ESTIMATING METHOD AND USE OF LANDFILL SETTLEMENT

by Michael L. Leonard, Sr., P.E., Member ASCE[1]
Kenneth J. Floom, Jr., P.E., Member ASCE[2]
Scott Brown, P.E.[3]

ABSTRACT

The majority of municipal solid waste (MSW) disposal procedures in the U.S. involve end-dumping of loose material followed by spreading by a dozer and compaction by the dozer or a landfill compactor. The compacted waste is then covered with soil, tarps, greenwaste or other alternative daily cover (ADC) materials. These cover materials, other than tarps and foam, consume a portion of the available airspace. The MSW is subjected to additional loads of future overlying layers. These loads cause additional compression of the waste. Also, cover soil is often temporarily stockpiled over waste, which compresses the waste. A significant factor contributing to airspace over time is settlement from decomposition of the waste.

Waste placement, initial compaction, stockpiling soils above waste, and use of ADCs are evaluated relative to short- and long-term airspace utilization. A proven method developed by the authors and used at three major southern California landfills for predicting settlement, including the contribution of aerobic/anaerobic refuse decomposition, is summarized. The decomposition predictions are based on waste composition and landfill gas (LFG) generation rates.

Finally, a clear and easy-to-use method for tracking airspace is discussed, with several recommendations presented for practical application by landfill owners/operators.

INTRODUCTION

Under stringent new Federal and State regulations, it is becoming more and more difficult to site, permit and construct a new MSW landfill. Many of the existing landfills are running out of disposal capacity and are also finding it time-consuming and costly to get permission from the regulatory agencies to expand vertically or laterally. The large regional landfills which appear to be encouraged by Subtitle D

[1] Project Director, TRC, 21 Technology Drive, Irvine, California 92618
[2] Project Manager, TRC, 21 Technology Drive, Irvine, California 92618
[3] Vice President, Solid Waste Services, TRC, 7761 Shaffer Parkway, Littleton, Colorado 80127

promulgation in 1994 are very slow in development. Again, this is due to the stringent siting restrictions, extensive environmental studies that are required, land use conflicts in areas with rapid expansion, and the difficulty for owners/developers to justify the economics in a very competitive market.

Airspace at existing landfills is therefore becoming an even more valuable asset. To maximize the return on their investment, owners/operators need to take advantage of all reasonable methods of enhancing and controlling this asset. The authors have worked as landfill site managers and site engineers for many years and have developed an understanding of the importance of implementing construction, monitoring and predictive techniques which optimize the use of airspace. Some of these techniques and their applications are discussed in this paper, which is offered primarily to encourage those involved with site management, operations and planning to develop and implement a well-thought-out approach specific to their respective facilities.

WASTE PLACEMENT, COMPACTION AND COVER

The majority of MSW disposal procedures in the U.S. and many other countries involve end-dumping of loose material (typically in the range of 0.36 to 0.54 metric tons/m^3 [600 to 900 pounds per cubic yard]) (see Table 1), followed by spreading by a dozer and compaction by the dozer and/or a landfill compactor.

TABLE 1
LANDFILL DENSITIES

SITE	LOCATION	REF.(1)	WASTE: COVER SOIL RATIO	INITIAL DENSITY metric tons/m^3 (lb/yd^3)(2)			LONG-TERM DENSITY metric tons/m^3 (lb/yd^3)(3)		
				Measured/ Reported Refuse	Total(4)(5) Refuse and Cover	Landfilling(5)(6)	Measured/ Reported Refuse	Total(4)(5) Refuse and Cover	Landfilling(5)(6)
Range	N/A	Various	1.8:1 - 6:1	0.22-0.97 (360-1620)	0.63-1.22 (1042-2025)	0.16-0.73 (270-1215)	0.29-1.68 (477-2805)	0.70-1.75 (1168-2914)	0.21-1.26 (358-2104)
Tajiguas Landfill	Santa Barbara County, CA	[22]	2.5:1	0.83 (1380)	1.15 (1912)	0.59 (986)	1.10 (1830)	1.38 (2300)	0.82 (1373)
El Sobrante Landfill	Riverside County, CA	[23]	--	--	--	--	1.04 (1740)	1.28 (2125)	0.78 (1294)
Olinda Alpha Landfill	Orange County, CA	[16]	--	--	--	--	0.80 (1333)	0.99 (1651)	0.67 (1111)
FRB Landfill	Orange County, CA	[12]	--	--	--	--	0.88 (1467)	1.15 (1910)	0.66 (1100)
Prima Deschecha Landfill	Orange County, CA	[12]	--	--	--	--	0.88 (1467)	1.15 (1910)	0.66 (1100)
Toland Road Landfill	Ventura County, CA	[4]	--	--	--	--	0.77-1.19 (1287-1980)	1.06-1.38 (1775-2295)	0.58-0.89 (965-1485)
		[24]	--	--	--	--	0.90 (1500)	1.44 (2392)	0.44 (731)
Experimental Fill	LA County, CA	[13]	3:1	0.36 (607)	0.76 (1265)	0.27 (455)	--	--	--
5 LA County Landfills	LA County, CA	[13]	--	--	--	--	0.80 (1338)	1.21 (2023)	0.51 (856)
Landfills Across Canada	Canada	[14]	--	--	--	--	0.29-1.29 (477-2149)	0.70-1.45 (1168-2422)	0.21-0.97 (358-1612)
General	General	[3]	--	--	--	--	0.52-1.13 (859-1891)	0.87-1.34 (1454-2228)	0.39-0.85 (644-1418)
OII Landfill	Monterey Park, CA	[18]	--	--	--	--	0.65-1.68 (1077-2805)	0.97-1.75 (1618-2914)	0.48-1.26 (808-2104)
3 LA County Landfills	LA County, CA	[27]	3:1	0.22 (360)	0.65 (1080)	0.16 (270)	--	--	--
2 Landfills	Southern England	[25]	3:1	0.22-0.45 (363-752)	0.65-0.81 (1082-1374)	0.16-0.34 (272-564)	--	--	--
General	General	[20]	3:1	0.43-0.97 (720-1620)	0.81-1.22 (1350-2025)	0.32-0.73 (540-1215)	--	--	--
Spadra Landfill #2	LA County, CA	[15]	3:1	0.31-0.70 (515-1168)	0.72-1.01 (1196-1686)	0.23-0.52 (386-876)	--	--	--
So. California Landfill	LA County, CA	[5]	--	--	--	--	1.11, 1.14 (1829, 1901)	1.31, 1.34 (2182, 2236)	0.82, 0.86 (1372, 1426)
Wisconsin Landfill	Madison, Wisconsin	[6]	3:1	0.66 (1107)	0.98 (1640)	0.50 (830)	--	--	--
California Landfill	General	[10]	3:1	0.39 (648)	0.78 (1296)	0.29 (486)	--	--	--
				0.37 (612)	0.76 (1269)	0.28 (459)			
				0.30 (504)	0.71 (1188)	0.23 (378)			
				0.28 (468)	0.70 (1161)	0.21 (351)			
				0.28 (468)	0.70 (1161)	0.21 (351)			
				0.30 (504)	0.71 (1188)	0.23 (378)			
General	Central Maine	[11]	3:1	0.30 (540)	0.73 (1215)	0.24 (405)	1.42 (2376)	1.56 (2592)	1.07 (1782)
				0.30 (504)	0.71 (1188)	0.23 (378)			
				0.41 (684)	0.79 (1323)	0.31 (513)			
Maine Landfill		[11]	--	--	--	--			

Notes:
(1) See Reference List
(2) In several cases the density was determined immediately after refuse placement and compaction, i.e., initial density.
(3) As determined for the site since start-up.
(4) Assumes a soil density of 1.92 g/cm^3 (120 pcf).
(5) Landfilling density = [w/(w+1)] x Refuse density; Total density = Landfilling density + Cover Soil density x [1/(w+1)]; Total density = Refuse density x [w/(w+1)] + Cover Soil density x [1/(w+1)], where w = Waste: cover soil volume ratio expressed as fraction or decimal.
(6) Defined as weight of refuse divided by total air space consumed by refuse, cover soil and other operations soil.

The compaction achieved varies but typically results in a refuse density in the range of 0.54 to 0.72 metric tons m^3 (900 to 1,210 lb/yd^3) (see Table 1). The compacted waste is then covered with soil (typically about 30 cm [or 1 foot]), tarps, foam, greenwaste or other alternative daily cover ADC materials. These cover soils or other materials, other than tarps which are removed daily and foam which decomposes, consume a portion of the available airspace. Cover soils are nominally compacted as they are placed but may vary significantly in type and density at a given site. Also, in some cases, an interim cover (thicker than daily cover) is applied to portions of a landfill which are going to remain inactive for extended time periods. Additional airspace may be consumed by stability or starter berms, temporary access ramps, bench thickening or drainage controls, LFG collection pipes and gravel-filled trenches, or other constructed elements which are within the air space prism.

At many MSW landfills, the weight of refuse in each incoming truck is determined by scales as the basis for payment. Also, at some landfills, the amount of soil taken from stockpiles and placed within the airspace prism is measured and recorded by scraper load count or survey. It is important to the site manager and engineer responsible for remaining airspace projections to know what data is collected and how accurate the data is.

WASTE SETTLEMENT OVER TIME

The MSW in a given layer is subjected to the additional loads of future overlying layers. These overburden loads and the self-weight of the refuse cause additional compression of the waste. Also, cover soil is often temporarily stockpiled over areas of previously-placed waste, which again adds to the compression of the waste. An additional significant factor, probably the most significant factor for MSW, contributing to landfill density increases and settlement over time is the decomposition of the organic portions of the waste material. MSW typically contains about 22 to 26 percent by weight of decomposable materials including putrescible waste, paper products, and green waste (SWANA, 1991). As these materials decompose, void spaces are created in the waste matrix which then compress under the weight of overlying layers to attempt to fill the void spaces. This compression results in the density increase and is reflected by settlement at the landfill surface. This settlement results in direct addition to the airspace available for placement of waste and can be very significant for deep waste fills. Therefore, it should be estimated and accounted for in initial site life projections, permits and analyses of remaining site capacity and life.

ESTIMATING SETTLEMENT, SITE CAPACITY AND SITE LIFE

Many models have been developed for estimating the airspace capacity of landfill sites and for predicting settlement (Edil et al, 1990; Fassett et al, 1995; Huitric, 1981; Landva and Clark, 1990; Ling et al., 1998; Ranguette, 1989; Sowers, 1973; Yen, 1995). Airspace volumes available between any two surfaces (e.g., the bottom of an excavation or top of liner and the top of waste fill) can be estimated by using civil engineering software programs to calculate the volume between the mapped surfaces or by-hand calculations using the method of slices or the average end area technique. The airspace consumed and remaining at anytime can be computed by using surface survey or aerial surveys to create the current surface contours for comparison to final waste permit contours. These computations account for the waste settlement which has occurred up to the current survey. However, for making projections of remaining site life or remaining time before operations need to move to a new lined area, it is important to estimate and account for the settlement yet to occur. A method developed by the authors for the OII landfill (a closed Superfund site in Monterey Park, California) is described below and can very quickly provide an estimate of this future settlement.

General Settlement Discussion

Settlement of landfills occurs in both the short- and long-term. Table 2 identifies mechanisms of settlement that occur at landfills.

TABLE 2

SETTLEMENT MECHANISMS

I. MECHANISMS THAT CAUSE LARGE SETTLEMENTS
• **Mechanical/Primary Compression.** Mechanical/primary compression is due to distortion, bending, crushing and reorientation of materials caused by the weight of overburden and compaction. Dodt, 1987; Sowers, 1973; Ranguette et al., 1989; Watts and Charles, 1990; and Edil, et al., 1990 indicate that this settlement occurs rapidly and is typically complete within approximately one month from the time the filling is complete. At the OII Landfill, mechanical and primary compression due to fills was estimated to range from 10 to 20 percent of new fill thicknesses based on empirical data collected during a soil fill placement. The actual primary compression depends on fill geometry, density of landfill and overburden, and landfill composition.
• **Biodegradation.** Aerobic and anaerobic decomposition of organic material by bacteria is the process known as biodegradation. For anaerobic decomposition of cellulose, which is the primary mechanism of biodegradation, bacteria converts carbon-based solid material and water into primarily carbon dioxide and methane. This conversion results in a loss of solid mass. Ranguette, et al., 1989; Watts and Charles, 1990; and Huitric, 1981 indicate that most settlement after landfill construction is due to this mechanism.
• **Physical Creep Compression (Including Raveling/Void Filling).** This mechanism is caused by: (1) erosion and sifting of finer materials into voids between larger particles (Sowers, 1973); (2) material moving into voids as a result of biodegradation; and (3) continued elastic compression. Void filling is partly related to a weakening of the support of the solids due to such things as biodegradation and corrosion, which causes a reduction of the rigidity of landfill materials (Huitric, 1981). Watts and Charles (1990) indicate that this form of settlement equals about 2 percent of the fill height per log cycle of time. For the OII landfill, physical creep compression was estimated to contribute from 0 to 7 feet of additional settlement over the next 90 years.
II. MECHANISMS THAT CAUSE SMALL SETTLEMENTS
• **Physical-Chemical/Corrosion.** This settlement mechanism includes the corrosion of steel and combustion of organics. The amount of settlement due to this mechanism is difficult to predict (Sowers, 1973), and, except for combustion, which is not likely with a properly maintained and operated LFG collection system and cover in place, would be small and more localized compared to other postconstruction settlement mechanisms.
• **Interaction.** Examples of interaction include methane supporting combustion, spontaneous combustion and organic acids causing corrosion (Sowers, 1973). This mechanism is closely associated with the occurrence of the other mechanisms. By itself, interaction is not expected to represent a significant amount of settlement over a large areal extent. It could result in large localized settlements; although with a properly maintained and operated LFG collection system and cover in place, the source of oxygen (e.g., air being pulled into the landfill) to support combustion will be significantly reduced.
• **Consolidation.** Consolidation settlement is caused by excess water squeezing from pore spaces in low permeable soil formations. Huitric, 1981 recognized that typical Los Angeles area landfills are not saturated and thus, settlement due to consolidation is not expected.

A summary of the long-term settlement mechanisms that are likely at a landfill and their relative contribution to total settlement (assuming a well-maintained cover is in place) are as follows:

LONG-TERM SETTLEMENT MECHANISM	RELATIVE CONTRIBUTION TO LONG-TERM SETTLEMENT
Biodegradation	High
Physical Creep Compression	Moderate
Physical-Chemical/Corrosion	Low
Interaction	Generally Low; Potentially High in Localized Areas
Consolidation	None to Low

Discussion Of Long-Term Settlement

Two long-term settlement mechanisms (biodegradation and physical creep compression) are of primary importance at landfills as illustrated above. Settlement due to biodegradation is the result of biological activity which transforms cellulose and water in the MSW into primarily methane and carbon dioxide, which then migrates from the landfill. This solid mass transformation to gas results in vertical downward movements (settlement).

Some long-term physical settlement may also occur at a landfill as a secondary effect of biodegradation. This settlement mechanism is associated with an elastic deformation of the structure of inert material remaining as biodegradation occurs. This component of settlement is termed physical creep compression. Its value is estimated as 2 percent of the fill thickness per log cycle of time based on studies of landfill settlement performed by Watts and Charles (1990).

Settlement Model Development And Predictions

The settlement model and settlement estimates for the OII Landfill are discussed according to the following subsections:

- Biodegradation Model
- Physical Creep Compression Model
- Total Settlement Determination
- Empirical Check of the Settlement Model

Biodegradation Model

Evaluation of future settlement due to biodegradation at the OII Landfill included the following steps:

- Estimation of trash prism thickness.
- Determination of gas generation curves for landfill segments.
- Determination of a settlement factor for 30.5 x 30.5-meter (100 x 100-foot) grids in each segment.
- Calculation of the settlement of each grid based on the above factors.

The estimated thickness of the trash prism was based on the bottom topography of the trash prism and the surface topography at the time of settlement estimation. The gas generation curves were determined by applying the calibrated gas generation model Gas IA below:

$$Q_{LFG} = 0.029\ G_{LFG}\ R\ (e^{-kN} - e^{-kt})$$

where:

Q_{LFG} = LFG generation rate at time t (m^3/day [ft^3/day])

G_{LFG} = total LFG generation capacity (m^3/metric ton MSW [(ft^3/ton MSW])

R = MSW disposal rate (metric tons/day [tons/day])

k = Decomposition rate constant (yr^{-1}) = $0.693/t_{1/2}$

N = time since landfill closure (yr)

t = time since the initial MSW placement (yr)

$t_{1/2}$ = the decomposition half life (i.e., time necessary for a unit of MSW to exhaust one half of its LFG generation potential).

A typical gas generation curve for the OII Landfill is shown in Figure 1.

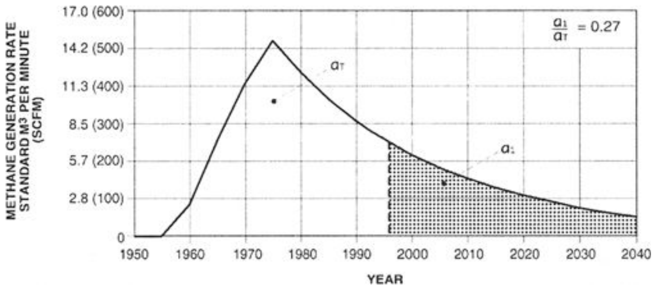

FIGURE 1
TYPICAL GAS GENERATION CURVE FOR THE OII LANDFILL

The shape of these curves is based on a combination of factors including the history of trash disposal, unit volume gas decay estimates and trash moisture conditions. Since the OII Landfill had been in place for numerous years prior to estimating settlement, the settlement model incorporated a settlement factor based on the ratio of the amount of gas generation (mass loss) yet to occur (a_1), and the total (past and future) estimated gas generation (a_t). The estimate of gas generation is calculated by integration of the area below the gas generation curve.

The estimated future settlement due to biodegradation is calculated using the following equation:

$$S_T = O \bullet T_R \bullet S_F$$

where:

S_T = Estimated future settlement due to biodegradation.

O = The decimal equivalent of the percentage of decomposable organics by weight within the prism at time of placement.

T_R = Thickness of trash.

S_F = Settlement factor = $\frac{a_1}{a_T}$

a_1 = Future gas generation (see Figure 1).

a_T = Total gas generation (see Figure 1).

Physical Creep Compression Model

Based primarily on work by Watts and Charles (1990), physical creep compression of the landfill is estimated to be about 2 percent of the fill thickness per log cycle of time.

The estimates of settlement due to physical creep compression were based on the period of time that most of the biodegradation was to have taken place (i.e., 40 to 50 years).

Total Settlement Determination

The total estimated settlement was determined by adding the biodegradation and physical creep compression settlement estimates for each of the 100 x 100 ft. grids, and smoothing and contouring the total settlement values.

Comparison of settlement due to the above two mechanisms indicated that future settlement due to biodegradation would be about 70 to 75 percent of the total estimated future settlement.

The total settlement isopach contours estimated for the OII Landfill are illustrated in Figure 2.

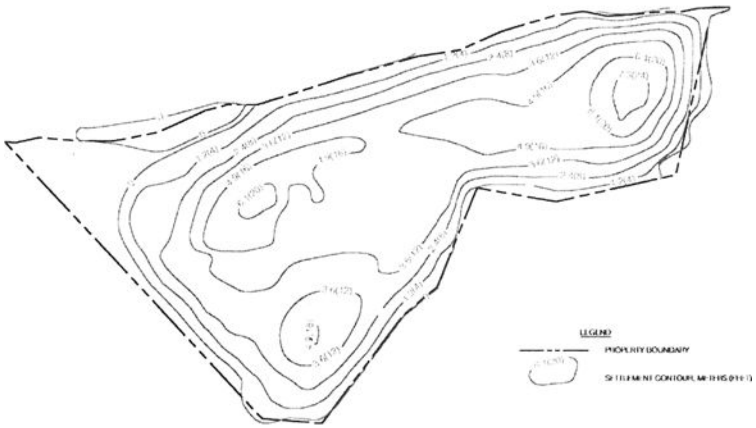

FIGURE 2
SETTLEMENT ISOPACH MAP FOR OII LANDFILL

The contours in Figure 2 were developed using the MacGRIDZO™ computer program, manually checked and smoothed to correct anomalous contour shapes along boundaries. Figure 2 forms the basis for determining remaining capacity. The data on Figure 2 can also be used for approximations of differential settlement to aid in design of final cover contours, establishing general grading requirements for drainage systems, and other structure performance.

Empirical Check Of The Settlement Model

The settlement model was checked by comparing its predicted settlement with settlement measurements obtained at 57 geotechnical instrumentation locations throughout the landfill over a 5-1/2-year period.

The biodegradation and physical creep compression models were also used to estimate settlement over the 5-1/2-year time period at the locations of the geotechnical instrumentation locations. The calculated settlement was then compared to the measured settlements to validate the model.

Figure 3 illustrates the settlement estimate of the biodegradation and physical creep compression model compared to the measured settlement.

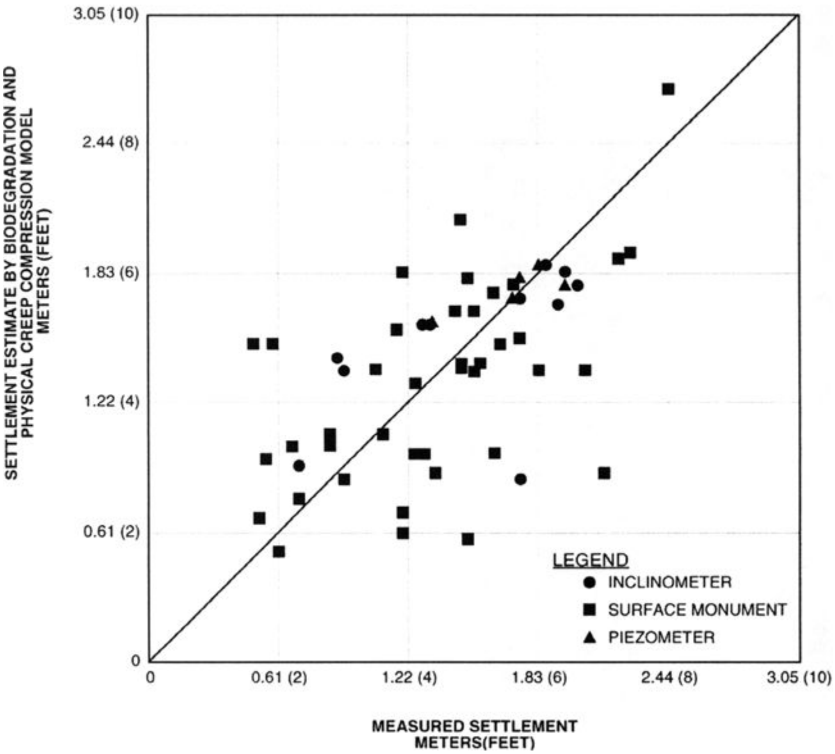

FIGURE 3
MEASURED SETTLEMENT VS. SETTLEMENT ESTIMATE BY BIODEGRADATION AND PHYSICAL CREEP COMPRESSION MODEL

On average, the model estimated settlement is slightly higher (10 percent higher) than measured settlement. This may be due to the fact that the model assumes 100 percent of the cellulose-based material will biodegrade within the time period over which biodegradation-based settlement is calculated. In reality, complete biodegradation of cellulose-based material may not have occurred within the expected time period and