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# Centrifuge Modeling of Solid Waste Landfill Systems—Part 1: Development of a Model Municipal Solid Waste

**ABSTRACT:** This paper presents the development of a model waste that has physical properties similar to those reported by investigators for municipal solid waste (MSW). The model waste was developed using a mixture of peat, E-grade kaolin clay and fraction-E fine sand. Unit weight, compressibility, and shear strength characteristics of the model waste were experimentally determined and shown to match well with those reported for MSW.

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

## Introduction

Every year, countries all over the world deal with the disposal of millions of tons of municipal solid waste. Municipal solid waste (MSW) mainly consists of everyday household waste items, such as product packaging, grass clippings, clothing, bottles, food scraps, newspapers, etc. Construction and demolition debris, municipal wastewater treatment sludge, and nonhazardous industrial wastes are materials that may also be disposed in landfills but are not generally considered MSW. According to the U.S. Environment Protection Agency, the United States generated over 230 million tons of MSW in 1999 and about 55 % of it was landfilled. Landfill can be defined as an area of land or an excavation in which waste is placed for permanent disposal. Landfills exist all over the world as it is one of the cheapest options for proper disposal of waste. Their number and capacity vary from country to country. The United States has about 2300 active landfills, New Zealand has over 115 active landfills, and the United Kingdom has over 1500 active landfills. Hence, MSW landfills are a major part of waste disposal in countries all over the world.

The behavior of MSW landfills under monotonic and seismic loading is a major concern as landfill failures can lead to ground water contamination and other geoenvironmental disasters (Augello et al. 1995 ; Koerner and Soong 2000 ). Study into the static and dynamic behavior of MSW landfills has often been limited to numerical analysis due to the difficulties associated with dealing with real waste in experiments. For example, present understanding of seismic behavior of MSW landfills is mainly based on parametric studies carried out using numerical packages, such as SHAKE91 (Bray et al. 1995 ; Nero et al. 1995 ; Bray and Rathje 1998 ; Rathje and Bray 2001 ) and the few recorded case histories following earthquakes (Anderson and Kavazanjian 1995 ; Augello et al. 1995 ; Matasovic et al. 1998 ). As an alternative, centrifuge testing has been used in the past by many researchers to study different aspects of MSW landfills using processed waste, Syllwasschy and Jessberger (1998) , or soil, Madabhushi and Singh (2001) . However, MSW is usually highly heterogeneous and variable in its content. Thus, the use of real MSW in a series of experiments to understand overall performance of a landfill 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. In this paper, the development of the model waste will be presented while its use in centrifuge testing will be described in the companion paper (Thusyanthan et al. 2006 ).

This paper presents the development of a model waste that has similar mechanical properties to that reported in literature for MSW. The model waste was developed using a mixture of peat, E-grade kaolin clay, and fraction-E fine sand. Table 1 provides the properties of fraction E sand and E-grade kaolin clay. Engineering properties, such as unit weight, compressibility, and shear strength of the model waste, are experimentally determined and compared with those of a typical MSW.

## Physical Modeling of Municipal Solid Waste

An ideal model waste should match the physical, chemical, and dynamic properties exhibited by the real MSW. 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 behavior of MSW and overall performance of a landfill, then it would be sufficient to produce a model waste that has the main relevant physical and dynamic properties of real MSW.

The main physical properties of MSW considered here are unit

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TABLE 1—*Properties of fraction E fine sand and E-grade kaolin clay.*

| Fraction E fine sand | | E-grade Kaolin clay | |
|---|---|---|---|
| Property | Value | Property | Value |
| Minimum voids ratio $e_{min}$ | 0.613 | Plastic limit | 30 % |
| Maximum voids ratio $e_{max}$ | 1.014 | Liquid limit | 51 % |
| Permeability at $e=0.72$ | $0.98\times10^{-4}$ m/s | Permeability | $10^{-9}$ m/s |
| Critical state friction angle $\varphi_{crit}$ | 32° | Critical state friction angle $\varphi_{crit}$ | 26° |

weight, compressibility, shear strength, and moisture content. Sharma and Lewis (1994) and Qian et al. (2002) provide a comprehensive summary on these properties published by various researchers. Dynamic properties of the MSW, which are the shear wave velocity, shear modulus reduction, and damping curves. Early investigators, in the absence of laboratory data, suggested that MSW would behave similar to a combination of peat and clay (Earth Technology, 1988 ; Singh and Murphy, 1990 ; Sharma and Goyal, 1991 ). Singh and Murphy (1990) suggested that the shear modulus and damping curves for waste to be intermediate between those for clay and peat that had been published by Seed and Idriss (1970) . Stewart et al. (1994) reported that the MSW modulus and damping curves recommended by Singh and Murphy (1990) , representing a response between that of peat and clay, gave reasonably good agreement between observed and predicted response at the top of Operating Industries, Inc.(OII) landfill. Bray et al. (1995) also used the shear modulus reduction and damping proposed by Singh and Murphy (1990) for seismic analysis of MSW landfills.

Laboratory data and backanalysis earthquakes on MSW landfills have produced many improvements on shear modulus reduction and damping curves of MSW (Matasovic and Kavazanjian, 1998 ; Idriss et al., 1995 ; Morochnik et al., 1998 ; Augello et al., 1998 ). Augello et al. (1998) concluded that the analysis with curves intermediate between clay, plasticity index (PI)=30 and PI =100 proposed by Vucetic and Dobry (1991) gave the best overall fit to the recorded motions in OII landfill.

## 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 modeling MSW. Since there are legislations requiring that all MSW landfills be covered with at least 15 cm of daily cover, usually sand, the MSW in a landfill can be expected to contain sand as well. Bray et al. (1995) reported that 10 % to 30 % of the recovered material from MSW landfill boreholes are soils used as daily cover. Therefore, a mixture of sand, clay, and peat materials might produce a reasonable model waste. In order to understand the ratios required to obtain real MSW behavior, three different mixtures (A,B, and 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 used. This peat had an initial 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 2).

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 repeatable consistency the peat was sieved using a BS 410-4 mm sieve (ASTM E11-No. 5). Known quantities of sand, clay, and peat were then mixed in a mechanical mixer until homogeneous. The mixture was again sieved using a BS 410-2.36 mm sieve (ASTM E11-No. 8) to obtain the final model waste mixture. Figure 1 shows the pictorial representation of the preparation of model waste mixtures.

During the sieving and mixing processes, evaporation could occur and reduce the moisture content of peat. Thus, the moisture contents of the final mixtures were measured. The measured moisture contents of Mixtures A, B, and C were 29, 23, and 17 %, respectively. The mixtures were stored in air-tight containers to maintain the moisture content. According to Qian et al. (2002) the average moisture content of reported MSW is 26 %, hence, Mixtures A and B seem to be more suited as model waste than Mixture C.

## Physical Properties of Model Waste

One-dimensional compression tests and direct shear tests were performed on all three mixtures to understand the variation of unit weight with vertical stress, compressibility, and shear properties. Both the compression tests and shear tests were performed in a standard shear box (100 mm × 100 mm × 50 mm).

### *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$^3$ depending on its constituents and compaction effort in placement (Bray et al. 1995 ; Matasovic and Kavazanjian 1998 ; Zornberg et al. 1999 ; Kavazanjian 2001 ). The bore hole sampling at OII landfill showed that the in situ unite weight of the solid waste varied in a nonsystematic manner between approximately 12 and 21 kN/m$^3$, with most values between 14 and 18 kN/m$^3$ (Matasovic and Kavazanjian 1998 ). The unit weight

TABLE 2—*Model waste mixtures.*

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

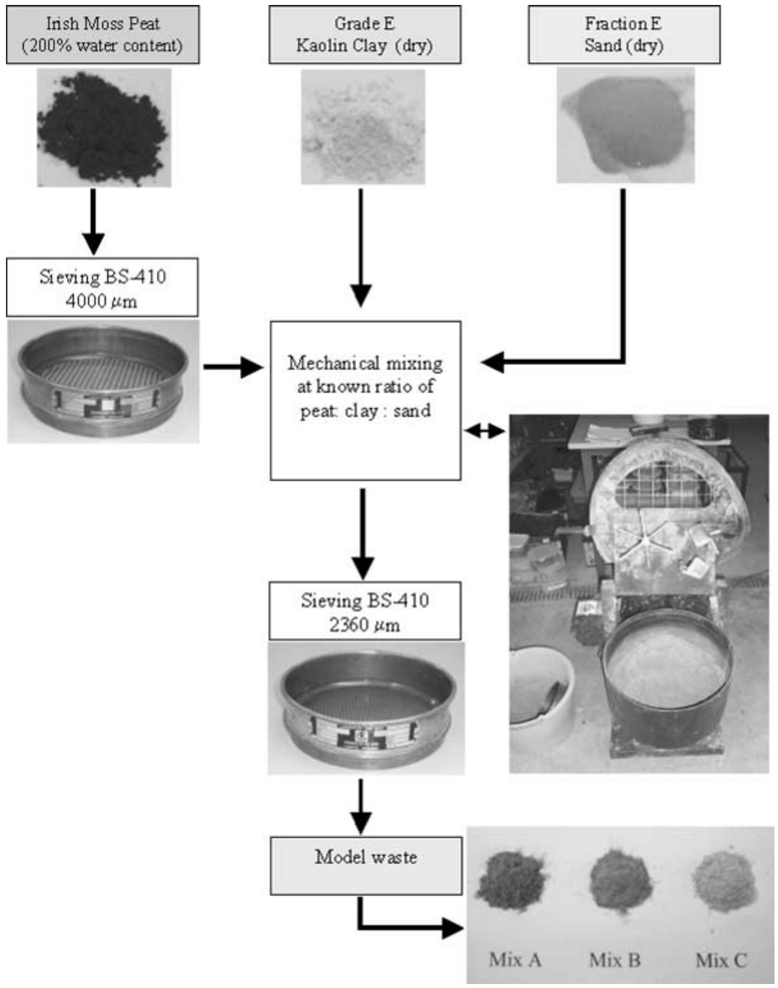


FIG. 1—*Preparation of model waste mixtures.*

profile for a MSW landfill located in southern California was investigated by Zornberg et al. (1999) by direct field measurements and spectral surface wave analysis surveys. The waste unit weight obtained from direct field measurements ranged approximately from 10 to 15 $kN/m^3$ at a depth of between 8 and 50 m below the landfill surface.

Powrie and Bewven (1999) performed compression tests on municipal solid waste in a purpose-built compression cell known as Pitsea compression cell, which is 2 m in diameter and 3 m in height. The test results show that the density at field capacity (total amount of moisture which can be retained in a waste sample subject to gravitational pull) increases with the average vertical stress up to 500 kPa and then flattens out (11.6 $kN/m^3$ at 500 kPa).

The variation of unit weight with vertical stress was investigated for all three model waste mixtures. Unit weight was calculated by dividing the initial weight of the mixture by the present volume of the mixture during the compression test. Figure 2 shows the variation of unit weight of the mixtures with vertical stress. All three mixtures exhibited the same trend of variation of unit weight with vertical stress; however, Mixture A had the highest and mixture C, the lowest unit weight for a given vertical stress. The variation of unit weight with vertical stress exhibited by the mixtures is very similar to that of real MSW reported in the literature, for example Powrie and Bewven (1999) .

## *Compressibility*

Compressibility of MSW is a vital parameter which determines the capacity of the landfill and helps in planning of MSW landfill sites. Conventional soil mechanics theory defines the primary compres-

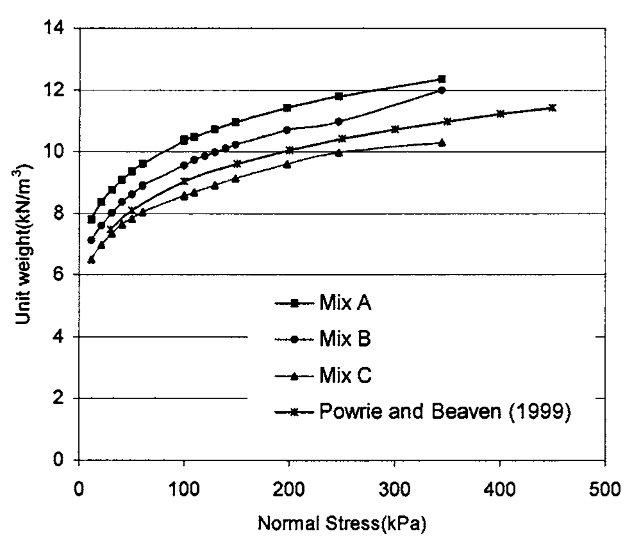


FIG. 2—*Variation of unit weight with vertical stress for model waste mixtures.*

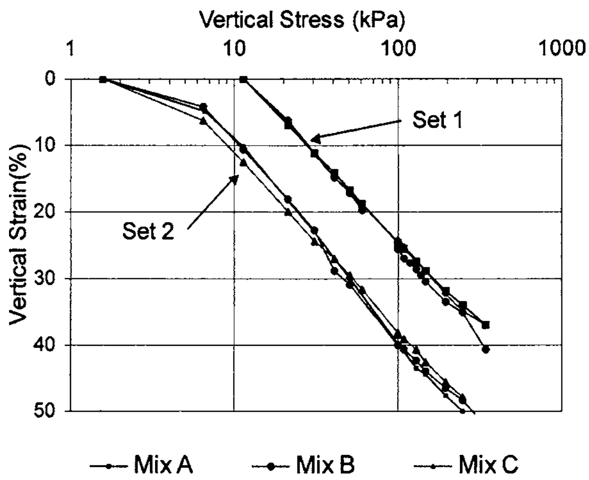


FIG. 3—*Vertical strain vs vertical stress for model waste mixtures.*

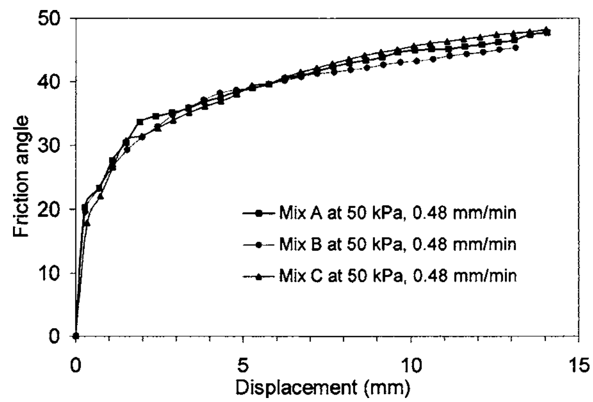


FIG. 4—*Shear strength of model waste mixtures.*

sion index ($C_c$) using change in voids ratio. However, the void ratio of waste cannot be determined easily, hence a modified parameter known as the coefficient of primary compression index ($C_{ce}$) is defined in terms of waste height. The definitions of $C_c$ and $C_{ce}$ are as follows:

$$C_c = \frac{\Delta e}{\log(\sigma_1/\sigma_0)} \tag{1}$$

$$C_{ce} = \frac{\Delta H}{H_0 \log(\sigma_1/\sigma_0)} \tag{2}$$

where $\Delta e$ is the change in void ratio, $H_0$ is the original thickness of waste layer, $\Delta H$ is the change in thickness of waste layer, $\sigma_0$ is the initial vertical stress, and $\sigma_1$ is the final vertical stress.

Landva et al. (2000) provided a comprehensive summary on previously reported coefficients of primary and secondary compression from 12 sources. The reported coefficients of primary compression ranged between 0.08 and 0.5 and had an average of 0.22. Qian et al. (2002) suggests that, depending on the initial compaction effect and composition of the waste, the coefficient of primary compression could vary from 0.17 to 0.36.

Figure 3 shows the compressibility of model waste mixtures. In the first series of experiments (Set 1), the mixtures were precompressed by the 11.4 kPa load; hence, 10 kPa was taken as the datum for strain measurements. In the second set of experiments (Set 2), mixtures were precompressed by 1.6 kPa. The results show that all three mixtures exhibit a very similar coefficient of primary compressibility ($C_{ce}$=0.25), which is within the range of $C_{ce}$ reported for MSW.

## *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, when characterizing the shear strength of MSW, thought should be given to these factors. The shear strength properties of MSW reported in literature have been determined by direct laboratory testing, field testing, or backanalyses from failures (Singh and Murphy, 1990 ; Fassett et al., 1994 ; Jessberger, 1994 ; Jones et al. 1997 ; Van Impe and Bouazza, 1998 ; Qian et al., 2002 ).

Kavazanjian et al. (1995) and Eid et al. (2000) used shear strengths from backcalculated case histories and direct shear tests on MSW to propose Mohr–Coulomb strength envelopes. Kavazanjian et al. (1995) proposed $\phi=0°$ with $c'=24$ kPa at normal stress below 30 kPa and $\phi=33°$ with $c'=0$ at higher normal stresses, while Eid et al. (2000) proposed $\phi=35°$ and cohesion $c'$ in the range 0 to 50 kPa. More recently, Pelkey et al. (2001) carried out simple and direct shear tests on a number of samples of municipal waste obtained from major landfills across Canada. The results, supporting the results of Singh and Murphy (1990) , showed that large shear strains (30%) were required to mobilize peak shear strengths. Pelkey et al. (2001) reported mobilized friction angles in the range from 30° to 55° at large strains from direct shear tests.

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 show that all three mixtures exhibit very similar shear characteristics, mobilized friction angle of 39° at displacements of 5 mm and increasing with displacement (Fig. 4). The friction angle exhibited by the model waste mixtures is within the range reported in literature for real MSW. The increase of the mobilized friction angle with shear displacement (or with shear strain) is a characteristic of MSW as reported by researchers (Pelkey et al. 2001 ; Singh and Murphy 1990 ). This behavior is exhibited by the model waste mixtures as seen in Fig. 4.

## *Particle Size Distribution*

Figure 5 shows the particle size distribution of model waste mix-

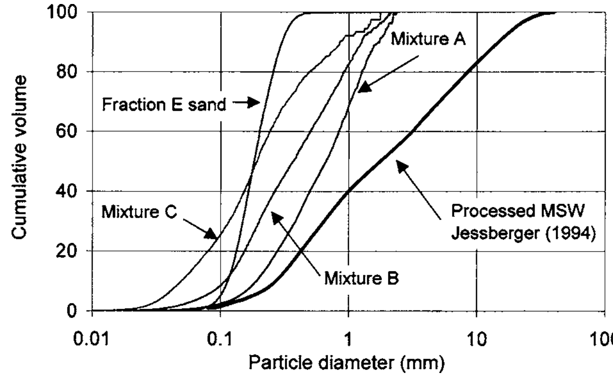


FIG. 5—*Particle size distribution of model waste mixtures.*

TABLE 3—*Suitability of Mixtures A, B, and C as model MSW.*

| Property | Mix A | Mix B | Mix C |
|---|---|---|---|
| Unit weight | * | ** | ** |
| Compressibility | ** | ** | ** |
| Shear characteristics | ** | ** | ** |
| Moisture content | ** | ** | * |
| Easy of handling | * | * | × |
| Total | 8* | 9* | 7* |

[a]Note: **=Well suitable; *=Reasonably suitable; and ×=Not suitable.

tures and fraction-E silica sand obtained using a single particle optical sizer (Nicomp Accusizer 780). The single particle optical sizing method (White, 2003 ) was used as it requires small quantity of sample and is reliable. The particle size distribution of processed MSW given by Jessberger (1994) is also plotted for comparison. The particle size of model waste mixtures are some what smaller than processed MSW as larger particles were not included in the model waste mixtures. This difference in particle size distribution is considered acceptable as the main impetus was to create a model waste to simulate the mechanical behavior of MSW in centrifuge testing. The uniformity coefficient ($D_{60}/D_{10}$) for the model waste Mixtures A, B, and C are calculated as 4.4, 4.7, and 5, respectively.

## Choice of Model Waste

Table 3 summarizes the suitability of Mixtures A, B, and C as MSW model waste. Mixture C tended to form kaolin dust while handling at its moisture content of 17 %, and Mixture A was not consistent in its compressibility due to high peat content. 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 and consistency.

It has been shown that all three mixtures exhibited similar shear characteristics when sheared at a strain rate of 0.48 mm/min. It is recognized that the direct shear tests on the model waste may not be totally drained as pore pressure generation is possible. A shear test on Mixture B was carried out at a higher strain rate of 1.2 mm/min (Fig. 6). The results of this test match reasonably well with the 0.48 mm/min test results suggesting that the excess pore pressure generation effects and strain rate effects are small.

Figure 6 also shows the effect of overconsolidation on shear strength. Mixture B consolidated to 100 kPa and sheared at 100 kPa exhibits a lower mobilized friction angle than that consolidated to 50 kPa and sheared at 50 kPa. Overconsolidated Mixture B (OCR =2) sheared at 50 kPa exhibits higher mobilized friction than that sheared at 50 kPa with OCR=1. This trend is similar to the results of simple shear and direct shear tests reported by Pelkey et al. (2001) .

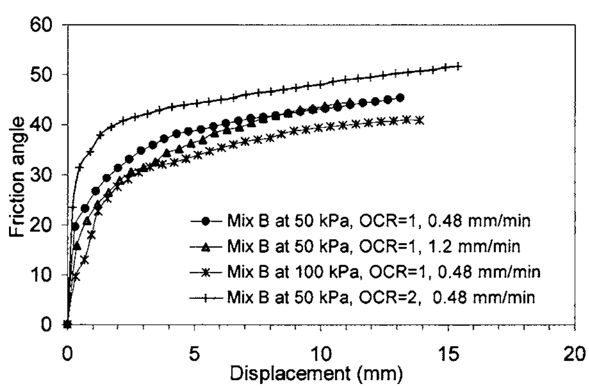


FIG. 6—*Strain rate and overconsolidation ratio (OCR) effects on shear strength of Mixture B.*

## Conclusion

Landfills are used worldwide and it is important to understand the behavior of MSW landfills. Centrifuge modeling can be used to understand the mechanics and performance of landfills. However, there is a need to develop a model waste that can be used in the small-scale centrifuge models to produce repeatable results. Such a model waste with physical properties similar to those reported in literature for MSW was developed using a mixture of sand, peat, and clay. Unit weight, compressibility, and shear strength characteristics of the model waste were experimentally determined and shown to match well with those values reported by investigators for real MSW. The results of this paper and the companion paper on usage of this model waste in centrifuge tests show that the model waste could be used to understand both the static and dynamic behavior of MSW landfills.


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## References


Anderson, D. G., and Kavazanjian, E, Jr, 1995, "Performance of Landfills under Seismic Loading," *Third International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics*.

Augello, A. J., Bray, J. D., Abrahamson, N. A. and Seed, R. B., 1998, "Dynamic Properties of Solid Waste based on Back-analysis of OII Landfill," *J. Geotech. Geoenviron. Eng.*, Vol. 124, No. (3), pp. 211–222.

Augello, A. J., Bray, J. D., Seed, R. B., Matasovic, N., and Kavazanjian, E. Jr., 1995,-"Solid waste landfill performance during

1994 Northridge Earthquake," *Third International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics*.

Bray, J. D., Augello, A. J., Leonards, G. A., Repetto, P. C., and Byrne, R. J., 1995, "Seismic Stability Procedures for Solid-Waste Landfills," *J. Geotech. Eng.*, Vol. 121, No. (2), pp. 139–151.

Bray, J. D., and Rathje, E. M., 1998, "Earthquake-Induced Displacements of Solid-Waste Landfills," *J. Geotech. Geoenviron. Eng.*, Vol. 124 No. (3), pp. 242–253.

Earth Technology, 1988, "In-Place Stability of Landfill Slopes, Puente Hills Landfill, Los Angeles, California", Report No. 88-614-1, The Earth Technology Corporation, Long Beach, CA.

Eid, H. T, Stark, T. D., Dougals, W. D., and Sherry, P. E., 2000, "Municipal Solid Waste Slope Failure 1. Waste and Foundation Properties," *J. Geotech. Geoenviron. Eng.*, Vol. 126, No. (5), pp. 397–407.

Fasset, J. B., Leonards, G. A., and Repetto, P. C., 1994, "Geotechnical Properties of Municipal Solid Waste and their Use in Landfill Design," *Waste Tech'94 Landfill Technology Proceeding*.

Idriss, I. M, Fiegel, G. L, Hudson, S. L, Mundy, P. K., and Herzig, R., 1995, "Seismic Response of the Operating Industries Landfill", *Earthquake Design and Perfomance of Solid Waste*, Geotechnical Special Publication No. 54, Reston, VA

Jessberger, H. L., 1994, "Geotechnical Aspects of Landfill Design and Construction. Part 2: Material Parameters and Test Methods," *Geotechnical Engineering, Proceedings of the Institution of Civil Engineers*, Vol. 107, No. (2), pp. 105–112.

Jones, R., Taylor, D., and Dixon, N., 1997, "Shear Strength of Waste and its Use in Landfill Stability Analysis," *Conference on Geoenvironmental Engineering, University of Wales, UK*.

Kavazanjian, E., Jr., 2001, "Mechanical Properties of Municipal Solid Waste", *Eighth International Landfill Symposium. Sardinia 2001, Italy*.

Kavazanjian, E. Jr., Matasovic, N., Bonaparte, R., and Schmertmann, G. R., 1995, "Evaluation of MSW Properties for Seismic Analysis," *Proceedings of GeoEnvironment 2000, Geotechnical Special Publication No. 46, ASCE, Reston, VA*.

Koerner, R. M. and Soong, T. Y., 2000, "Stability of ten large landfill failures," *GeoDenver-2000, ASCE Geotechnical Special Publication No.103, Reston, VA*.

Landva, A. O., Valsangkar, A. J and Pelkey, S. G, 2000, "Lateral Earth pressure at rest and compressibility of municipal solid waste," *Can. Geotech. J.*, Vol. 37, No. (6), pp. 1157–1165.

Madabhushi, S. P. G., and Singh, S., 2001, "Behaviour of Landfill Liners under Earthquake Loading," *VIII International Conference on Civil and Structural Engineering computing*.

Matasovic, N., and Kavazanjian, E. Jr., 1998, "Cyclic Characterization of OII Landfill Solid Waste," *J. Geotech. Geoenviron. Eng.*, Vol. 124, No. (3), pp. 197–210.

Matasovic, N., EERI, M. Kavazanjian, Ed. Jr., and Anderson, R. L. 1998, "Performance of Solid Waste Landfills in Earthquakes," *Earthquake Spectra*, Vol. 14, No. (2).

Morochnik, V., Bardet, J. P., and Hushmand, B., 1998, "Identification of Dynamic Properites of OII Landfill," *J. Geotech. Geoenviron. Eng.* ASCE, Vol. 124, No. 3, pp. 186–196.

Nero, D. E. D., Corcoran, B. W., and Bhatia, S. K., 1995, "Seismic Analysis of Solid Waste Landfills," *Earthquake Design and Performance of Solid Waste*, Geotechnical Special Publication No. 54., pp. 61–72, Reston, VA.

Pelkey, S. A., Valsangkar, A. J., and Landva, A., 2001, "Shear Displacement Dependent Strength of Municipal Solid Waste and its Major Constituents," *Geotech. Test. J.*, Vol. 24, No. (4), pp. 381–390.

Powrie, W., and Bewven, R. P., 1999, "Hydraulic Properties of Household Waste and Implications for Landfills," *Geotechnical Engineering, Institution of Civil Engineers Proceedings*, Vol. 137, No. (4), pp. 235–247.

Qian, X., Koerner, R. M., and Gray, D. H., 2002, *Geotechnical Aspects of Landfill Design and Construction*, Prentice–Hall, Englewood cliffs, NJ.

Rathje, E. M., and Bray, J. D., 2001, "One and Two Dimensional Seismic Analysis of Solid Waste Landfills," *Canadian Geotechnical Engineering*, Vol. 38, pp. 850–862.

Seed, H. B., and Idriss, I. M., 1970, "Soil Modulus and Damping Factors for Dynamic Response Analysis," Report No. UCB/EERC-70/10, Earthquake Engineering Research Center, University of California, Berkeley, CA.

Sharma, H. D., and Lewis, S. P., 1994, *Waste Containment Systems, Waste Stabilization, and Landfills-Design and Evaluation*, Wiley-Interscience, New York.

Sharma, H. D., and Goyal, H. K., 1991, "Performance of a Hazardous Waste and Sanitary Landfill Subjected to Loma Prieta Earthquake," *Proc. 2nd International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, St. Louis, Missouri*, pp. 1717–1725.

Singh, S., and Murphy, B., 1990, "Evaluation of the stability of Sanitary Landfills," *Geotechnics of Waste Fills-Theory and Practice*, ASTM STP *1070*, A. Landva and G. D. Knowles, Eds., Philadelphia, PA, pp. 240–258.

Stewart, J. P., Bray, J. D., Seed, R. B., and Sitar, N., 1994, "Preliminary Report on the Principal Geotechnical Aspects of January 17, 1994 Northridge Earthquake," Report No. UCB/EERC-94/08, College of Engineering, University of California at Berkeley, Berkeley, CA.

Syllwasschy, O., and Jessberger, H. L., 1998, "Horizontal Earth Pressure in Municipal Solid Waste Landfills," *International Congress on Environmental geotechnics-3*,

Thusyanthan, N. I., Madabhushi, S. P. G., and Singh, S., 2005, "Centrifuge Modeling of Solid Waste Landfill Systems: Part 2—Centrifuge Testing of Model Waste," *Geotech. Test. J.*, Vol. 29, No. 3 (this issue).

Vam Impe, W. F., and Bouazza, A., 1998, "Large Shear Tests on Compacted Bales of Municipal Solid Wastes," *Soils and Foundations Japanese Geotechnical Society*, Vol. 38 No. (3), pp. 199–200.

Vucetic, M., and Dobry, R., 1991, "Effect of Soil Plasticity on Cyclic Response," *J. Geotech. Eng.*, Vol. 117 No. (1), pp.89–107.

White, D. J., 2003, "PSD Measurement Using the Single Particle Optical Sizing (SPOS) Method," *Geotechnique*, Vol. 53, No. 3, pp. 317–326.

Zornberg, J. G., Jernigian, B. L., Sanglerat, T. R., and Cooley, B. H., 1999, "Retention of Free Liquids in Landfills Undergoing Vertical Expansion," *J. Geotech. Geoenviron. Eng.*, Vol. 125, No. (7), pp. 583–594.91.