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Centrifuge Modeling of Solid Waste Landfill Systems—Part 2: Centrifuge Testing of Model Waste

ABSTRACT: This paper presents the use of the model waste developed in the companion paper, "Centrifuge modeling of solid waste landfill systems—Part 1: Development of a model municipal solid waste," in centrifuge testing. Two centrifuge tests were performed using the model waste to understand the static and dynamic behavior of municipal solid waste (MSW) landfills. First centrifuge test demonstrates the use of model waste to study the settlement profile in a landfill. In the second centrifuge test model earthquake loadings were applied to the model waste to investigate its dynamic behavior. The results were used to obtain shear modulus reduction and damping curves of the model waste. These curves were shown to match with those reported for MSW validating the use of model waste to study the seismic behavior of MSW landfills.

KEYWORDS: municipal solid waste, modeling, centrifuge, landfills, seismic behavior

Introduction

Full-scale experiments associated with landfills are expensive and time consuming. Centrifuge testing provides an elegant way of performing experiments on small-scale models at prototypes stresses Schofield (1980) . The centrifuge modeling principle and testing has been used in the past by many researchers to study different aspects of landfills. For example, Jessberger and Stone (1991) investigated the subsidence effects on clay barriers and Evans (1994) studied contaminant migration through intact and damaged clay liners using consolidated clay in a drum centrifuge. Zimmie et al. (1994) studied the long-term performance of landfill covers. Syllwasschy et al. (1996) studied the radial stresses on leachate collection shafts by centrifuge tests using model shaft and processed MSW. Syllwasschy and Jessberger (1998) used a nonmovable retaining wall system in a centrifuge model with processed MSW to understand the horizontal earth pressures developed in solid waste landfills.

One further advancement in the use of centrifuges is dynamic centrifuge modeling (Schofield 1981). Dynamic centrifuge testing involves applying model earthquakes to the centrifuge model inflight, while the model is experiencing prototype stresses. Dynamic centrifuge testing is a promising tool for studying the seismic behavior of landfills. For example, Madabhushi and Singh (2001) used dynamic centrifuge testing to investigate the integrity of clay liners, founded on liquefiable deposit, during and post earthquake loading. Field data of seismic behavior of landfills is very limited, hence the results from dynamic centrifuge testing can be vital for understanding the dynamic behavior of landfills systems.

The main difficulty associated with centrifuge modeling of landfills is the physical modeling of landfill components, mainly clay liner system (compacted clay, geomembrane/geonet) and MSW. Researchers in the past have used consolidated clay to model the compacted clay liner of real landfills and processed MSW to model MSW. Use of processed MSW has many drawbacks as explained in the companion paper Thusyanthan et al. (2005) . This paper presents the use of the model waste in centrifuge testing. Two centrifuge tests were performed using the model waste. These two centrifuge tests demonstrate the use of the model waste to understand the static and dynamic behavior of MSW. The centrifuge tests were performed at 50-gravities (50 g) on the 10 m diameter beam centrifuge at Schofield Centre, Cambridge. The first test (IT-01) was designed to understand the settlement profile of a typical landfill cross section. The shear wave velocity of the model waste was also measured at different gravity levels in this test. The second test (IT-02) was a dynamic centrifuge test, in which the response of model waste to dynamic loading was investigated. This provides insight into the amplification of acceleration through a MSW landfill during an earthquake.

Settlement of MSW in a Landfill-Centrifuge Test IT-01

The aims of this centrifuge test (IT-01) were to understand the settlement profile of model waste in a landfill model and to measure the shear wave velocity of the model waste at different gravity levels.

Model Preparation and Testing

The cross section of the landfill model used is shown in Fig. 1. Prototype and model scale dimensions are given in Fig. 1(dimensions in brackets are model scale). The centrifuge test was performed in a rectangular strong box of internal dimensions 200 mm by 670 mm by 535 mm. A transparent Perspex of thickness 70 mm forms the front of the strong box. Thus, any deformations of the model inside the strong box can be observed while the model is flying at 50

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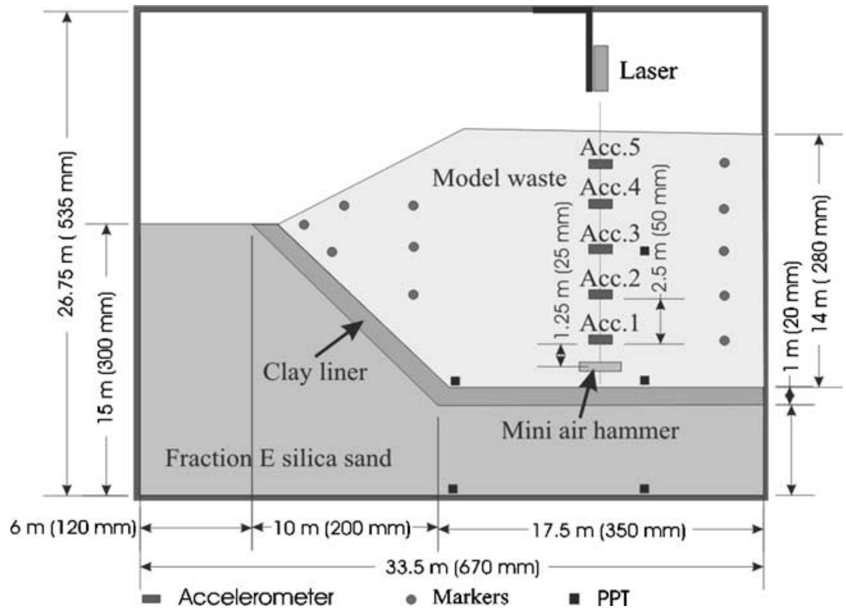

FIG. 1—*Cross section of IT-01 model* (*model scale dimensions in brackets*).

gravities. Three digital cameras were set up orthogonal to the Perspex to capture the cross-sectional view of the model. The model was prepared in stages. First, fraction-E dry silica sand was air pluviated to a depth of 300 mm in the strong box. 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 a network of drainage holes at the base of the strong box. Once the sand was fully saturated, water 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 200 mm and a side slope of 45°. Figure 2 shows the model preparation sequence.

The 20 mm clay liner strips, which were trimmed from one-dimensional consolidated clay, were placed on both the excavated bottom surface and the side slope. This clay, at 50g, represents a clay of 1 m in thickness. The model waste was then placed into the landfill in 25mm thick layers; each layer was compacted by static load to produce a compacted unit weight in each layer of 6 kN/m^3. Pore pressure transducers were placed as the base and the middle depth of model waste to measure any pore pressures in the model waste. A miniair hammer (Ghosh and Madabhushi 2002), which is capable of inducing small amplitude shear waves, was placed in the model waste after the first compacted waste layer (i.e., on 25 mm thick waste layer). Accelerometers (Acc.1–5) were placed in each layer of model waste along with some markers that would be used in posttest measurements of layer settlements.

The complete model was loaded into the centrifuge and swung up in 10 g increments to 50 g, maintained at 50 g until model waste settlement was complete. The top surface settlement of the model waste was continuously recorded by a laser, which was mounted on the top plate of the centrifuge test package. Digital pictures of the model cross section were also acquired throughout the test duration. The acquired pictures were subsequently used in particle-image velocimetry PIV (White et al. 2003) analysis to understand the precise movement of the clay liner. The miniair hammer was activated for a short period at each of the 10 g increments (i.e., 10, 20, 30, 40, and 50 g) and the accelerometer readings were recorded.

Results

Shear Wave Velocity of Model Waste

The time lags in the arrival times of recorded accelerometer signals were used to calculate the shear wave velocity of the model waste at different g levels. The movement of the accelerometers during increase of centrifuge acceleration phase was taken into account by using the compressibility of model waste. Cross correlation between the signals was used to obtain the best estimate of the time lag. The percentage error in the measured shear wave velocity due to the sampling rate and accuracy of accelerometer locations is about 10 %. Figure 3 shows the measured shear wave velocity versus effective vertical stress. The shear wave velocity increases from about 20 to 90 m/s with increasing vertical effective stress. The relationship $v=18.1(\sigma')^{0.41}$, where v(m/s) is shear wave velocity and σ'(kPa) is vertical effective stress, matches well with the results (Fig. 3).

Kavazanjian et al. (1994) performed spectral analysis of surface waves (SASW) testing on ten landfills in southern California to obtain shear wave velocity profile up to depths of 50 m. The results showed increase of shear wave velocity with depth. The shear wave velocity was also dependent on the age of the waste. The reported shear wave velocity near the surface of young waste (1–2 years) and older waste (5–7 years) were on of the order of 90 and 170 m/s, respectively. The shear wave velocities 20 m below surface were on the order of 140 to 170 m/s in young waste and 290 to 350 m/s in older waste. Downhole tests performed by Houston et al. (1995) in five boreholes at the Northwest Regional Landfill Facility, located in northwestern Maricopa County, Arizona, showed an increase of shear wave velocity from 124 m/s at the surface of refuse to 229 m/s at 10 m depth. Matasovic and Kavazanjian (1998) also performed SASW testing on 27 locations in Operating Industries, Inc. (OII) landfill located in southern California. The mean of the results showed the variation of shear wave velocity, stating from about 150 m/s at the surface to about 240 m/s at 50 m depth.

Measured shear wave velocity of model waste is at the lower end of the reported shear wave velocities of MSW. This however is ex-

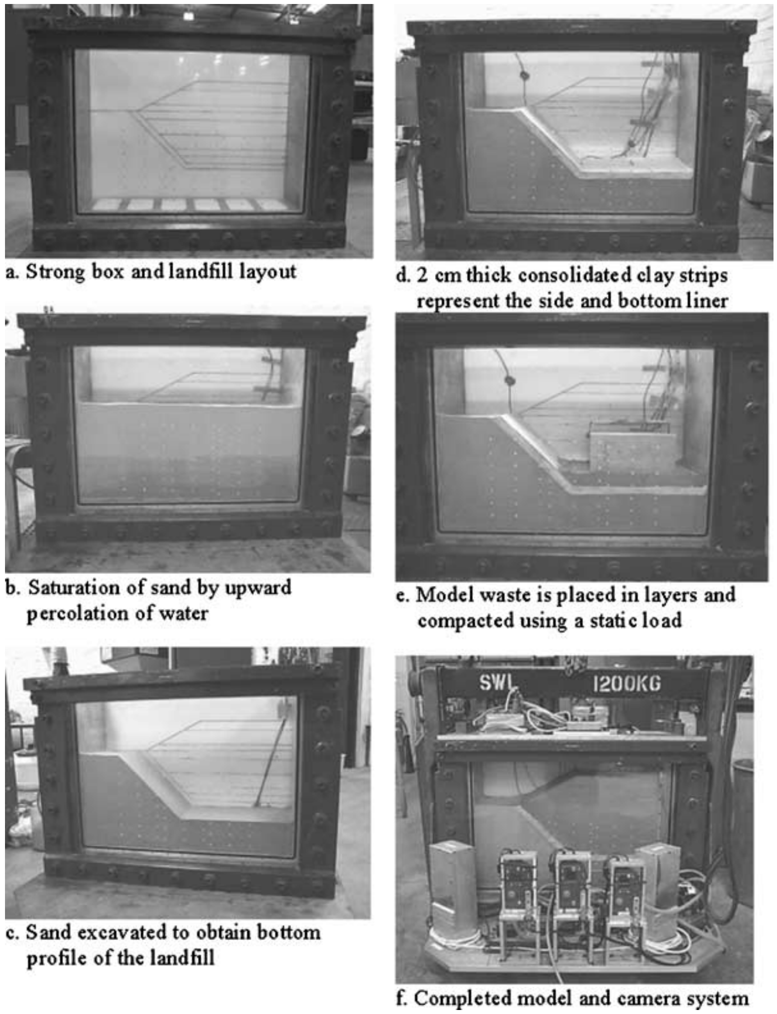

FIG. 2—*The sequence of model preparation.*

pected as the shear wave velocity of model waste was measured at lower confining stress compared to that in the field.

Settlement Profile of MSW Landfill

Settlement of MSW landfills depend on the compaction method and waste constituents. Typically, a MSW landfill can settle between 5 % and 30 % of initial height after closure. Understanding the settlement profile of a landfill near the side slopes can be useful in designing the cover liner, leachate collection and gas recovery systems. As the settlement suffered by the model waste in a centrifuge is due to the action of body forces, settlements are more representative of physical deformation that occur in landfills. The ultimate settlement of MSW in landfills comprises of immediate settlement as well as long-term biological degradation. This ultimate settlement is represented by the settlement of the model waste during the centrifuge test. It is to be noted that the model waste does not model the time-dependent biological degradation of MSW.

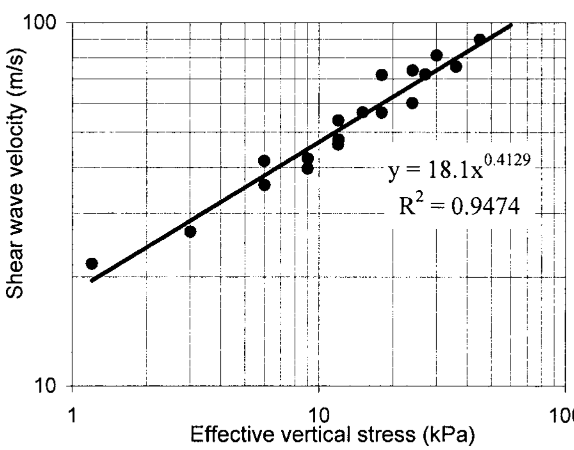

FIG. 3—*Relationship between shear wave velocity and vertical effective stress.*

Figure 4 shows the posttest settlement of the model waste in centrifuge test IT-01 in prototype scale. This settlement includes the settlement of clay foundation. Settlement of clay foundation was measured by applying the PIV technique (White et al. 2003) on the digital images. The PIV analysis showed that the clay foundation settled by about 0.5 mm during IT02 swing up. The measurements of waste settlement were obtained by posttest excavation of the model. The top surface of the waste had settled by 80 mm (29 % of its initial height and 4 m in prototype scale). The crest of the waste experienced 32 mm horizontal and 70 mm vertical movement (1.6 m horizontal and 3.5 m vertical prototype movement). The unit weight of the model waste at 50 g was roughly 8.7 kN/m^3.

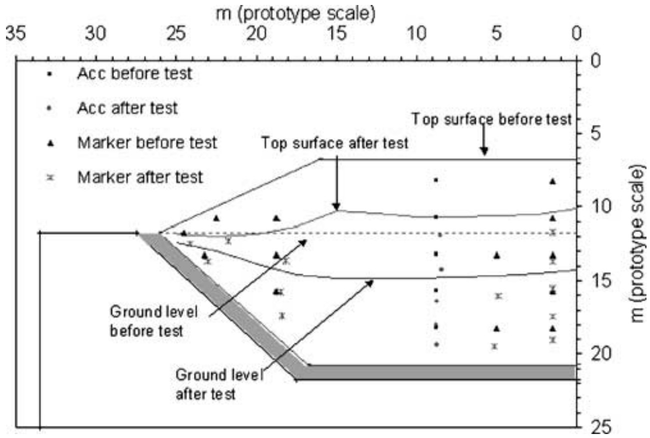

FIG. 4—*Settlement profile of the landfill model from IT-01 test.*

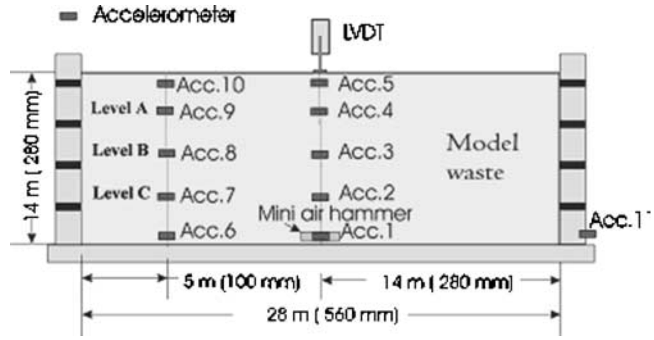

FIG. 6—*Cross section of IT-02 model* (*model scale dimensions in brackets*).

Posttest Observations

Posttest observations of the model show that a settlement-induced cracking had occurred near the side liner (Fig. 5). The crack was approximately 10 mm width in the model scale, hence 500 mm in the prototype scale. This type of cracking will have implications on the design of landfill cover systems.

Seismic Behavior of MSW—Centrifuge Test IT-02

The aim of the dynamic centrifuge test (IT-02) was to understand the seismic behavior of the model waste.

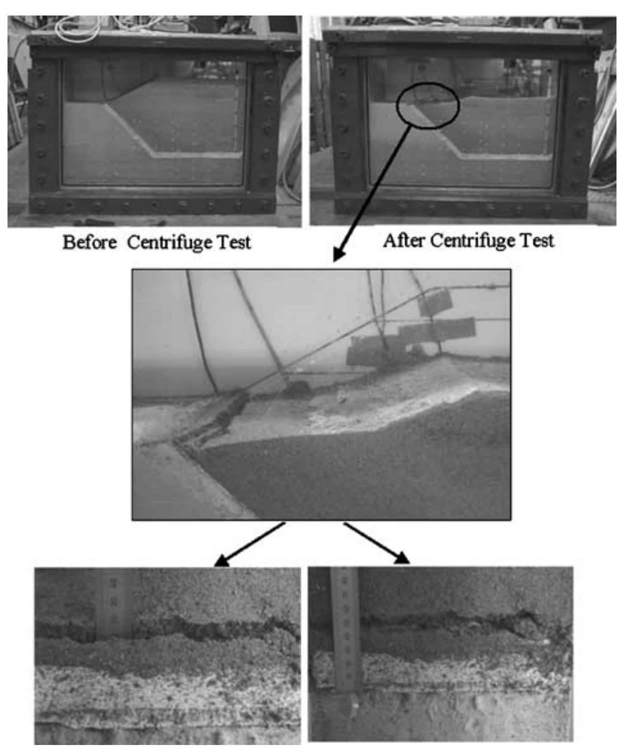

FIG. 5—*Posttest observations of settlement induced cracking in waste side liner.*

Model Preparation and Testing

The dynamic centrifuge test on model waste was performed in a equivalent shear beam box of internal dimensions 235 mm by 560 mm by 222 mm, whose design and performance was described by Zeng and Schofield (1996) . 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^3. Accelerometers (Acc's) were placed in each layer as shown in Fig. 6. Shear wave velocity of model waste was measured as described in the previous test. A linearly variable displacement transducer was mounted on top of the container to measure the model waste settlement during the swing up and during the test.

The model was swung up to 50 g in stages of 10, 20, and 40 g. At 50 g, miniair hammer was activated and the accelerometer signals recorded at 50 kHz. 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 were recorded at a sampling frequency of 4 kHz.

Results

Amplification of Acceleration through MSW

An average shear wave velocity of 70 m/s and 100 m/s was measured at the base and the surface of the model waste respectively. The acceleration signals recorded during all seven earthquakes showed amplification from base to top surface. Figure 7(*a*) shows the acceleration signals during Earthquake 3. All acceleration signals are given in prototype scale. 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

TABLE 1—*Applied earthquakes in prototype scale* (*model scale in brackets*).

Earthquake-E	Frequency (Hz)	Duration (s)	Maximum base acceleration Acc.6 (g)
E.1	0.6 (30)	15 (0.3)	0.08 (3.76)
E.2	0.8 (40)	15 (0.3)	0.12 (6.13)
E.3	1 (50)	15 (0.3)	0.18 (8.90)
E.4	1 (50)	15 (0.3)	0.14 (6.76)
E.5	1 (50)	15 (0.3)	0.24 (11.80)
E.6	1 (50)	15 (0.3)	0.28 (14.20)
E.7	1 (50)	15 (0.3)	0.15 (7.41)

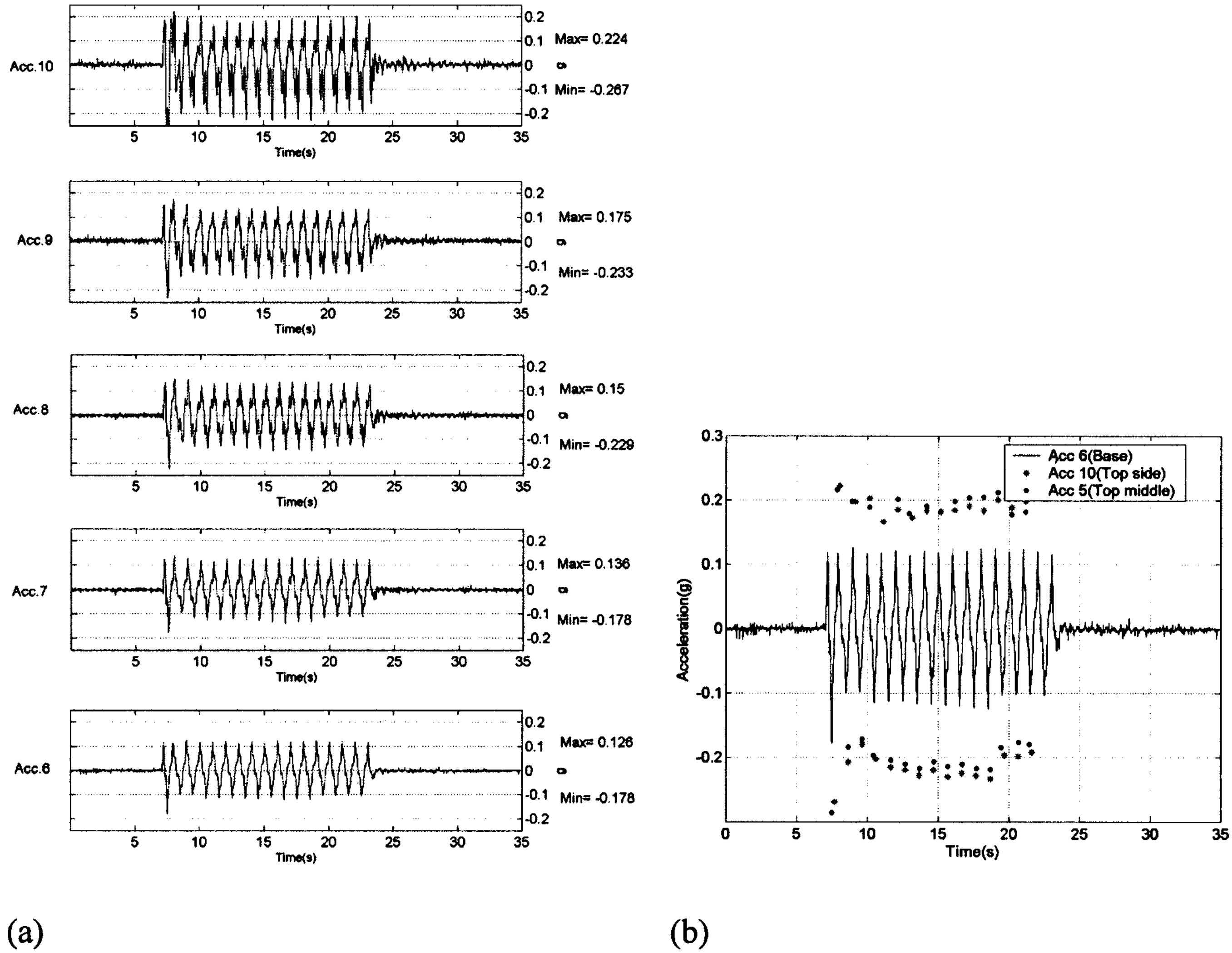

FIG. 7—*a) Acceleration signals from earthquake 3 (E.3) in prototype scale, and b) peak acceleration in each cycle in E.3 (axis in prototype scale)*

peak to peak acceleration from base to top surface was used to calculate the amplification. Acc.1 and Acc.3 failed to work in the test thus Acc.6 was used as base acceleration. The base acceleration of the model waste (Acc.6) and the peaks of the top surface acceleration in Earthquake 3 is presented in Fig. 7(*b*). Peak to peak acceleration of Acc.5 and Acc.10 were very similar. This shows that the boundary effects of the box end walls are less than 100 mm from the walls. Figure 8 shows the amplification between Acc.6 and Acc.5 for all 7 model earthquakes. It can be seen from Fig. 8 that the amplification is as high as three for input magnitudes less than 0.05 g and decreases linearly up to 0.1 g input magnitude, then stays fairly constant at about 1.75 untill 0.2 g input magnitude and then appears to decrease again. The amplification for input magnitude beyond 0.2 g cannot be stated conclusively as there is only one data point beyond 0.2 g input magnitude.

The peak ground acceleration close to the surface of the waste (Acc.5) against the peak base acceleration (Acc.6) for each cycle from all the earthquakes have been plotted along with the recorded and numerical results of Kavazanjian and Matasovic (1995) and Bray and Rathje (1998) in Fig. 9. The curve proposed by Singh and Sun (1995) for a refuse fill of 100 feet high is also produced in Fig. 9. The dynamic centrifuge test results agree well with the soft soil site amplification curve and also fall within the range of results obtained by nonlinear analyses of landfills.

Shear Modulus Reduction and Damping Curves of Model Waste

The acceleration data obtained from the dynamic centrifuge test IT02 was analyzed to characterize the shear modulus reduction and damping curves of the model waste. Details of the stress/strain, shear modulus, and damping calculations are given in Thusyanthan

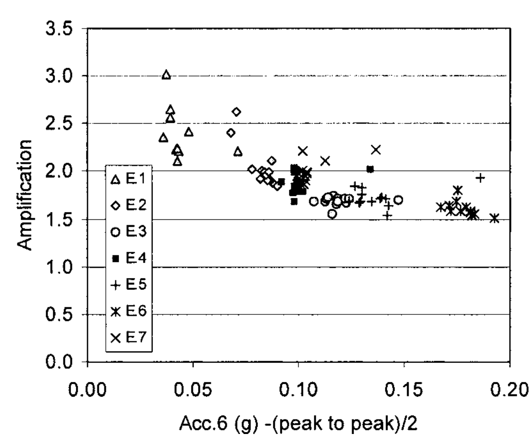

FIG. 8—*Amplification of base acceleration.*

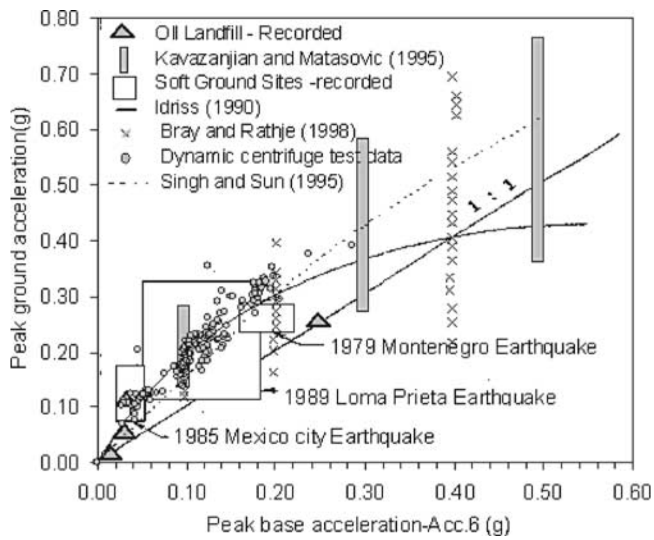

FIG. 9—*Comparison between recorded, numerical, and dynamic centrifuge data.*

(2005) and Brennan et al. (2005) . Apart from the initial couple of cycles, all rest of the cycles in the acceleration signals were relatively similar throughout the earthquake duration in test IT02. Thus, for a given depth (i.e., Level A) the plots of shear stress versus shear strain for each cycle were very similar throughout the earthquake duration. Figure 10 shows the stress-strain loop of model waste obtained from acceleration signal of Acc.6, 7, and 8 for one cycle of loading. The dashed line, which joins maximum shear stress and shear strain to minimum shear stress and shear strain, was used to calculate the shear modulus (G) of model waste.

Figure 11 shows the values of $G/G_{\max}$ for model waste at level A, B, and C for all the simulated model earthquakes in test IT02. The values of $G/G_{\max}$ of model waste compares well with the shear modulus reduction curves developed by Matasovic and Kavazanjian (1998) for OII landfill solid waste. The $G/G_{\max}$ values of model waste are also well within the best-estimate range of shear modulus reduction produced by Augello et al. (1998) , based on backanalysis of five earthquake events at the OII landfill. It may be concluded from these comparisons that the model waste has a shear modulus reduction curve that is similar to that of MSW in the OII landfill.

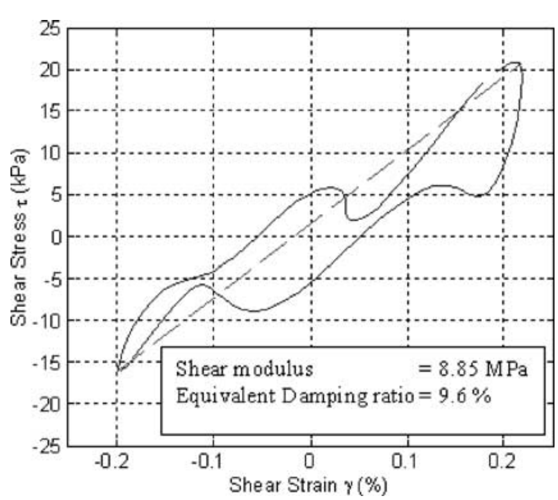

FIG. 10—*Stress-strain loop of model waste obtained from Acc. 6, 7, and 8 of E.7*

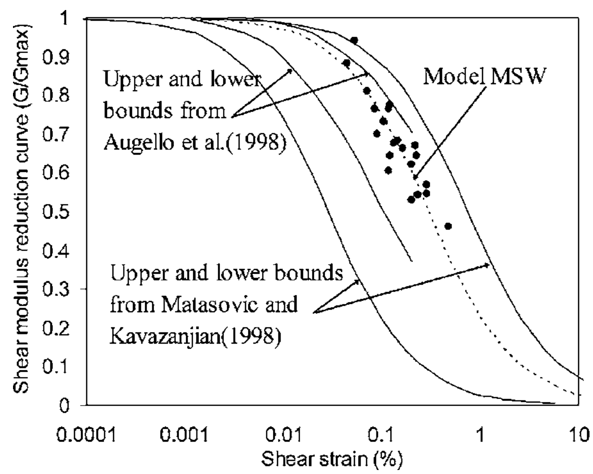

FIG. 11—*Shear modulus reduction of model waste model waste.*

The equivalent damping ratios obtained from the centrifuge data for model waste is shown in Fig. 12. As with the shear modulus values, the damping ratios were similar for a given earthquake and at a given depth for most of the cycles in earthquake loading. Hence only the values for the prototype time 12 s to 13 s are shown in Fig. 12. As can be seen from Fig. 12, the equivalent damping ratios of the model waste are mainly within the best-fit range given by Augello et al. (1998) and Matasovic and Kavazanjian (1998) . Hence, it can be concluded that the model waste has equivalent damping ratios similar to that of MSW in the OII landfill.

Conclusion

Two centrifuge tests were performed using the model waste developed in the companion paper to demonstrate its use in understanding the static and dynamic behavior of MSW landfills. The shear wave velocity of the model waste was measured in the centrifuge test IT01. The settlement profile of MSW in a landfill was also obtained in this test. The Second centrifuge test, IT02, which was a dynamic centrifuge test, provided insight into the dynamic behavior of model waste. Results from dynamic centrifuge test on the model waste agree with the recorded past earthquakes and falls within the range of results from nonlinear analyses of landfills (Bray and Rathje 1998).

Dynamic centrifuge test data was used to obtain the shear modu-

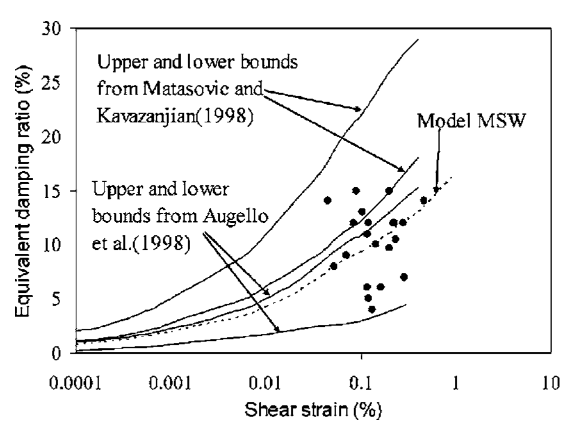

FIG. 12—*Equivalent damping ratios of model waste.*

lus reduction and damping curves of the model waste. The shear modulus reduction and the equivalent damping ratios of the model waste are mainly within the best-fit range given by Augello et al. (1998) and the results of Matasovic and Kavazanjian (1998) . Hence, it could be concluded that the model waste can effectively model the seismic behavior of MSW. Further work in dynamic centrifuge modeling with the model waste developed in this research can provide better understanding of seismic behavior of MSW landfills.

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