Unit Weight of Municipal Solid Waste

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Abstract: The unit weight of municipal solid waste (MSW) is an important parameter in engineering analyses of landfill performance, but significant uncertainty currently exists regarding its value. A careful review of reliable field data shows that individual landfills have a characteristic MSW unit weight profile. Based on in situ unit weight data and trends observed in large-scale laboratory tests, a hyperbolic relationship was developed to represent this characteristic MSW unit weight profile. Within the context of this characteristic profile, landfill-specific values of MSW unit weight depend primarily on waste composition, operational practices (i.e., compaction, cover soil placement, and liquids management), and confining stress. Guidance is provided for developing landfill-specific MSW unit weight profiles, including procedures for performing large-scale tests for in situ measurement of MSW unit weight at a landfill.

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Introduction

The unit weight of municipal solid waste (MSW) is an important material property in landfill engineering. MSW unit weight is required for many engineering analyses of landfill systems, including static and dynamic slope stability, geomembrane puncture, pipe crushing, and landfill capacity evaluation. However, the value of the unit weight of MSW continues to be a major source of uncertainty in landfill performance analyses. Significant scatter exists in the reported values of MSW unit weight. Hence, it is difficult for an engineer to estimate with confidence a representative MSW unit weight profile for use in engineering analyses.

Significantly different MSW unit weight profiles have been reported in the literature. The TC5-Environmental Geotechnics Committee report (Konig and Jessberger 1997), citing the data of Fassett (1993) and other researchers, reports unit weight values from 3 kN/m^3 for uncompacted or poorly compacted waste to 17 kN/m^3 for compacted waste. As compiled by Zekkos et al. (2005b), values of in-place MSW unit weight reported at 37 different landfills varied from 3 to 20 kN/m^3. The majority of these studies do not report the method used to establish the MSW unit weight. Landva and Clark (1986) presented results from in situ near-surface test pits in several Canadian landfills and emphasized the difference between the unit weights of refuse, soil cover, and combinations of the two. The total unit weight near the landfill surface of combinations of refuse and soil cover estimated from the data reported by Landva and Clark (1986) ranged from 8 to 17 kN/m^3. Presumably, the values cited by the other researchers also represent the total unit weight of the refuse/soil cover mixture, as this is the parameter of relevance for engineering analysis. This combined refuse/soil unit weight is referred to throughout this paper as MSW unit weight.

The MSW unit weight profile of Kavazanjian et al. (1995) is one of the most commonly cited MSW unit weight profiles in the literature (even though the lead author has revised it several times since then). This profile starts from a value of about 6 kN/m^3 near the surface and reaches a value of about 13 kN/m^3 at depths of 45 m or larger. It was developed primarily based upon values reported by landfill operators for relatively dry landfills, i.e., landfills conforming to U.S. EPA restrictions against the introduction of liquids. However, subsequent studies indicated that, even for dry landfills, the unit weight values in the 1995 profile were relatively low. Kavazanjian (1999) explains that "in developing the [1995] curve, it was assumed that the operator reported values of unit weight represented the total unit weight of soil and refuse when, in fact, they represented only the weight of the refuse in a unit volume of landfill." Therefore, in subsequent work, this 1995 profile was adjusted upwards to account for the daily and interim cover soil typically placed in the landfill over the waste. Kavazanjian et al. (1996) report MSW unit weight values from 10 to 13 kN/m^3 near the ground surface increasing to 13–16 kN/m^3 at a depth of 30 m at six California landfills, based upon correlation with shear wave velocity measurements. Kavazanjian (1999) shows a "typical" unit weight profile with minus and plus one standard deviation bounds (based upon correlation with shear

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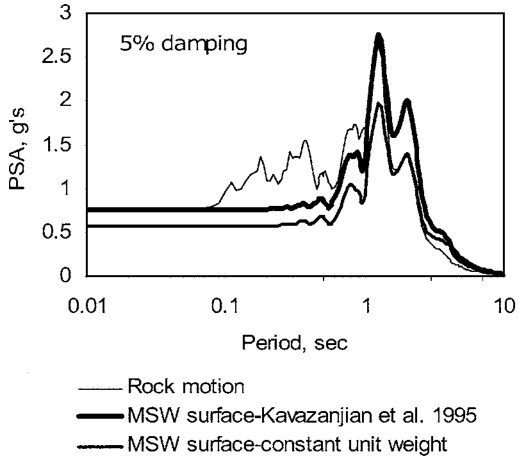

Fig. 1. Comparison of site response analyses

wave velocity) increasing from approximately 12 to 16 kN/m^3 near the ground surface to 14–17 kN/m^3 at a depth of 60 m. Kavazanjian (2001) states that at some conventional MSW landfills (e.g., landfills with high soil content or high moisture content) unit weight may be "routinely in excess of 15 kN/m^3" and that due to the higher moisture content, "MSW unit weights in bioreactor and leachate recirculation landfills are likely to be significantly higher than conventional MSW landfills, with values sometimes approaching or exceeding 20 kN/m^3 at depth."

Influence on Engineering Analyses

The selection of a representative MSW unit weight profile has an important effect in many engineering analyses. Dixon and Jones (2005) noted that MSW unit weight was the only material property that was important to all of the different types of landfill analyses considered in their paper. For instance, the strength of the clay/geosynthetic interface within the base liner system of a landfill is a function of the effective overburden stress, which is directly dependent on the MSW unit weight. The unit weight profile also affects the capacity evaluation of a landfill. Matasovic and Kavazanjian (1998) report that a 60 m high landfill with an average unit weight of 10 kN/m^3 will have an estimated refuse capacity 40% less than a landfill with the average unit weight of approximately 15 kN/m^3, as was measured in situ at the Operating Industries, Inc. (OII) Landfill.

Unit weight is also important for seismic evaluations. The MSW unit weight affects the calculated value of the small strain shear modulus (the product of the mass density of the material and the square of the shear wave velocity) and thus influences the natural period and seismic response of the landfill. Kavazanjian (2001) notes that the impact of unit weight on seismic response "may be beneficial or detrimental, depending on the natural period of the landfill and the predominant period of the earthquake." It is not only the average unit weight but also the distribution of unit weight within the landfill that affects seismic response. For example, Fig. 1 shows acceleration response spectra (5% damping) calculated at the top of a 60 m high landfill founded on rock using SHAKE2000 (Ordonez 2000) and two different MSW unit weight profiles. The Yerba Buena Island ground motion from the 1989 Loma Prieta Earthquake was used as the outcropping rock motion in this analysis. Both MSW unit weight profiles had the same average unit weight. However, one of the analyses employed the Kavazanjian et al. (1995) unit weight profile and the other employed a constant unit weight of 10.5 kN/m^3. The resulting response spectra have significant differences in terms of the intensity of the calculated motion at the top of the landfill. Seismic displacements are also influenced by the distribution of unit weight. To illustrate this point, seismic displacements of a cover system were calculated using Newmark-type analyses and the ground motions at the top of the landfill from the analyses shown in Fig. 1 and from a second set of analyses conducted using the near-fault Takatori Station, 1995 Hyogoken-Nanbu (Kobe) earthquake record. For both input ground motions, calculated seismic cover displacements for cover system yield accelerations of 0.05–0.15 g were about two times higher from the response analyses that employed the Kavazanjian et al. (1995) unit weight profile than those that employed the constant unit weight profile. Hence, the selection of an appropriate MSW unit weight profile is essential for reliable engineering analyses.

Methods Used to Estimate MSW Unit Weight

Reported in-place unit weight values for MSW from more than 37 landfills were collected and evaluated by Zekkos et al. (2005b). The primary methods used to evaluate the unit weight of MSW in these studies were as follows.

1. Surveys and landfill records: Landfill records allow the total weight of the materials (including both waste and soil) placed in the landfill to be estimated and topographic surveys allow the volume of the in-place materials to be estimated. With these data, the average in-place total unit weight of MSW can be estimated. Although this method may provide a reasonable overall estimate of the average MSW unit weight, it does not provide a reliable means of assessing the increase in unit weight with increasing overburden pressure, i.e. the distribution of unit weight with depth.
2. Unit weight of "undisturbed" specimens: Unit weight can be measured accurately if truly representative intact undisturbed specimens can be retrieved. However, even if intact samples can be retrieved from a MSW landfill, this method is not recommended, because it is doubtful that the specimen will be either representative or undisturbed, as large particles are not likely to be adequately sampled and sample disturbance will likely lead to "uncorrectable" errors.
3. In situ large-scale methods: In situ large-scale methods generally mimic the sand-cone density test but are performed at a larger scale. Large-scale test pits near the surface or large-diameter deep boreholes are excavated and the retrieved waste material is weighed. The excavated cavity's volume is estimated either by surveying or by replacing the waste material with calibrated material of known unit weight such as uniform gravel. If the replacement method is used, the volume of the cavity is estimated by dividing the weight of calibrated material placed in the cavity by the known unit weight. The unit weight of MSW is calculated by dividing the measured weight of the excavated MSW by the estimated volume of the cavity.

Of these three methods, the in situ large-scale method is judged by the writers to be the most reliable approach for evaluating the in-place unit weight of MSW, because it typically involves large volumes of material, including large-sized particles, minimizing errors due to disturbance and non-representative material, and it accounts for changes that have occurred in the material since its placement in the landfill.

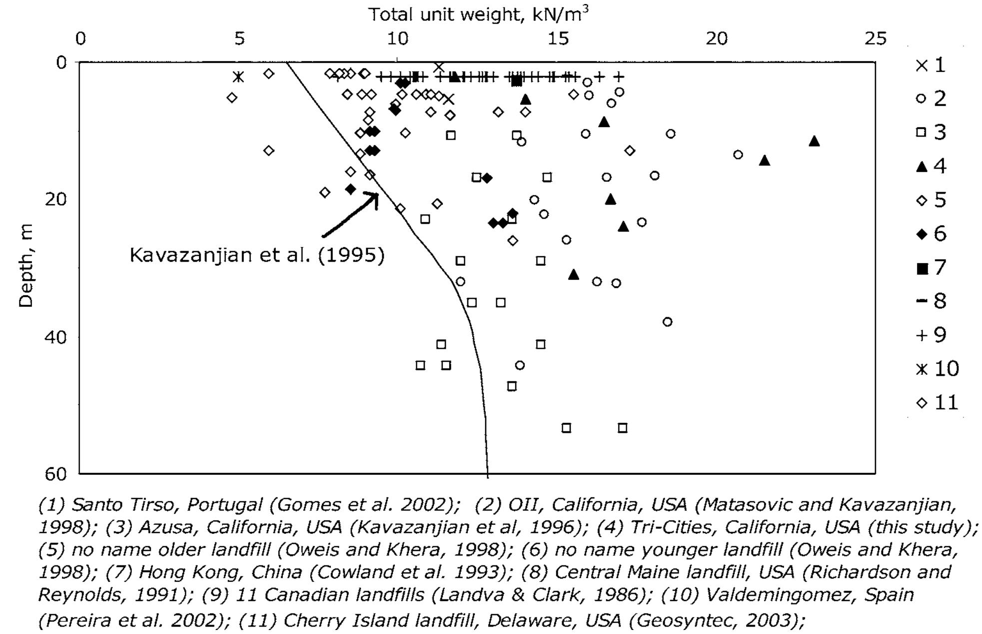

Fig. 2. Unit weight values from in-situ large-scale tests

Available in Situ Unit Weight Data

Fig. 2 presents in-place large-scale MSW unit weight measurements from 11 different studies [Gomes et al. (2002); Matasovic and Kavazanjian (1998); Kavazanjian et al. (1996); Oweis and Khera (1998); Cowland et al. (1993); Richardson and Reynolds (1991); Landva and Clark (1986); Pereira et al. (2002); Geosyntec (2003) and this study]. The Kavazanjian et al. (1995) MSW unit weight profile is also shown for reference. There is considerable scatter in the reported unit weights, with values from 5 kN/m^3 to more than 18 kN/m^3. Although Fig. 2 shows no obvious trend, when the measured unit weight values for each landfill are examined separately a consistent trend of unit weight increasing with depth is observed, suggesting the existence of a landfill-specific "characteristic unit weight profile." The existence of a characteristic unit weight profile for a specific MSW landfill is a reasonable hypothesis, not only because consistent trends have been observed at existing landfills, but also because modern "controlled" landfills generally have relatively uniform waste streams, with wastes of similar composition, organic content, and moisture content (or, at least, waste streams that evolve gradually over time), and have standard waste disposal operating procedures (e.g., use of standard thicknesses of waste lifts and of daily and interim covers, consistent surface water and landfill liquid management procedures, and standardized waste compaction methods). Therefore, a particular landfill may reasonably be expected to have an internally consistent unit weight profile in which the unit weight increases with depth in response to the increase in overburden stress. Landfills or individual waste units that deviate significantly from the assumption of consistent waste stream and operational practices may not have a consistent unit weight profile.

Fig. 3 shows in-place unit weight profiles developed at six U.S. landfills using in situ large-scale methods. For the Tri-Cities Landfill in Fremont, Calif., in situ tests performed by the writers using a 760 mm diameter bucket auger yielded unit weight values of about 10 kN/m^3 near the surface and approximately 16 kN/m^3 at a depth of 30 m. Two data points from this landfill indicate unit weight values in excess of 20 kN/m^3 at depths between 10 and 20 m; however, these samples included concrete debris and are not considered representative of typical MSW. For the OII Landfill (Matasovic and Kavazanjian 1998) near Los Angeles, in situ tests indicated a roughly constant unit weight profile of about 15 kN/m^3, possibly due to the relatively large amount of cover-soil that was employed near the top of the landfill. At the Azusa Landfill, also near Los Angeles, the measured in situ unit weight was approximately 12 kN/m^3 at a depth of about 10 m, reaching a value of approximately 15 kN/m^3 at a depth of approximately 50 m (GeoSyntec 1995; Zornberg et al. 1999). Data from the Cherry Island Landfill in Delaware (GeoSyntec 2003) show a unit weight value of approximately 8 kN/m^3 near the surface reaching values of approximately 12 kN/m^3 at a depth of 10 m. At depths greater than 10 m, the Cherry Island waste material was sub-

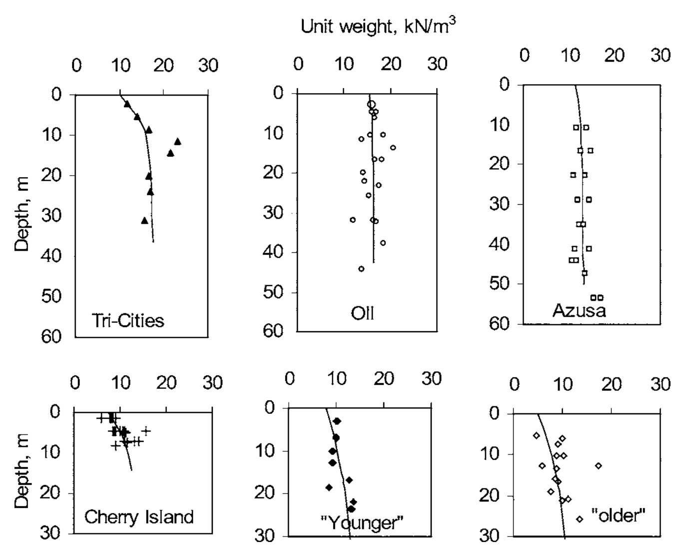

Fig. 3. MSW unit weight profiles from in situ tests for individual landfills

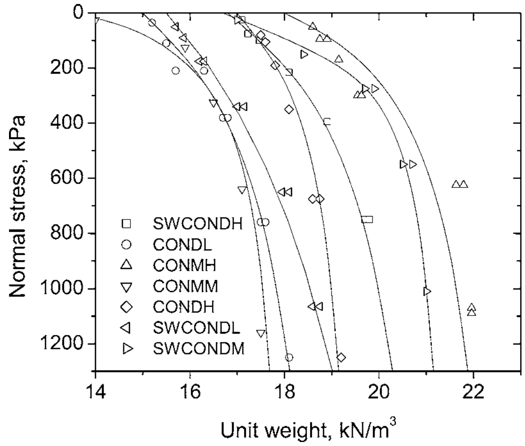

Fig. 4. Large-scale 1D compression tests on OII landfill MSW (descriptions provided in Kavazanjian et al. 1999)

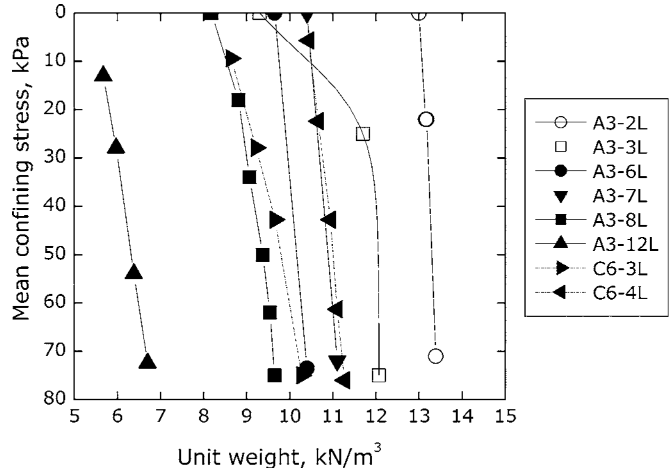

Fig. 5. Unit weight versus isotropic confining stress from some large triaxial Tri-Cities landfill MSW specimens

merged below the water table and thus does not satisfy the requirement for consistent operational conditions when compared to the shallower waste. For the submerged conditions at Cherry Island, values of 14.5–16 kN/m^3 for the total (saturated) unit weight were reported. Data from Oweis and Khera (1998) for two unidentified landfills in New Jersey, denoted as the "older" and "younger" landfills in Fig. 3, show MSW unit weights near the surface of about 7 and 10 kN/m^3, respectively, with a more pronounced increase in the unit weight with depth for both of these landfills than at the OII or Azusa landfills.

Total unit weight is proportionally affected by the moisture content of a material. Measured moisture contents at the OII Landfill were 15–42%, at the Tri-Cities Landfill were 12–25%, and at the Azusa landfill were 8–50% with an average of about 25%. Moisture contents at the Cherry Island Landfill varied from 20 to 50% for the waste above the water table. As the waste at all of these locations was "drained," these values all represent moisture contents at or below field capacity. The systematic trends in the data shown in Fig. 3 suggest that a landfill-specific total unit weight model for engineering analyses can be developed for typical MSW landfills with moisture contents at or below field capacity. However, the considerable scatter in unit weight values shown in Fig. 2 indicates that landfill-specific information is needed and that in situ tests may be required to evaluate reliably the MSW unit weight at a specific landfill.

Insights from Large-scale Laboratory Data

Laboratory studies can provide important insights regarding the factors that affect MSW unit weight because testing conditions can be carefully controlled. In laboratory testing, the specimen composition, moisture content, compaction conditions, confining stress, and the resulting unit weight can be known with a high degree of certainty. However, due to the large particle sizes of typical MSW, testing using traditional laboratory equipment is inadequate, and larger testing devices are required to prepare specimens that are representative of the field conditions.

Kavazanjian (1999) presented data from large-diameter (457 mm) one-dimensional compression tests performed on reconstituted waste samples from the OII Landfill. Particles up to 100 mm in size were used in these tests. The results are shown in Fig. 4. Kavazanjian (1999) states that the specimens with higher soil content and higher moisture content tended to have the higher total MSW unit weights. For example, considering two of the specimens with the higher unit weight values, specimen CONMH was so moist that free liquids squeezed out of the specimen during consolidation and specimen SWCONDM was composed almost entirely of soil-like material. The relationship between the MSW unit weight and the normal stress for individual tests in Fig. 4 appears to be hyperbolic in shape. Results from isotropic compression tests conducted on reconstituted 152 mm diameter specimens at the University of Texas as part of the testing program on waste from the Tri-Cities Landfill described subsequently, and compression tests under K_0 conditions on 300 mm square specimens at the University of Patras using waste material from the Tri-Cities Landfill also indicated a hyperbolic relationship between MSW unit weight and confining stress.

Fig. 5 presents results from large (300 mm diameter) isotropically consolidated triaxial tests performed at the University of California, Berkeley on reconstituted MSW specimens from the Tri-Cities Landfill. Results from two different sample groups are shown: Group A3, which was retrieved from a depth of 25.6–26.2 m and was 16 years old, and Group C6, which was retrieved from a different borehole at a depth of 7.6–9.6 m and was 3 years old. All specimens were prepared by compaction in layers using a 9.5 kg weight dropped repeatedly from a constant height until the specimen reached the target density or the target compaction effort was applied. Table 1 lists the unit weight after

Table 1. Unit Weight and Waste Composition of Some Tri-Cities Landfill Laboratory Specimens

		% by weight composition				
Specimen	γ_t (kN/m^3)	<20 mm	Paper	Soft plastics	Wood	Gravel
A3-2L	13	100	0	0	0	0
A3-3L	9.3	100	0	0	0	0
A3-6L	9.7	76	13	4	7	0
A3-7L	10.4	62	14	3	11	10
A3-8L	8.2	62	14	3	11	10
A3-12L	5	14	56	5	13	12
C6-3L	8.1	62	18	5	5	12
C6-4L	10.2	62	18	5	5	12

compaction, the percentage by weight of material less than 20 mm in size, and the composition of the larger than 20 mm waste materials in these tests. Material that is smaller than 20 mm is "soil-like" in appearance and constitutes the matrix of MSW. Particles that are larger than 20 mm are largely materials such as paper, soft plastics, and wood. The moisture content of the smaller than 20 mm material was approximately 12–13% for both waste groups and the organic content of the less than 20 mm material was 15–30% for the A3 Group and 10–16% for the C6 Group. The larger than 20 mm material had somewhat higher moisture content (i.e., 20–30%) than the smaller than 20 mm material. Moisture content in this study was defined as the ratio of the weight loss to the weight that remained after heating at a temperature of 55 °C until the specimen has dried to a constant mass. A temperature of 55 °C was employed rather than the temperature of 105 °C typically used in soil moisture content testing to minimize the potential for the loss of waste constituents. More information on the specimen preparation and sample composition is provided in Zekkos (2005).

Specimen A3-2L included only particles less than 20 mm in dimension and was prepared at a target density of 13 kN/m^3 with relatively high compaction energy. The relationship between unit weight and confining stress for this specimen is almost linear, with a relatively small increase in the unit weight with increasing confining stress. Specimen A3-3L was comprised of the same material as Specimen A3-2L but was prepared with minimal compaction effort. The unit weight is significantly less than that of Specimen A3-2L at low confining stress but increases significantly with increasing confining stress. Specimen A3-6L included larger particles (particles up to 80 mm in dimension) than Specimen A3-2L (which included only the less than 20 mm material) and was prepared with similar energy input. The resulting unit weight was significantly smaller for A3-6L than for Specimen A3-2L. The smaller unit weight of A3-6L is attributed to both the lower unit weight of the larger particles (paper, plastic, and wood) and an increase in the void ratio of the specimen. Specimen A3-7L included more large particles (38% by weight larger than 20 mm material) than Specimen A3-6L (24% by weight larger than 20 mm material) but also included gravel in the larger fraction and was compacted with larger input energy than A3-6L. The resulting unit weight for Specimen A3-7L is larger than A3-6L. Specimen A3-8L included the same material as Specimen A3-7L but was compacted with less energy. Again, similar to the specimens that included only particles less than 20 mm (A3-2L), the compacted unit weight is lower for Specimen A3-8L than for Specimen A3-7L but the effect of confining stress is more pronounced. Specimen A3-12L was composed almost entirely of particles larger than 20 mm (86% by weight larger than 20 mm) and was compacted with input energy similar to Specimen A3-6L. The unit weight of Specimen A3-12L is significantly lower over the entire confining stress range compared to the unit weight of all the other specimens that have more of the smaller (less than 20 mm) material and generally follows an almost linear trend with increasing confining pressure.

Similar trends as those discussed previously for the A3 group of samples from the Tri-Cities Landfill were observed for the C6 Group of samples (Zekkos et al. 2005b). The unit weight versus confining pressure relationships for two specimens of the C6 Group are shown also in Fig. 5. Specimen C6-4L included 62% less than 20 mm material and was prepared with similar input compaction energy as Specimen A3-7L. The resulting unit weights are similar. Specimens C6-3L and C6-4L had the same composition, but C6-3L was prepared with less compaction energy than Specimen C6-4L. The unit weight at low isotropic confining stress (10 kPa) is similar for Specimens C6-3L and A3-8L, but as confining stress increases the increase in unit weight for Specimen C6-3L is more pronounced. This trend is attributed to the difference in composition between the two specimens, with Specimen C6-3L including more compressible, light, large particles such as paper and plastic, whereas Specimen A3-8L included more wood and less paper and plastic.

Fig. 6 shows similar results for specimens from the OII Landfill (GeoSyntec 1996). Two 454 mm diameter odometer specimens with the same composition were reconstituted at two different unit weights. For the specimen that was reconstituted at a lower unit weight (i.e., with less compaction effort), the effect of changing normal stress on the unit weight is more pronounced than for the initially denser specimen. Both specimens appear to be converging upon the same unit weight at high normal stresses.

Analysis of data from laboratory tests such as those shown in Figs. 4–6 indicate that the relationship between MSW unit weight and confining stress can be described by a hyperbolic equation. Fig. 7 shows data for the unit weight of the Tri-Cities Landfill specimens composed solely of the less than 20 mm fraction material from the A3 waste group as a function of the energy input during specimen compaction using a weight dropped repeatedly from different heights. For each of the different combinations of weight (W), drop height (h), and layer's target thickness (t), a hyperbolic function can capture the relationship between the unit weight and the compaction effort. Aburatani et al. (1998) presented a similar hyperbolic plot from field and laboratory data on MSW from Japan.

The effect of time under confinement on the unit weight of MSW undergoing mechanical compression (i.e., secondary compression without any degradation) was also investigated through laboratory tests. Measurements were performed on MSW specimens from Sample Groups A3 and C6 from the Tri-Cities Landfill that remained under isotropic (vacuum) confining stress for a maximum of 3 months. The unit weight of these specimens was evaluated from volume change calculated using measurements of the axial and radial deformation. The confining stress in these tests ranged between 25 and 90 kPa. Regression of the data (presented in Zekkos et al. 2005a) results in the following relationship between the unit weight and the time under confinement (t in days)

$$\frac{\gamma_t(t)}{\gamma_t(t=1\ \text{day})} = 0.0172\log(t) + 1.0 \qquad (1)$$

Extrapolating Eq. (1) to greater times indicates that there would be less than a 10% increase in unit weight due to time under confinement effects over 50 years due to mechanical compression. Eq. (1) is equivalent to a MSW modified secondary compression index, $C_{\alpha\varepsilon}$, of about 0.016. Equivalent secondary compression indices from the individual tests varied from 0.01 to 0.04 with higher values observed for specimens with lower unit weights and greater proportions of larger than 20 mm material.

A separate series of tests performed at confining stresses up to 276 kPa indicated that the effect of time under confinement was probably independent of the confining stress (Zekkos et al. 2005a). Although the absolute unit weight and the composition of the MSW in these tests did have some influence on the effect of time under confinement on the unit weight (Zekkos et al. 2005b), when these relationships are projected to a landfill time scale (e.g., 50 years) the resulting increases in unit weight are for practical purposes similar and also small.

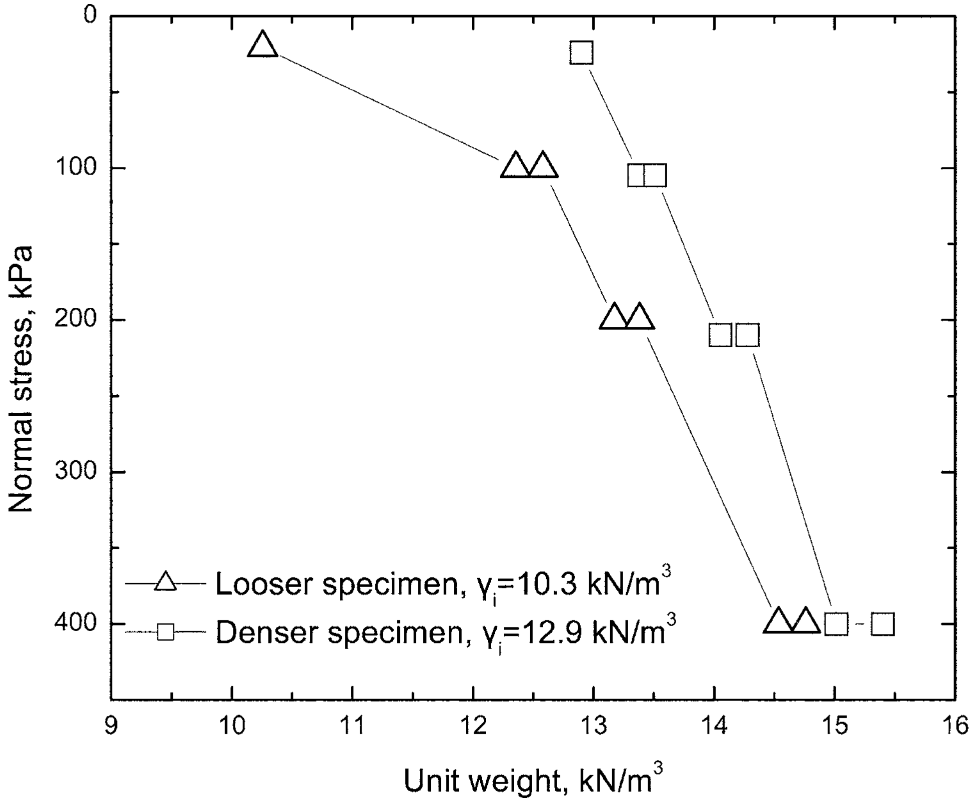

Fig. 6. Unit weight versus normal stress for 1D compression of specimens from the OII landfill with the same composition and different as-placed unit weight (from GeoSyntec 1996)

Unit Weight Model for Municipal Solid Waste

From examination of the available field and laboratory data, a hyperbolic relationship between the total unit weight of MSW of a given composition and density state was hypothesized. The density state could be produced through compaction effort, application of confining (or overburden) stress, or both. The shape of the hyperbola depends to a large extent on the initial MSW unit weight, which is controlled by the compaction effort and the MSW composition (e.g., amount of soil, types of waste materials, and moisture content).

Fig. 8 illustrates the hypothesized hyperbolic unit weight model. For low degrees of input compaction effort (e.g., light compaction and low confining stress) the MSW material will be at point *L*. In this state, there is still significant densification that can take place as confining stress increases, i.e., as additional waste or soil overburden is placed. For high degrees of input compaction energy (i.e., high initial compaction; point H), some

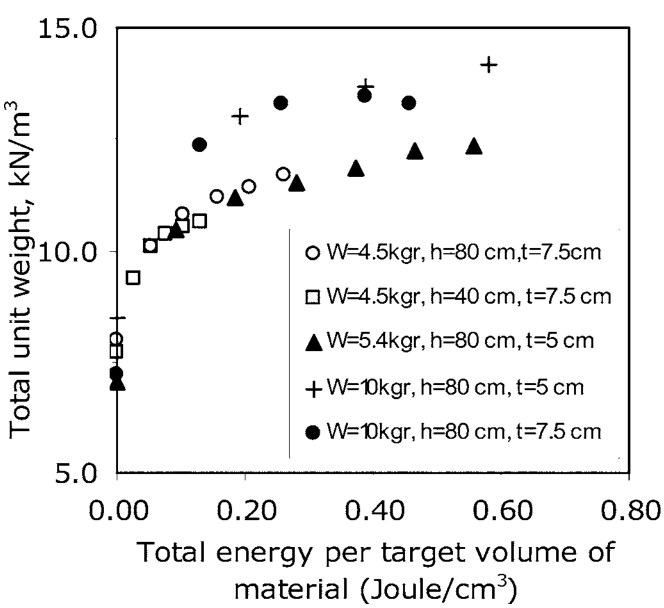

Fig. 7. Unit weight versus energy input during specimen preparation

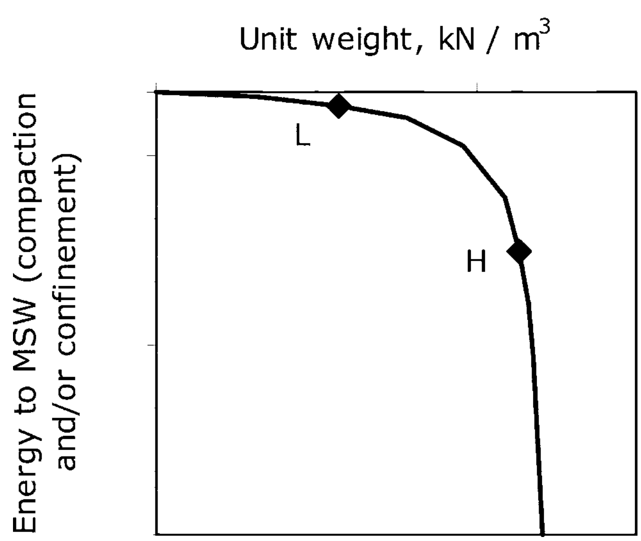

Fig. 8. Conceptual model of MSW unit weight and energy input

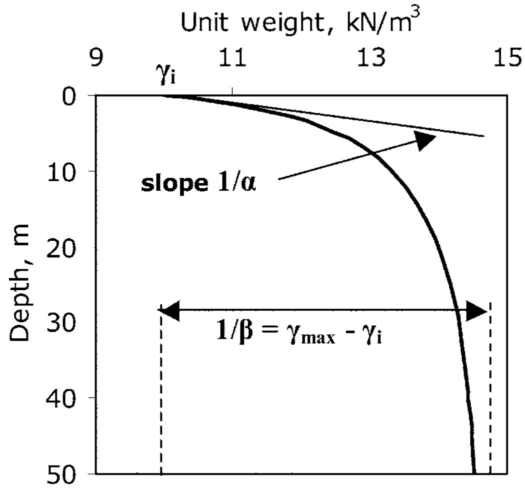

Fig. 9. Physical meaning of the hyperbolic parameters α and β

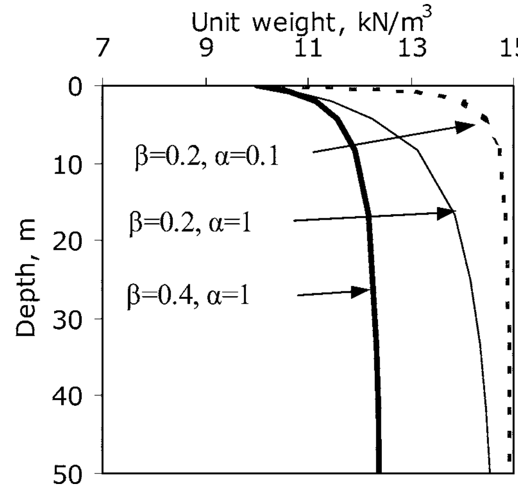

Fig. 10. Effect of the hyperbolic parameters on the unit weight profile

additional compression is still possible, but the resulting increase in unit weight is not as significant and a more linear increase in unit weight with confining stress (i.e., depth) occurs. In fact, for high initial unit weight the increase in unit weight with confining stress can be so small that it might not be recognizable in the field (i.e., the unit weight may appear to be constant with depth, as it appears for the OII Landfill profile shown in Fig. 3). Similar trends can be observed for other geomaterials (e.g., sands and clays). What differentiates MSW from these other geomaterials is the larger range of initial unit weight values typically encountered in engineering practice.

The following equation presents the proposed hyperbolic model for MSW total unit weight (γ) as a function of mean confining stress:

$$\gamma = \gamma_i + \frac{\sigma_m}{\alpha_m + \beta_m \sigma_m} \tag{2}$$

where γ_i=near-surface in-place unit weight; σ_m=mean stress at which the MSW unit weight is to be estimated; and α_m and β_m =modeling parameters. The first term in Eq. (2) represents the effect of the waste placement conditions (e.g., waste composition, moisture content, and compaction level) and the second term reflects the effect of confining stress on the MSW unit weight. However, to estimate the mean stress, the coefficient of lateral earth pressure at rest, K_0 is needed. Field and laboratory testing provide K_0 values that range from 0.2 to 0.8 for MSW (e.g., Landva et al. 2000; Dixon et al. 1999). Uncertainty about K_0 introduces additional uncertainty in the unit weight profile. To avoid this issue, an equivalent form of Eq. (2) can be formulated in terms of vertical overburden stress (σ_v)

$$\gamma = \gamma_i + \frac{\sigma_v}{\alpha_v + \beta_v \sigma_v} \tag{3}$$

In the previous expressions, it is assumed that pore pressures are negligible and therefore the total stresses (mean and vertical) that are used in the above equations are also effective stresses. From a practical perspective, this means that use of Eq. (3) is limited to landfills in which the moisture content is at or below field capacity (i.e., conventional relatively dry landfills and most leachate recirculation landfills, but not bioreactor landfills) and the effect of capillary tension in the waste is negligible.

Estimation of the vertical overburden stress requires knowledge of the unit weight of the overburden material and thus an iterative procedure would be required to estimate a MSW unit weight profile using Eq. (3). A more convenient equation for MSW unit weight can be written as a function of depth. A unit weight equation based upon depth has the advantage that no lateral stress coefficient nor iterations are required. Additionally, this form of the relationship is more robust, because field data typically consist of a known unit weight at a known depth and not at a known vertical or mean stress. Hence, the recommended hyperbolic MSW unit weight equation has the form

$$\gamma = \gamma_i + \frac{z}{\alpha + \beta z} \tag{4}$$

where γ_i=near-surface in-place unit weight (kN/m^3), z=depth (m) at which the MSW unit weight (γ) is to be estimated; and α (m^4/kN) and β (m^3/kN)=modeling parameters.

The physical meanings of the α and β parameters are illustrated in Fig. 9. The parameter β is a function of the difference in unit weight between that at the surface and at great depth (or high confining stress) where the unit weight profile becomes nearly constant. The inverse of β is the asymptotic value of the difference in the unit weight at great depth and at the surface. The parameter β typically ranges between 0 and 1 m^3/kN. If the unit weight at great depth is close to the near-surface in-place unit weight value, β is about 1 m^3/kN. If the unit weight at depth is much higher than that near the surface, β approaches 0. If $\beta=0$, then the unit weight increases linearly with increasing depth and does not approach an asymptotic value. Values of β greater than 1 m^3/kN are possible but do not affect the shape of the hyperbola significantly.

The parameter α is a function of the rate of unit weight increase with depth near the surface. The ratio of $1/\alpha$ is the initial slope of the unit weight versus depth curve near the surface. The parameter α takes on values typically within a range of 0–10 m^4/kN. If the unit weight increases significantly at shallow depths, small values of α should be used. If the unit weight does not increase significantly near the surface, larger values should be used. Fig. 10 illustrates how the α and β parameters affect the shape of the MSW unit weight profile.

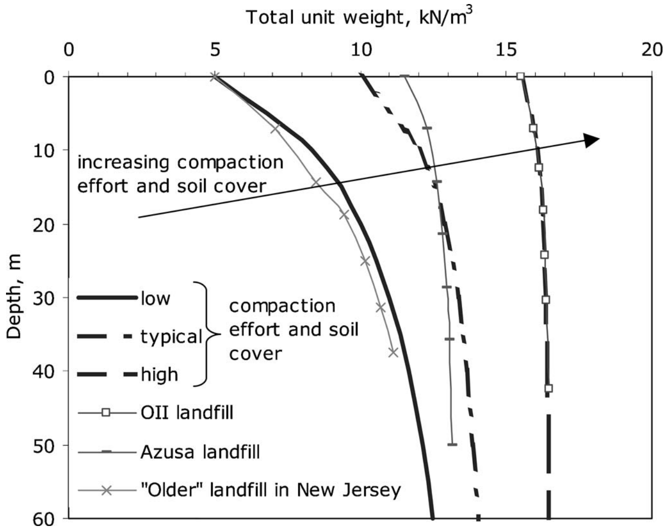

Fig. 11. Recommended unit weight profiles for conventional municipal solid-waste landfills. The near-surface in-place unit weight depends on waste composition (including moisture content) in addition to compaction effort and the amount of soil cover. The effect of confining stress is represented by depth.

MSW Unit Weight Model

The model described by Eq. (4) was fit to the field data presented in Fig. 3. The fitted hyperbolas are shown in Fig. 3 as solid lines for each landfill. In the fitting process, the near-surface in-place unit weight was assigned based upon the field data and then the hyperbolic parameters β and α were estimated based upon a visual "best fit" to the data.

Fig. 11 illustrates a family of representative MSW unit weight profiles developed using this model. Model parameters for the three representative profiles shown in Fig. 11 (for low, typical, and high near-surface in-place unit weight) are provided in Table 2. The in-place near-surface MSW unit weight for a particular waste material primarily increases with compaction effort and soil content and the increase in unit weight with confining stress at depth becomes less pronounced with increasing near-surface in-place unit weight (moving from the continuous curve on the left-hand side toward the dashed curve to the right-hand side). The recommended curves are supported by the field-fitted hyperbolas, some of which are shown in this figure, and the laboratory test data described previously.

Moisture content is not explicitly included in the MSW unit weight model because for conventional landfills it was found to be of lesser importance and was not measured consistently in the field studies of MSW unit weight. Reliable moisture content measurements ranged from approximately 10%–50%. The curves shown in Fig. 11 are considered reasonable for typical conventional landfills, i.e., landfills with moisture contents at or below field capacity. The moisture content of the waste, although not explicitly included in Fig. 11, may affect where, within the family of typical unit weight profiles, a particular landfill falls, i.e., an increase in moisture content will move the representative unit weight curve for a given landfill to the right in Fig. 11.

Table 2. Hyperbolic Parameters for Different Compaction Effort and Amount of Soil Cover

Compaction effort and soil amount	γ_i (kN/m^3)	β (m^3/kN)	α (m^4/kN)
Low	5	0.1	2
Typical	10	0.2	3
High	15.5	0.9	6

Waste compressibility, as represented by the modified compression indices, $C_{c\varepsilon}$, can be estimated from the recommended unit weight curves for low, typical, and high in-place near-surface unit weight. Defining the modified compression index $C_{c\varepsilon}$ as the slope of the volumetric strain-log vertical stress plot and assuming no loss of mass (no degradation), it can be shown that for material that has a total unit weight of γ_{t1} at an initial vertical effective stress σ'_{v1} and a total unit weight of γ_{t2} at vertical effective stress σ'_{v2}, the equivalent modified compression index is given by the following equation:

$$C_{c\varepsilon} = \frac{\Delta e}{1+e_0}\frac{1}{\log\left(\frac{\sigma'_{v1}}{\sigma'_{v2}}\right)} = \frac{\gamma_{t2}-\gamma_{t1}}{\gamma_{t2}}\frac{1}{\log\left(\frac{\sigma'_{v1}}{\sigma'_{v2}}\right)} \quad (5)$$

Using Eq. (5) and discretizing the three recommended unit weight profiles at different depth intervals, values of the MSW equivalent compression index $C_{c\varepsilon}$ that correspond to the representative unit weight profiles in Fig. 11 can be estimated. Using this approach, the resulting $C_{c\varepsilon}$ values are 0.015–0.04, 0.13–0.22, and 0.36–0.55 for high, typical, and low near-surface in-place unit weight, respectively. These values are consistent with previous recommendations on the compressibility of MSW (e.g.,Sowers 1973; Fassett 1993; Kavazanjian et al. 1999).

The parameters of the hyperbolas fitted to the field unit weight data of Fig. 3 are plotted in Fig. 12 to illustrate the relationship of the near-surface in-place unit weight, γ_i, with the β parameter (Chart 1) and the relationship of β with the α parameter (Chart 2). The majority of the field data are in the lower left-hand side of the charts (low initial unit weight, small β and α), with the denser OII Landfill data being in the upper-right portion of these charts due to its large initial unit weight and small difference between its initial unit weight and unit weight at depth. It is reasonable to expect that as the amount of daily soil cover, moisture content, or compaction effort increases, the unit weight near the surface, γ_i, and the α and the β parameters will also increase. As explained previously, the larger the β parameter, the smaller the difference between the unit weight at the surface and at depth, and the larger the α parameter, the smaller the increase of the unit weight near the surface (see Fig. 10).

The field data suggest that γ_i, α, and β increase as the amount of cover-soil or compaction effort increases. This observation is supported by the results of the large-scale triaxial laboratory data shown in Fig. 5. Because the laboratory unit weight data is for isotropic stress conditions, "equivalent" field depths were estimated by calculating the depth at which the isotropic stress in the laboratory is equal to the mean field stress under K_0 ("at rest") stress conditions. A value of K_0 equal to 0.5 was assumed, which is consistent with Poisson's ratio values measured in the triaxial tests for specimens with 100% of the constituents smaller than 20 mm. The laboratory data in Fig. 5 were fit to Eq. (4) and values of γ_i, α, and β, were derived. The resulting values of α and β are shown in Fig. 12 for the Tri-Cities Landfill A3 sample group specimens. Specimen A3-3L included 100% less than 20 mm material and was prepared without compaction. Specimen A3-1L included the same material but was compacted with more effort than specimen A3-3L. Comparison of the parameters de-

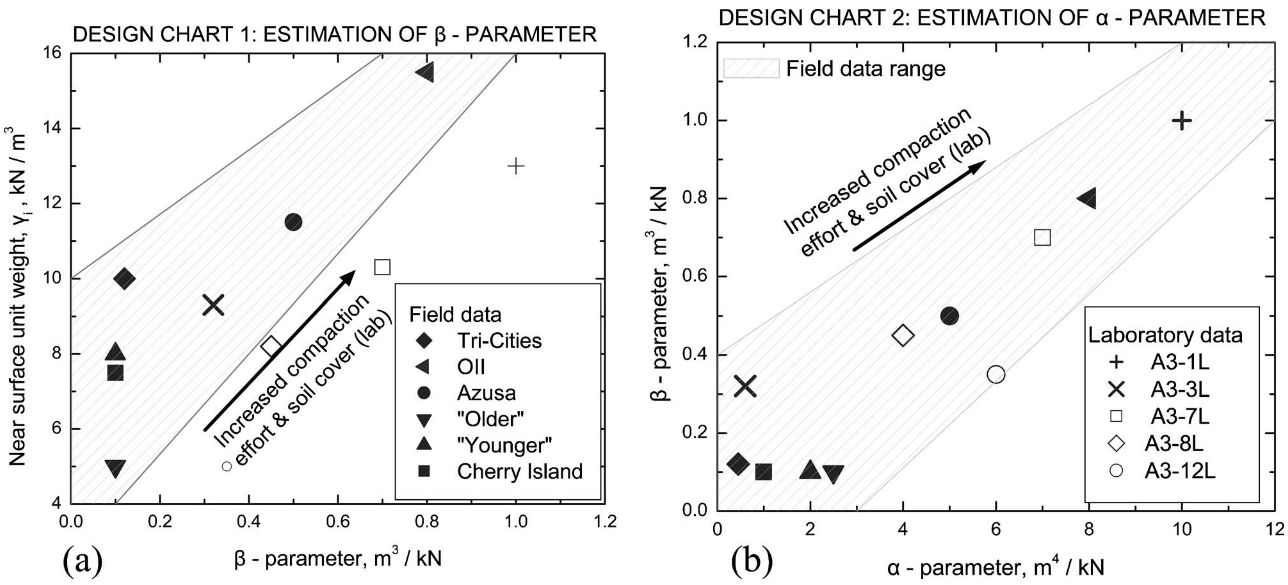

Fig. 12. Design charts for the estimation of the β and α parameters from the near-surface unit weight

rived from these two tests indicate that as the compaction energy increases from one specimen to the other, the γ_i, β, and α fitted parameters increase, moving the data toward the upper right-hand portion of the Fig. 12 charts. Similarly for Specimens A3-8L (low compaction energy) and A3-7L (high compaction energy), both of which are composed of 62% less than 20 mm and have the same composition, the trend of increasing γ_i, β, and α values with increasing energy was also observed. The laboratory data also suggest that as the amount of fine particles (e.g., soil) within the waste increases, γ_i, β, and α increase and the data points move toward the upper right-hand portion of both charts in Fig. 12. Specifically, for Specimens A3-12L, A3-7L, and A3-1L, with 14, 62, and 100% less than 20 mm material, respectively, which were all prepared using a similar amount of compaction energy, the data fall progressively toward the upper and right-hand parts of the charts in Fig. 12.

Application of MSW Unit Weight Model in Practice

Based on the framework developed previously for characterizing the MSW unit weight versus depth profile, recommendations for selecting an appropriate landfill-specific characteristic unit weight profile are provided for three situations: (1) Analysis or design based on a comprehensive geotechnical investigation, (2) analysis or design based on a limited investigation, and (3) analysis or design of a future landfill (i.e., with no investigation). Application of the model relies upon the assumption of fairly consistent waste composition and landfill operational practices.

Scenario 1: Analysis or Design Based on a Comprehensive Geotechnical Investigation

Step 1: Evaluation of the Near-Surface In-Place Unit Weight Using Test Pits

The first step for the development of a reliable MSW unit weight profile at an existing landfill is the measurement of the near-surface in-place unit weight, γ_i. Test pits are the recommended method to measure γ_i because they involve a large amount of material and can easily be performed using a backhoe. Test pits should ideally involve the largest practical amount of material so that they are representative of landfill conditions. The volume of the excavated waste material can be estimated using survey measurements or using a gravel or water replacement technique and the weight of the excavated material can be measured using the landfill scales. The accuracy of the landfill scales and the volume of excavated waste must be considered in the estimation. Past experience shows that landfill scales are accurate to within 2% for a 10 m^3 load of MSW. Typically, a volume of 10 m^3 should include a representative amount of the largest waste fraction and should therefore provide a reliable estimate of the unit weight at the test location (Landva and Clark 1986). Because MSW is a material with large variability (e.g., see near-surface in-place unit weight data provided in Landva and Clark 1986), ideally at least two test pit measurements should be performed. If the measured unit weight is significantly different between the two tests, a third test pit is recommended.

Step 2: Evaluation of the Unit Weight at Larger Depths Using Large Diameter Boreholes

At greater depths, test pits are not practical and, thus, large-diameter bucket auger boreholes, preferably having a minimum auger diameter of 760 mm, should be used to estimate the in-place MSW unit weight at depth. The waste material is removed and weighed from a segment of the boring drilled over a length of 2–3 m, resulting in a nominal waste volume of about 1 m^3. A "calibrated" backfill material is then placed in the cavity immediately after drilling. This backfill material compensates for overdrilling of the boring (due to the fibers and particle interlocking) by filling in the "overdrilled" volume and also compensates for "squeezing" of the borehole (cavity deformation due to stress relief) by restoring the lateral stress over the excavated length of borehole. It is recommended that uniform pea gravel that can be tremied into the boring at a consistent unit weight be used as the calibrated backfill material.

An example of the recommended procedure is that used at the Tri-Cities Landfill, which is presented in Zekkos et al. (2005b). Gravel was placed using a tremie pipe which extended to approxi-

mately 6 m above the bottom of the borehole. When the 2–3 m excavated interval was filled, the weight of the placed gravel was measured (by measuring the weight of the source gravel before and after placement of gravel in the borehole) and the volume of the excavated interval was estimated. The weight of the waste material removed from the borehole interval was measured using the landfill scale and thus the in-place unit weight of MSW at this location could be estimated. The test was repeated to estimate the unit weight at several depths. At least 1 m of "virgin" waste material was removed from the boring before another unit weight measurement was performed to ensure that subsequent tests were performed in waste material uncontaminated by gravel. Gravel removed from the boring was not reused.

Step 3: Development of the Unit Weight Profile

Based on the data obtained from the previous steps, a reliable landfill-specific unit weight profile can be established by fitting the field data to the hyperbolic unit weight model presented previously. Because of the scarcity and the importance of this type of data, engineers who perform field tests for MSW unit weight are invited to submit them to an online database that has been established to facilitate additional analysis and independent model development. The database of MSW unit weight values is available online at the Geoengineer website (http://waste.geoengineer.org/).

Scenario 2: Analysis Based on a Limited Investigation

Step 1: Evaluation of the Near-Surface In-Place Unit Weight

Because in situ large-scale borehole tests require significant effort and resources, it may not be possible to perform these tests on many projects. However, near-surface test pits require significantly less effort and can significantly reduce the uncertainty with respect to MSW unit weight. The test pits will provide the value for the landfill-specific near-surface in-place unit weight, γ_i.

Step 2: Use Design Charts to Estimate α and β Parameters

After a "representative" near-surface in-place unit weight is estimated from the test pits, the design charts provided in Fig. 12 may be used to estimate the α and β parameters. From the near-surface in-place unit weight, γ_i, and Fig. 12(a), β may be estimated. With β known, α may be estimated from Fig. 12(b). Using Eq. (4), the representative unit weight profile can be developed. Considering the influence of unit weight on the results of engineering analyses, if this approximate method is employed, an appropriate level of conservatism or a sensitivity study that incorporates reasonable variations of the MSW unit weight profile should be employed in the analyses.

The importance of landfill-specific information cannot be overemphasized. However, if test pits are not possible, the engineer may be able to make a reasonable assumption of the near-surface in-place unit weight based on the information provided by the landfill operator, the information presented in Zekkos et al. (2005b), information in a MSW database (e.g., http://waste.geoengineer.org), or experience. The procedure described above can then be used to develop the characteristic unit weight profile for analysis and design.

Scenario 3: Design of a Future Landfill (or Lateral Expansion of an Existing Landfill)

In the design of a new MSW landfill, where in situ data do not exist, a representative unit weight profile may be developed from the family of unit weight profiles shown in Fig. 11 (and whose parameters are given in Table 2). The representative profile should be selected based upon the anticipated near-surface in-place unit weight, which will be dependent upon waste composition and landfill operational procedures. Similarly to Scenario 2, appropriate conservatism or a sensitivity analysis that incorporates reasonable variations of the representative MSW unit weight profile is recommended.

Model Limitations

The MSW unit weight model developed herein is an empirical model based upon field and laboratory test data. These data included both relatively dry waste (e.g., the Tri-Cities waste) and relatively wet waste (e.g., the OII, Azusa, and Cherry Island waste with a moisture content of 50%). However, in all cases the waste was "fully drained," i.e., was at or below field capacity. The data also included relatively fresh waste and relatively degraded waste. Hence, the model developed herein should be applicable to any landfill in which the waste is at or below field capacity, i.e., all conventional landfills and most leachate recirculation landfills, provided the assumption of consistent waste composition and landfill operational procedures is satisfied. Increasing waste compaction, increasing soil content, increasing moisture content, increasing unit weight of waste constituents, and decreasing waste particle size (e.g., particle size reduction due to waste preprocessing) all would move the near-surface in-place unit weight from the lower end of the range of typical values toward the upper end of the range. Appropriate conservatism or sensitivity studies are recommended to compensate for uncertainty with respect to the unit weight.

As previously stated, moisture content can be an important factor in estimating the total unit weight of MSW. This is particularly true for cases in which the moisture content is above field capacity (e.g., at bioreactor landfills or when the waste becomes submerged and fully saturated). Also of interest to engineering practice is the evolution of MSW unit weight over time at an existing landfill due to the addition of liquid. The effect of adding liquid or having very wet waste can be addressed, to some extent, through the use of phase relationships. For example, using the phase relationship of $\gamma_t = \gamma_d[1+w]$, the increase of the unit weight of MSW can be easily calculated if the increase in the moisture content is known. However, the phase relationship approach ignores the potential for compression of the waste solids due to an increase in effective stress from the increase in unit weight of the overlying material as well as the potential for rebound of the waste solids due to buoyancy effects when the waste is submerged.

Similarly, while the effect of degradation is implicitly included in the MSW unit weight model by inclusion of data from older landfills in the database used to develop the model, the evolution of unit weight within a landfill as the waste degrades may be of interest in some circumstances. However, there is no reliable field data on the influence of waste degradation on the evolution of the in-place unit weight at a MSW landfill. Rational mechanisms by which MSW unit weight increases, decreases, and does not change with degradation can all be postulated. Comparison of the unit weight profiles for the older and younger New Jersey landfills in Fig. 3 suggest that unit weight may decrease with degradation, but the lack of knowledge on waste composition and waste placement processes for these two landfills renders these data inconclusive. The impact of degradation on unit weight is

likely to depend upon the composition of the waste (e.g., percent organics), waste processing (e.g., particle size reduction, compaction), the climatic conditions and in-situ moisture content, and the degree of degradation. In the absence of conclusive field data, many engineers typically assume that waste degradation is accompanied by a corresponding volume change (settlement) and that MSW unit weight stays relatively constant over time. Further study of the effects of waste degradation is warranted.

Conclusions

Estimating MSW unit weight is often the first step in performing engineering analyses of landfill systems. The use of an appropriate MSW unit weight profile is important for performing reliable engineering analyses of landfill performance. Although there is significant scatter in the unit weight values reported in the literature, internally consistent waste composition and waste handling practices and predictable confining stress effects suggest the existence of a characteristic profile of unit weight versus depth at many landfills. Based upon analysis of available laboratory and field data, a characteristic MSW unit weight profile represented by a hyperbolic equation was found to exist for individual landfills.

Using field data and large-scale laboratory data, factors that affect the unit weight of MSW have been studied and a framework for the development of representative MSW unit weight profiles for conventional landfills was developed. The available data indicate that MSW unit weight is principally governed by waste composition and landfill operational practices (i.e., compaction effort, cover soil placement, and liquids management) during waste placement, which may be represented by a near-surface in-place unit weight term, and the effective confining stress currently acting on the waste, which may be represented by a depth term. Mechanical secondary compression (waste aging in the absence of degradation) has a marginal effect on MSW unit weight. A hyperbolic model that captures the key factors in determining the unit weight of MSW at a particular landfill has been developed and calibrated with the available field data.

Guidelines for developing a reliable MSW unit weight profile for a specific landfill under three likely scenarios have been provided. These guidelines include recommended procedures for performing in situ large-scale unit weight tests and for developing estimates of the unit weight versus depth profile. To establish the unit weight profile of MSW for a specific landfill with confidence, in situ unit weight data are required. Reliable in situ large-scale unit weight testing can be accomplished by performing shallow test pits to measure the near-surface in-place unit weight of the MSW, and large-diameter borings to measure MSW unit weight at greater depths. At a minimum, shallow test pits and the use of Fig. 12 are recommended to develop reliable estimates of the MSW unit weight at existing landfills. For analysis of new landfills, use of typical unit weight profiles (Fig. 11) combined with sensitivity studies is recommended.

The effect of waste degradation on unit weight is largely unknown but is implicitly accounted for in the proposed methodology by the field measurements of unit weight in older landfills that includes degradation effects. The impacts of leachate recirculation, waste submergence, and bioreactor landfill operation on MSW unit weight are also largely unknown.

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