FRAMEWORK FOR THE ESTIMATION OF MSW UNIT WEIGHT PROFILE

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SUMMARY: Knowledge of the unit weight of Municipal Solid-Waste (MSW) is required for many engineering analyses. However, unit weight continues to be a significant source of uncertainty in these analyses due to a variety of factors, including the heterogeneous nature of solid waste, a paucity of data, and the lack of systematic analysis of the available data. Analysis of available in-situ and laboratory data on the unit weight of MSW, described herein, indicates both the existence of a "characteristic unit weight profile" for MSW and the need for site-specific unit weight data to develop an accurate unit weight profile for a particular landfill. A hyperbolic model is shown to capture the influence of compaction effort and overburden stress on MSW unit weight. Calibrated against laboratory and field data, the hyperbolic model provides a rational basis for developing landfill-specific MSW unit weight profiles for design.

1. 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, and landfill capacity evaluation. However, estimating the unit weight of MSW continues to be a significant source of uncertainty in landfill engineering. Significant scatter exists in the reported values in the literature of the total unit weight of MSW. Hence, it is difficult for an engineer to estimate with confidence the MSW unit weight profile for use in engineering analyses.

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2. LITERATURE REVIEW

Reported unit weight values for MSW from more than 37 landfills were collected for evaluation and analysis. Details of this study are presented in Zekkos (2005). The methods used to estimate the unit weight of MSW in these studies can be divided into three categories:

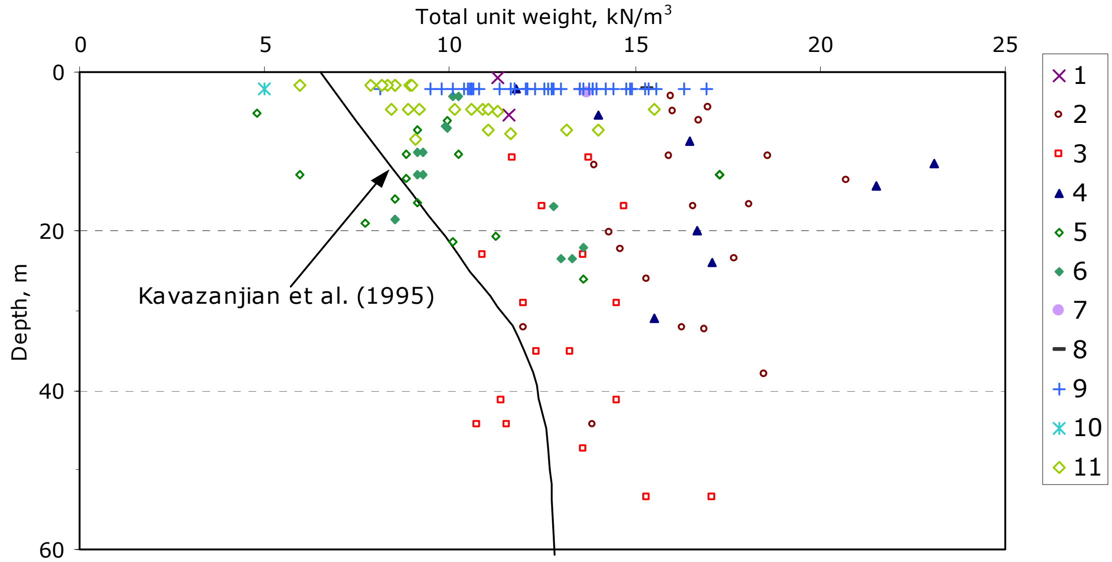
1. Surveys and landfill records: Landfill records allow the total weight of the materials (including both waste and soil) placed in the landfill to be estimated and topographic surveys (both land-based and aerial) allow the volume of the in-place materials to be estimated. When these two pieces of data are combined, the in-place total unit weight of MSW can be estimated. This method allows the estimation of an average unit weight only and fails to consider either the compressibility of the underlying waste or the degradation of waste. Although this method may provide a reasonable estimate of the initial MSW unit weight after placement in the landfill, it does not provide a reliable means of assessing the increase in unit weight with increasing overburden pressure.
2. Unit weight of retrieved "intact" samples: Unit weight can be measured on "intact" samples if intact samples can be retrieved. However, even if intact samples can be retrieved, this method is not recommended, as the large particles characteristic of MSW and disturbance during sampling do not allow for reliable unit weight measurements.
3. In-situ large-scale methods: In-situ large scale methods generally mimic the ASTM standard sand-cone density test, but are performed at a much larger scale. Large-scale test pits near the surface and/or large-diameter boreholes at depth are excavated and the excavated waste material is weighed. The 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. 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 considered by the writers to be the most reliable approach to evaluating the in-place unit weight of MSW because it typically involves large volumes of material and, as an in-situ method, it accounts for changes that have occurred in the material since its placement in the landfill. Guidelines on the performance of this method are provided by Zekkos (2005).

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 1995). This 1995 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 higher. This profile was developed in part based upon Method 1 (surveys reported by landfill operators) and applies to relatively dry landfills, i.e. landfills conforming to US 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"*. In subsequent work, this 1995 profile was adjusted upwards to account for the daily and interim cover soil typically placed in the landfill with the waste.

3. IN-SITU DENSITY DATA

Figure 1 illustrates in-situ large-scale unit weight measurements of MSW from 11 different studies. The Kavazanjian et al. (1995) recommended curve is at the lower end of the range of data. There is considerable scatter in the reported unit weights with values ranging from 5 kN/m^3



(1) Santo Tirso, Portugal (Gomes et al. 2002); (2) OII, California, USA (Matasovic and Kavazanjian, 1998); (3) Azusa, California, USA (Kavazanjian et al, 1996); (4) Tri-Cities, California, USA (this study); (5) no name older landfill (Oweis and Khera, 1998); (6) no name younger landfill (Oweis and Khera, 1998); (7) Hong Kong, China (Cowland et al. 1993); (8) Central Mayne landfill, USA (Richardson and Reynolds, 1991); (9) 11 Canadian landfills (Landva & Clark, 1986); (10) Valdemingomez, Spain (Pereira et al. 2002); (11) Cherry Island landfill, Delaware, USA (Geosyntec, 2003);

Figure 1. Unit weight values from in-situ large-scale tests.

to more than 18 kN/m^3. Although Figure 1 shows no obvious trend, when the measured unit weight values for each landfill are examined separately, a consistent trend of unit weight increasing with increasing 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, because controlled landfills generally accept waste of similar composition, organic content, and moisture content over their lifespan, and they also have standard operation procedures (e.g. same type of daily cover, standard volume of daily cover, and similar compaction methods). Therefore, a specific landfill may be reasonably expected to have an internally consistent unit weight profile in which the unit weight increases consistently with depth in response to the increase in overburden stress.

Figure 2 shows in-place unit weight profiles developed at 6 USA landfills using in-situ large scale methods. Tests performed by the writers at the Tri-Cities landfill in the San Francisco Bay Area, California using a 760 mm diameter bucket auger yielded unit weight values of about 10 kN/m^3 near the surface reaching about 16 kN/m^3 at a depth of 30 m. The two data points from this landfill with unit weight values in excess of 20 kN/m^3 at depths between 10 m and 20 m represent tests performed in construction debris and for that reason are not considered representative of the MSW unit weight. Tests performed at the OII landfill (Matasovic and Kavazanjian, 1999) near Los Angeles, California, suggest a roughly constant unit weight profile of about 15 kN/m^3. The relatively high initial value and small increase with depth of MSW unit weight at the OII landfill can be explained by the larger than typical amount of cover soil that was placed during the operation of the landfill. In the Azusa landfill, also near Los Angeles, California, the unit weight is about 12 kN/m^3 at a depth of about 10 m, reaching a value of about 15 kN/m^3 at a depth of about 50 m (Kavazanjian et al. 1996). Data from the Cherry Island Landfill in Delaware (GeoSyntec, 2003) suggest a unit weight value of about 8 kN/m^3 near the surface reaching values of about 12 kN/m^3 at a depth of 10 m. Data from Oweiss and Khera

(1998) for two unidentified landfills in New Jersey, denoted as the "older" and "younger" landfills, suggest MSW unit weights near the surface of about 7 kN/m^3 and 10 kN/m^3 respectively, with a more pronounced increase in the unit weight with depth than at OII or Azusa. The systematic trends in the data in Figure 2 suggest that a unit weight model for engineering analyses can be developed. However, the considerable scatter in unit weight values shown in Figure 1 indicate that landfill-specific MSW unit weight data remain important and that in-situ tests may be required to evaluate reliably the MSW unit weight at a specific landfill.

Figure 5 presents results from large (diameter 300 mm, height of 600-630 mm) isotropically consolidated triaxial tests performed on reconstituted MSW specimens from the Tri-Cities landfill performed at the University of California at Berkeley. Results from two different sample groups are shown: Group A3, which was retrieved from a depth of 25.6 to 26.2 m and was 16 years old and Group C6, which was 3 years old and was retrieved from a different borehole at a depth of 7.6 to 9.6 m. All specimens were prepared by compaction in layers using a 9.5 kg weight dropped repeatedly from different heights until the specimen reached the target density.

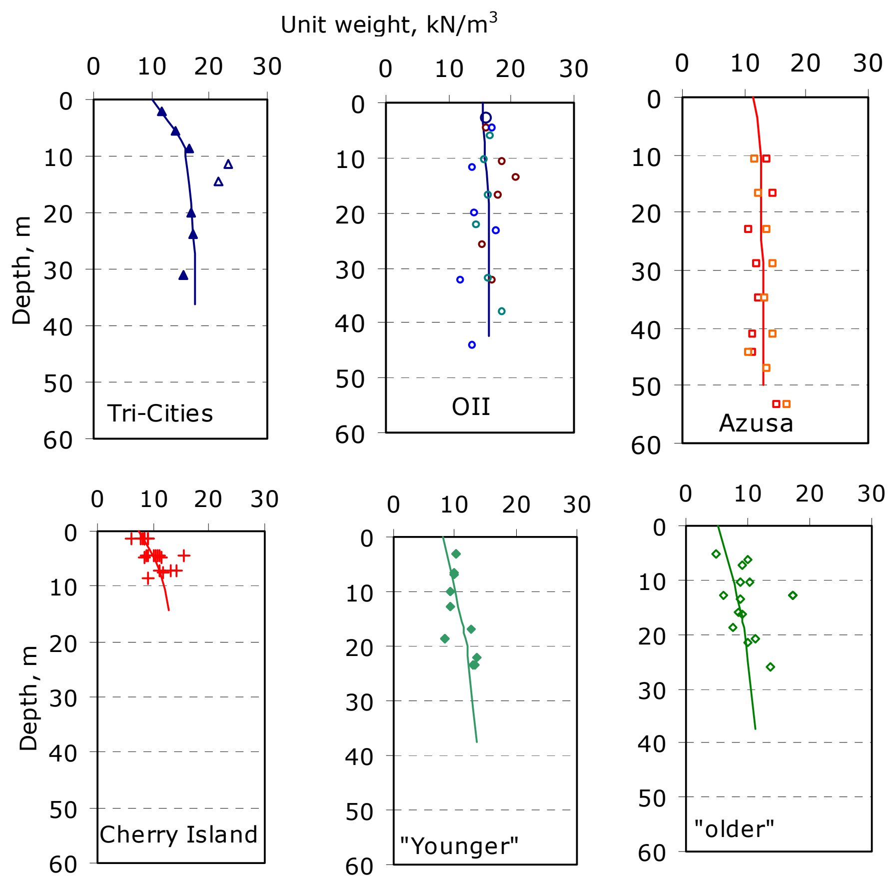


Figure 2. MSW unit weight profiles from in-situ tests for individual landfills.

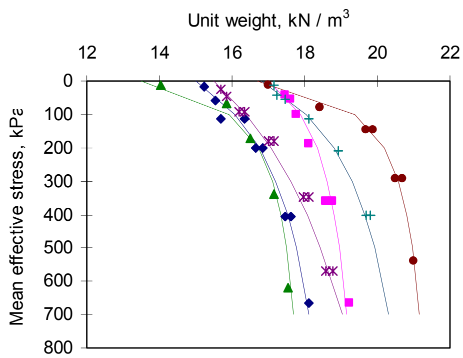


Figure 3. Large-scale 1-D compression tests (Kavazanjian, 1999)

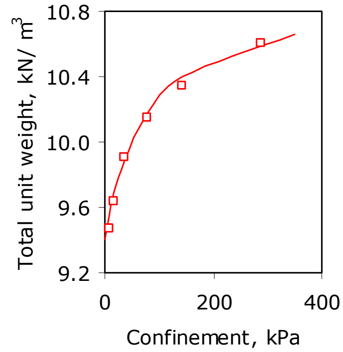


Figure 4. Unit weight data from 152 mm Resonant Column specimens

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 significant compaction energy input. The relationship between unit weight and confining stress is almost linear with a small increase in the unit weight with increasing confinement. Specimen A3-3L included the same material but was prepared with minimal compaction effort. The unit weight at low confining stress is significantly lower than that of specimen A3-2L, but it increases significantly with increasing confining stress. Specimen A3-6L included particles up to 80 mm in dimension (76% less than 20 mm material, 13% paper, 4% plastics, 7% wood) and was prepared with the same energy input as specimen A3-2L. Whereas the energy input was the same, the resulting unit weight is significantly lower than the unit weight of specimen A3-2L that included only the less than 20 mm material. The lower unit weight of this specimen is attributed to both the lower unit weight of the larger particles and the increase in the void ratio of the specimen. Specimen A3-7L included more large particles (62% less than 20 mm material, 14% paper, 3% plastics, 11% wood, 10% gravel) than specimen A3-6L, but it also included gravel in the larger fraction and was compacted with higher energy input than A3-6L. The resulting unit weight for A3-7L is higher than A3-6L. An almost linear increase of the unit weight with confining stress is observed for A3-7L. Specimen A3-8L included the same material as specimen A3-7L but was compacted with less energy. Again, similar to the specimens that included the less than 20 mm fraction only, the resulting unit weight is lower for A3-7L than for A3-8L but the effect of confining stress is more pronounced.

Similar trends as those discussed above for the A3 samples from the Tri-Cities Landfill were observed for the C6 samples. Complete details of the testing on the C6 samples are presented in Zekkos (2005). Only two specimens of the C6 group are shown in Figure 5. Specimen C6-4L included 62% less than 20 mm material, 18% paper, 5% plastics, 5% wood, 12% gravel and was prepared with similar energy input as specimen A3-7L. The resulting unit weights are similar. Specimen C6-3L was prepared with less energy than specimen C6-4L. The unit weights at low isotropic confining stress (10 kPa) are 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.

Analysis of these data from laboratory tests indicate that the relationship between MSW unit weight and confining stress can be described by a hyperbolic equation. Figure 6 also illustrates that a hyperbolic function can capture the relationship between the unit weight and compaction energy. Aburatani et al (1998) presented a similar plot from field and laboratory data on MSW.

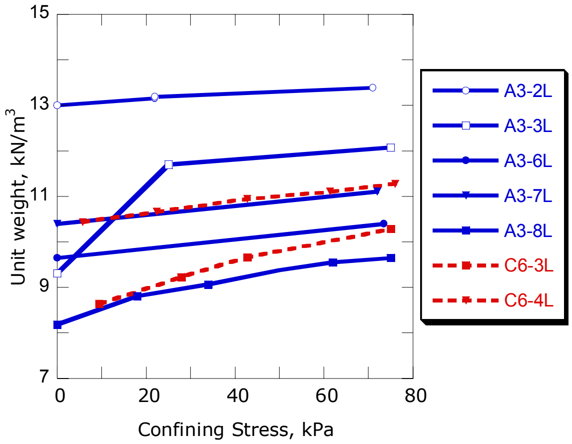


Figure 5. Unit weight vs. confining stress

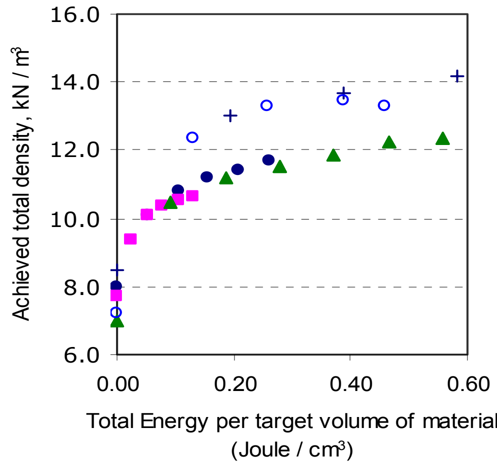


Figure 6. Unit weight vs. energy input during specimen preparation

The effect of time under confinement on the unit weight of MSW undergoing mechanical compression can also be investigated through laboratory tests. Figure 7 shows normalized unit weights plotted as a function of time under isotropic confinement from a total of 16 large diameter triaxial MSW specimens of sample groups A3 and C6 for the Tri-Cities Landfill. The density of the specimens was evaluated by measurements of the axial deformation using LVDTs and radial deformation using a pi-tape. The confining stress in these tests ranged between 25 kPa and 90 kPa. While density and the composition of the MSW do have some influence on the effect of time under confinement on the unit weight (discussed in detail by Zekkos, 2005), 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. Based on these data, the recommended relationship between the unit weight and the time under confinement (in days) is given by the equation:

$$\frac{\gamma_t(t)}{\gamma_t(t=1\ \ day)} = 0.0173 \cdot \log(t) + 1.006 \qquad (1)$$

Data shown in Figure 8 from tests performed using waste from the Tri-Cities Landfill at the University of Texas at Austin suggest that the time under confinement effects in the MSW unit weight are similar at higher levels of confining stress.

Equation 1 indicates that there is less than a 10% increase in unit weight due to time under confinement effects over 50 years due to mechanical compression. However, the equation does not consider the effect of degradation. The effect of degradation is difficult to study in the laboratory, but it is postulated that, on the average, degradation will not significantly affect unit weight. As the material degrades, the unit weight may reduce locally but degradation may also make the waste locally collapse into a denser state. Therefore, whereas degradation could result in locally higher or lower unit weights, the net global effect of degradation on unit weight is postulated to be negligible. The local effects, along with the inherent variability of MSW, may explain some of the scatter observed in the data of Figures 1 and 2.

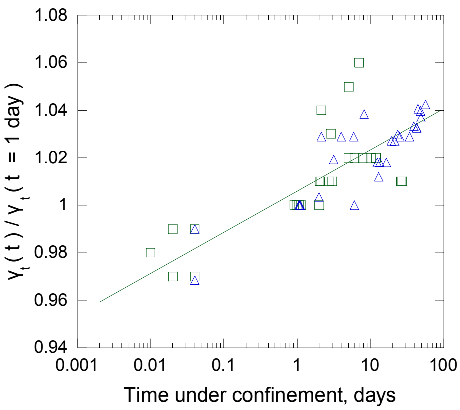


Figure 7. Effect of time under confinement on the total unit weight.

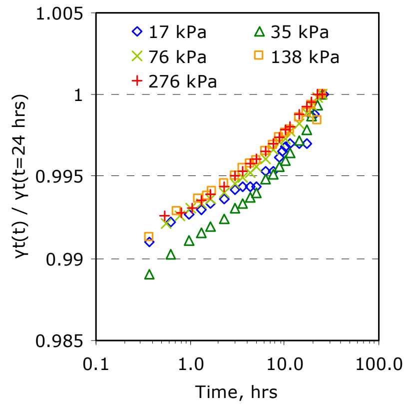


Figure 8. Time under confinement effects on the total unit weight

4. RECOMMENDED UNIT WEIGHT MODEL FOR MUNICIPAL SOLID-WASTE

Analysis of the data presented above indicates that MSW unit weight can be described by a hyperbolic function of the energy transmitted to the MSW material, both in the field and in the lab, i.e. there is a hyperbolic relationship between the unit weight of MSW of a given composition and the energy applied to get it to its current state. This energy could be produced through compaction, confining stress, or both. The shape of the hyperbola depends to a large extent on the initial MSW unit weight (i.e. due to compaction energy and its composition, e.g. the amount of soil). Figure 9 is an illustration of this conceptual model. For low degrees of input compaction energy (e.g. light compaction and low confining stress) the material would be at point L. At this state, there is still significant compaction that can take place as confining stress increases, i.e. as additional waste is placed. For high degrees of input compaction energy, (i.e. high initial compaction; point H), some additional compression is still possible, but that increase is not as significant and a more linear increase in unit weight with confining stress (i.e. depth) occurs. In fact, the increase can be so small, that is not recognizable in the field (e.g. OII landfill in Figure 2). Similar trends can be observed for other geomaterials (sands, clays etc.) but what differentiates the MSW is the greater range of possible initial unit weight values.

Figure 10 illustrates the conceptual model of a family of hyperbolic representative MSW unit weight profiles. For a particular landfill, as compaction effort and the amount of soil cover placed increases, the MSW unit weight increases near the surface and the increase with confining stress at greater depths becomes less pronounced (from the continuous curve on the left toward the dashed curve to the right). The following equation may be used to describe the hyperbolic model for MSW unit weight (γ):

$$\gamma = \gamma_i + \frac{z}{a + b \cdot z} \qquad (2)$$

where γ_i is the as-placed unit weight near the surface (i.e. the initial unit weight), which can be measured with the use of shallow test pits, and z is the depth at which the MSW unit weight is estimated. In this equation, depth represents the influence of vertical or mean effective stress. Equation (2) is provided in terms of depth for simplicity, because if the more fundamental factor of confining stress is used, an estimate of unit weight is required to estimate confining stress.

The parameter "b" is a function of the difference in unit weight between the surface and at great depth (or confining stress). The inverse of the b-parameter is the asymptotic value of the difference in the unit weight at great depths and that at the surface. The parameter b typically ranges between 0 and 1 m^3/kN. Higher b-values are possible, but do not affect the shape of the hyperbola significantly more than if a value of 1 m^3/kN is used. If the unit weight at large depth is close to that near the surface, b is about 1 m^3/kN. If the unit weight at depth is much higher than near the surface, b goes to 0. If b = 0, then the change in unit weight with increasing depth is linearly proportional to the change in depth (or confining stress).

The parameter "a" is a function of the unit weight increase near the surface. The ratio of 1/a is the initial slope of unit weight increase vs. depth near the surface. The a-parameter takes values typically within a range between 0 and 10 m^4/kN. If the unit weight increases significantly at shallow depths, small values of the a-parameter should be used. If the unit weight does not increase significantly near the surface, larger values should be used. The physical meanings of the "a" and "b" parameters are shown in Figure 11. Figure 12 illustrates how the "a" and "b" parameters affect the shape of the unit weight profile.

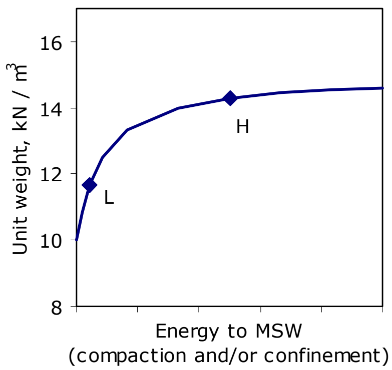


Figure 9. Conceptual model of MSW unit weight and energy input.

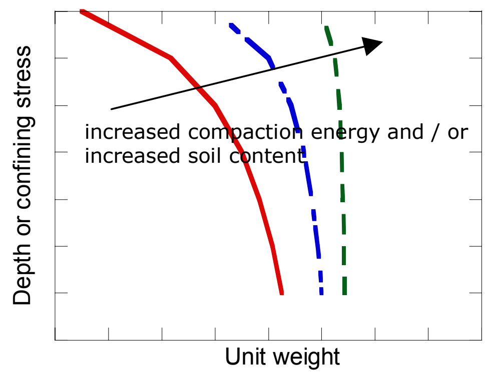


Figure 10. Conceptual effect of depth (or confining stress) on MSW unit weight.

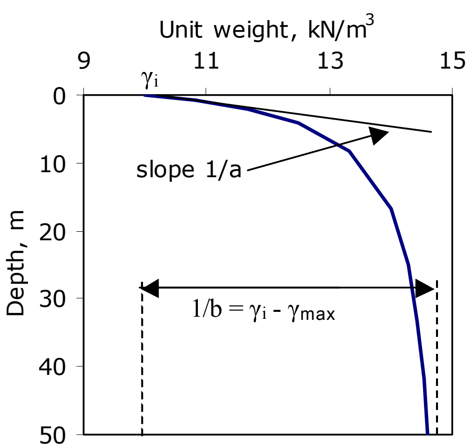


Figure 11. Physical meaning of the "a" and "b" hyperbolic parameters

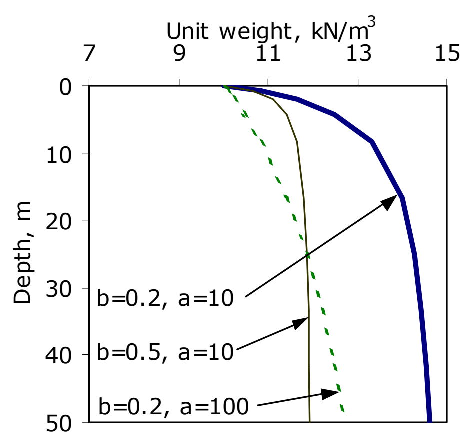


Figure 12. Effect of the hyperbolic parameters on the unit weight profile

5. MODEL CALIBRATION

The conceptual model described by Equation 2 was fit to the field data presented in Figure 2. The fitted hyperbolas are shown in Figure 2 as solid lines for each landfill. The six MSW unit weight profiles shown in Figure 2 are plotted together for comparison in Figure 13 along with "representative" MSW unit weight profiles for low, typical and high compaction effort and/or soil content. In the fitting process, the near-surface unit weight is assigned based upon the field data and then the hyperbolic parameters "b" and "a" are estimated. The hyperbolic parameters γ_i, "b," and "a" that describe the three representative MSW unit weight profiles are given in Table 1. Either the hyperbolic relationship with the parameters of Table 1 or the recommended curves of Figure 13 can be used to develop preliminary estimates of the MSW unit weight profile of a landfill. If landfill specific data is available, the hyperbolic relationship in Equation 2 can be used directly to estimate the MSW unit weight profile with greater reliability.

Table 1. Hyperbolic parameters for different compaction effort and amount of soil cover.

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

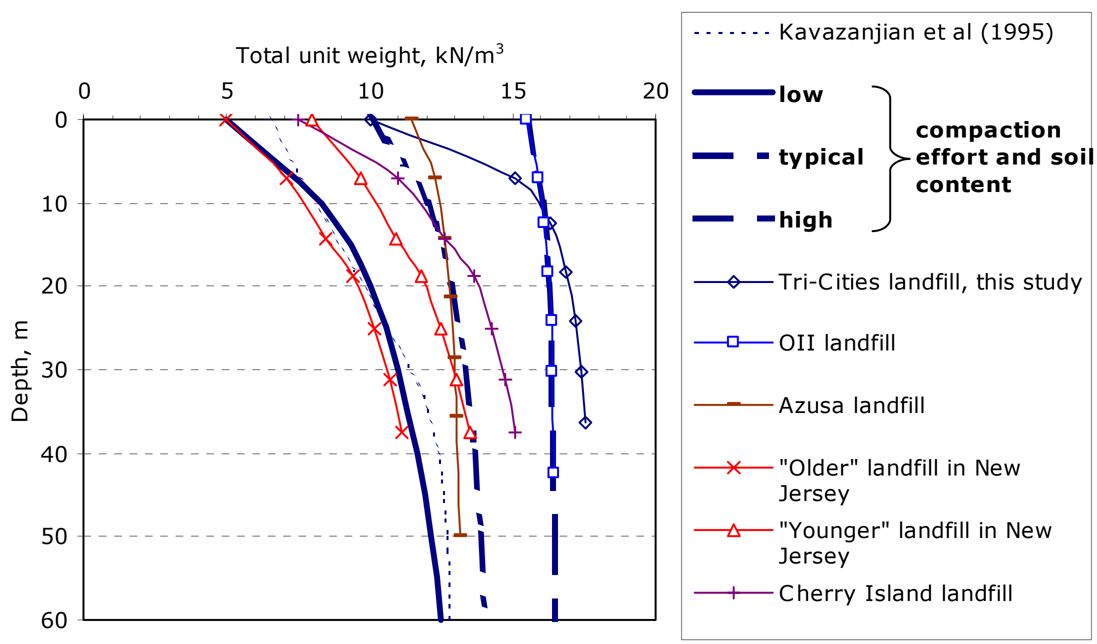


Figure 13. Unit weight profiles for six different landfills and recommended profiles

6. CONCLUSIONS

MSW unit weight data are required for performing a variety of engineering analyses. Based upon analysis of field and laboratory data, a hyperbolic relationship was found to capture the variation of MSW unit weight with the variations of compaction effort, soil content, and confining stress (depth). The hyperbolic model was fit to available in-situ landfill unit weight data to a depth of approximately 60 m below ground surface. Consistent trends were identified in the relation of unit weight with compaction and confinement and recommended MSW unit weight profiles were developed for use in preliminary engineering analyses. A methodology for developing landfill-specific MSW unit weight profiles was developed to provide greater accuracy when required.

To facilitate additional analysis of this important parameter, a database of MSW unit weight values has been created and is available online at the Geoengineer website (http://www.geoengineer.org). Researchers or practitioners that perform in-situ tests on MSW are encouraged to inform us about their data and submit them for inclusion in this database. Currently available data as well as future data will be available through this website.

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