch, Cambridge). This peat had a water content of 200%. 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 (table 1).

Peat has many constituents of varying size such as roots and seeds. The size and amount of these larger size constituents vary from bag to bag. Thus in order to have consistency and control over the peat, it was sieved using a BS-410 (4 mm) sieve. Known quantities of sand, clay and peat were mixed in a mechanical mixer until homogeneous. The mixture was again sieved by a BS-410 (2.36 mm) sieve to obtain the final model waste mixture. Fig. 1 shows the pictorial representation of the preparation of model waste mixtures.

The moisture content of mixtures A, B and C were 29%, 23% and 17% respectively. The average dry gravimetric moisture content of typical MSW is 26% [10], hence from moisture content point of view mixture A and B seems to be more suited as model waste than mixture C.

TABLE I: MODEL WASTE MIXTURES

	Mix A	Mix B	Mix C
Weight ratios			
Peat	2	1	1
Clay	1	1	2
Sand	1	1	1
Dry gravimetric moisture content	29 %	23 %	17%

## PHYSICAL PROPERTIES OF MODEL WASTE MIXTURES

One-dimensional compression tests and direct shear tests were performed on all three mixtures to understand the variation of unit weight with vertical effective stress, compressibility and shear properties. Both the compression tests and direct shear tests were performed



Fig. 1: Preparation of model waste mixtures.

in a standard shear box ( $100 \text{ mm} \times 100 \text{ mm} \times 50 \text{ mm}$ ). An odometer was not used for compression tests because of the inability of the available odometer to measure large compression of the mixtures and the fact that larger volume of the mixtures could be tested in the shear box.

#### Unit weight

MSW density is one of the main parameters required for both static and dynamic analysis of landfills. The unit weight of MSW can range from 5 to 18 kN/m<sup>3</sup> depending on its constituents and compaction effort in placement [11], [10] & [14]. It also varies with vertical effective stress [15].

The variation of unit weight with vertical effective stress was investigated for all three mixtures. Unit weight was calculated by dividing the initial weight of the mixture by the present volume of the mixture during the compression test. Fig. 2 shows the variation of unit weight of the mixtures with vertical effective stress. All three mixtures exhibited the same trend of variation of unit weight with effective stress; however mixture A had the highest and mixture C the lowest unit weight for a given effective stress. The variation of unit weight with effective stress exhibited by the mixtures B and C is very similar to that of real MSW reported by researchers [15].



Fig. 2: Variation of unit weight with effective stress for model waste mixtures.

#### Compressibility

Compressibility of MSW is a vital parameter which determines the capacity, future design and planning of MSW landfill sites. MSW compressibility is expressed by coefficient of primary compression ( $C_{ce}$ ).

$$C_{ce} = \frac{\Delta H}{H_0 \log(\sigma_1/\sigma_0)} \tag{1}$$

where

 $H_0$  = original thickness of waste layer  $\Delta H$  = change in thickness of waste layer

 $\sigma_0$  = initial vertical stress

 $\sigma_1$  = final vertical stress

Researchers have reported that, depending on the initial compaction effect and composition of waste, the coefficient of primary compressibility could vary from 0.17 to 0.36 [10] & [16].

Fig. 3 shows the compressibility of model waste mixtures. In the first series of experiments (set 1), the mixtures were pre-compressed by 10 kPa load, hence 10 kPa was taken as the datum for strain measurements. In the second set of experiments (set 2), mixtures were pre-compressed by 1 kPa. The results show that all three mixtures exhibit very similar coefficient of primary compressibility ( $C_{ce} = 0.25$ ), which is within the range of  $C_{ce}$  reported for MSW.



Fig. 3: Vertical strain vs effective stress for model waste mixtures.

#### Shear strength

The shear strength of municipal solid waste depends on many factors such as its constituents, the mode of placement (i.e. the compaction, amount and type of daily cover), and the age. Hence while characterising the shear strength of MSW, thought should be given into these factors. The shear strength properties of MSW reported in literature have been determined by direct laboratory testing, field testing or back-analyses from failures.

Direct shear tests were performed on the model waste mixtures to understand the shear characteristics. A strain rate of 0.48 mm/min was used in the tests. The test results at normal effective stress of 50 kPa shows that all three mixtures exhibit very similar shear characteristics, mobilised friction angle of 45° at displacements of 10 mm and increasing with displacement (Fig.4a). The increase of mobilised friction angle with shear displacement (or with shear strain) is a characteristic of MSW as reported by many researchers [17]. This same behaviour is exhibited by model waste mixtures.

A test carried out on mixture B at a higher strain rate of 1.2 mm/min gave slightly lower friction angle initially but similar results as that of test at 0.48 mm/min after about 7mm displacement (Fig. 4b). Mixture B sheared at 100 kPa exhibits lower mobilised friction angle than that sheared at 50 kPa and over consolidated mixture B sheared at 50 kPa exhibits higher mobilised friction than that sheared at 50 kPa. This trend is similar to the results of simple shear and direct shear tests reported [17].

## CHOICE OF MODEL WASTE

Table 2 summarizes the suitability of mixtures A,B and C as model waste. Mixture C tended to form kaolin dust while handling at its moisture content of 17%. Thus even though all three mixtures have the potential to be used as

model MSW, mixture B was chosen as the most suitable due to ease of handling.



Fig. 4a: Shear strength of model waste mixtures.



Fig. 4b: Strain rate and Over-consolidation ratio(OCR) effects on shear strength of mixture B.

TABLE 2:- SUITABILITY OF MIXTURES A, B AND C AS MODEL

MWS.					
Properties	Mix A	Mix B	Mix C		
Unit weight	*	**	**		
Compressibility	*	**	**		
Shear characteristic	**	**	**		
Moisture content	**	**	*		
Easy of handling	*	*	×		
Total	7*	9*	7*		

 $(* suitable, \times not suitable)$ 

It has been shown that the physical properties of mixture B agree well with those of a typical MSW. Reference [17] reports simple shear test results on real MSW at normal stress of 59 kPa and at strain rate of 1.5 mm/min. A direct comparison with the reported data is not possible as the present test is direct shear test. However for small displacements away from boundaries the behaviour of the sample in a direct test is the same as in a simple shear test. Thus comparison is possible for small displacements. Fig. 5 shows such a comparison of mixture B with the reported data. The shear strain can be obtained by dividing the displacement by sample thickness. It is important to note that shear strain values for mixture B in Fig. 5 are valid only small displacements (i.e. displacement < 2 mm, shear strain < 6 %). It can be seen from Fig. 5 that the initial stress-strain characteristics of the model waste mixture B matches well with that reported in [17] for the real MSW. This justifies the use of model waste to study the dynamic behaviour of MSW.

Fig. 6 shows the particle size distribution of model waste mixtures obtained using a single particle optical sizer (Nicomp Accusizer 780).





Fig. 6: Particle size distribution of model waste mixtures.

#### CENTRIFUGE FACILITY

A dynamic centrifuge test was carried out on the model waste (mixture B) to understand its seismic behaviour. The centrifuge test was performed at 50g on the 10m diameter beam centrifuge at Cambridge [18]. Model earthquakes of varying frequency and intensity were applied to the centrifuge model using the stored angular momentum actuator [19].

## CENTRIFUGE MODEL AND TESTING

The dynamic centrifuge test on model waste was performed in a equivalent shear beam box (ESB) of internal dimensions 235 mm  $\times$  560 mm  $\times$  222 mm, whose design and performance is described in [20]. The model waste was placed into the container in layers and each layer was compacted by static load to give a compacted unit weight of 9 kN/m<sup>3</sup>. Accelerometers (Acc's) were placed in each layer as shown in Fig.7. A mini-air hammer [21], which is capable of inducing small amplitude shear waves, was placed at the base of the container along with Acc.1. A linearly variable displacement transducer (LVDT) was mounted on top of the container to measure the model waste settlement during the swingup and during the test.

Fig. 8 shows the model prior to testing on the beam centrifuge. The model was swung up to 50g in stages of 10g, 20g and 40g. At 50g, mini-air hammer was activated and the accelerometer signals recorded at 30kHz. Seven earthquakes of varying intensity and magnitude were then fired using the stored angular momentum actuator. Table 1 provides the details of the fired earthquakes in prototype scale. All dynamic data was recorded at 4 kHz.



Fig. 7: Instrument layout and model waste in ESB container.

TABLE 2: EARTHQUAKES (Prototype scale)

Earthquake	Frequency (Hz)	Duration (s)	Maximum prototype base acceleration (g)
E.1	0.6	15	0.08
E.2	0.8	15	0.12
E.3	1	15	0.18
E.4	1	15	0.14
E.5	1	15	0.24
E.6	1	15	0.28
E.7	1	25	0.15



Fig. 8: Centrifuge package on the stored angular momentum actuator.

#### RESULTS

#### Shear wave velocity in model waste

Acc.1 and Acc.3 failed to work in the experiment. Hence the shear wave velocity was calculated based on the readings of Acc.2, 4 & 5 when the mini-air hammer was fired. An average shear wave velocity of 70m/s was calculated by dividing the distances between the accelerometers by the time lags in acceleration signal arrival times. Fig. 9 shows the recorded acceleration signals when mini air hammer was fired. The distances between the accelerometers were estimated by using the LVDT reading at 50g and post excavation measurements.



## Amplification of acceleration from base to top

The acceleration signals recorded during all 7 earthquakes showed amplification from base to top surface. Fig. 10 shows the acceleration signals during earthquake 3. Amplification of the acceleration from the base of model waste to the top surface was calculated for each cycle in the earthquake for all the earthquakes. The ratio of peak to peak acceleration from base to top surface was used to calculate the amplification. The base acceleration of the model waste (Acc.6) and the peaks of the top surface acceleration in earthquake 3 is presented in Fig. 11. Peak to peak acceleration of Acc.5 and Acc.10 were very similar. Fig. 12 shows the amplification between Acc.6 and Acc.5 for all 7 model earthquakes. It can be seen from Fig.12 that the amplification decreases linearly up to 0.1g input magnitude, then stays fairly constant at about 1.75 till 0.2g input and then starts to decease again.

The prototype peak ground acceleration (peak to peak Acc.10) against the prototype peak base acceleration (Acc.6) for each cycle from all the earthquakes have been plotted on top of the chart produced by [22](Fig.13). The curve proposed by [3] is also drawn in Fig. 13. The dynamic centrifuge test results agree well with the soft soil site amplification curve and also falls within the range of results obtained by non-linear analyses of landfills.



Fig. 10: Acceleration signals from E.3 (prototype).



Fig.11: Peak acceleration in each cycle in E.3 (prototype).



Fig. 12: Amplification of base acceleration.



Fig. 13: Modified from [22] (Kavazanjian and Matasovic, 1995).

#### Settlement

A total settlement of 19.2 mm was recorded by the LVDT at 50g before the earthquakes were fired. This represents a prototype settlement of 0.96 m. Hence the over-all unit weight of model waste is increased to 10 kN/m<sup>3</sup> before shaking.

The total settlement of the top surface of the model waste after each earthquake is plotted in Fig.14. At 50g, the prototype depth of the model waste was 9.04 m, hence the settlements recorded are insignificant (less than 0.3 % of total depth). However the settlements in E.1, E.2, E.3 & E.6 show a linear trend between induced settlement and peak base acceleration. This aspect needs further investigation.



Fig.14: Total settlement of model waste in earthquakes.

#### Frequency analysis

The natural frequency of the model waste in the container at 50g is 96.8 Hz, which in prototype scale is 1.94 Hz. Fig. 15a, b & c shows the fourier amplitudes of the base and top acceleration signals from the earthquakes 1, 2 & 3. The frequency of the applied earthquakes 1,2 & 3 in prototype scale is 0.6, 0.8 and 1 Hz respectively.



Fig.15a: Frequency content in Earthquake 1.



Fig.15b: Frequency content in Earthquake 2.



Fig.15c: Frequency content in Earthquake 3.

The following observations can be made from figures. 15a, b & c:

- amplification of energy at higher harmonics of the fundamental earthquake frequency occur in all 3 earthquakes. The maximum amplification factor is in the range 5 to 10 and occurs at frequencies between 3 Hz to 5 Hz.
- amplification of energy at the fundamental frequency of earthquake 1 (0.6 Hz) & earthquake 2 (0.8 Hz) is similar and near unity, However the amplification of energy at the fundamental frequency of earthquake 3 (1 Hz) is almost 2.
- the energy content near the natural frequency of the model waste (1.94 Hz) is amplified approximately by 2.5 in all three earthquakes.

## **CONCLUSIONS**

A model waste with physical properties similar to typical MSW has been produced. 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.

Results from dynamic centrifuge tests on the model waste agree with the recorded past earthquakes and falls within the range of results from non-linear analyses of landfills. Frequency analysis of accelerations signals show that the amplification factor varies with the frequency and is approximately 2.5 near the natural frequency of model waste. Higher amplification factors, in the range 5 to 10, were observed between 3 Hz and 5 Hz.

Further work in dynamic centrifuge modelling with the designed model waste can provide better understanding of seismic behaviour of MSW landfills.

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