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Waste Compressibility, Settlement and the Design of Landfills

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Summary The paper reviews published attempts to rationalise settlement prediction for municipal solid waste (MSW) landfills, and provides practical guidance on the most appropriate techniques. Key parameters effecting short term and long term MSW compressibility are identified and reviewed. Analysis is provided of published case histories of MSW landfill and laboratory-scale compression testing of MSW. An empirical numerical tool is described herein which provides estimates of MSW compressibility and aids the planning and design of landfills. The use of the technique is outlined to optimise utilisation of available airspace for area fill sites; to provide assurance that a preselected surface topography is realised upon site closure; and to provide a rational basis for operational monitoring of landfilling progress.

1. INTRODUCTION

Many municipal landfills are filled with little thought given to long term land-use and site physical performance. As a consequence, many former sites have been shown to exhibit excessive and uneven surface subsidence, poor vegetation growth, inadequate and poorly placed surface capping and unexpectedly high generation of landfill leachate and landfill gas.

Successful restoration and redevelopment of former municipal landfill sites is often perceived by prospective end-users of the land and the general public alike to be frustrated by:

- lack of information about the composition and extent of wastes placed;
- poor long term planning at the time of landfilling initiation, especially concerning the landform required for the intended future use of the site;
- inadequate resources for landscape design and restoration works;
- lack of coordination concerning long term needs between responsible professionals, eg landfill designers, engineer regulators, landfill operators, town planners, horticulturists and land developers.

As urged by Burness (1993), in the light of these problems it is becoming increasingly necessary to share ideas, discuss common problems and develop practical solutions and approaches. This paper attempts to contribute to the latter need by introducing an approach to estimate short and long term settlement of municipal landfills. By properly understanding the geotechnical behaviour of the wastes placed in the site, and the likely settlements

arising, an approach is outlined which enables a preselected landform to be developed. It also allows the site airspace and active life to be maximised by designing an engineered overfilling. Other benefits include a better understanding of long term settlement effects on the final cover layers (e.g. avoiding overstress and rupture) and improved design of surface drainage systems and structures on the site.

2. MECHANISMS OF SETTLEMENT

Settlements of landfills are not well understood and have proved more difficult to estimate. Geotechnical engineers generally compute time dependent settlements in landfills filled with municipal solid waste (MSW) using classical soil mechanics principles based on Terzaghi one-dimensional consolidations and secondary compression. The mechanisms governing domestic waste settlement, however, are many and complex. The extreme heterogeneity of the wastes; their own "particle" deformability; the large voids present in the initial refuse fill; and their biodegradation play an important role in this complex mechanical-chemical process.

Under its own weight, refuse settlement can be quite large with magnitudes as large as 25% to 40% of the original MSW fill thickness (Edil *et al*, 1990; Frantzis, 1991; Leach & Goodger, 1991). A long term loss of up to 22% of the mass of dry refuse could result from gas formation in decomposition of typical household refuse (DOE, 1986). Given that many Australian and New Zealand landfills are built in deep, former quarry sites, subsidence of the final surface at these magnitudes has in many cases lead to unacceptable degree of concave or grossly uneven

topography within a few years of completion of filling.

MSW settlements will vary significantly depending of the composition of the wastes and upon the degree of compaction applied to the refuse at the time of placement. The use of modern waste compactors with a mass typically of 10-40 tonnes will result in higher compaction densities (and lower short term compressibility). Magnitudes of long term settlements, however, depend on the proportion of putrescible constituents in the waste. Current campaigns to remove recyclable materials from municipal waste streams may bring about increased proportions of organic constituents being landfilled, and larger long term settlements of those sites than otherwise would be the case.

Prediction of landfill settlement and analyses of compressibility behaviour has been likened to peat and a highly compressible clay (Kurzeme and Walker, 1985). Settlement behaviour is often classified as occurring as several distinct phases (Sowers, 1973; Watts and Charles, 1990):

- short-term, stress-dependent consolidation due to the weight of successive layers of refuse;
- long-term, time-dependent compression made up of physical creep and biodegradation components:
 - (i) crushing, distortion, bending, reorientation of materials within the fill;
 - (ii) viscous behaviour and consolidation phenomena involving both solid skeleton and single particles and components;
 - (iii) decomposition, collapse and solubilisation of organic matter, combined with physio-chemical changes such as oxidation, corrosion and combustion;
 - (iv) internal ravelling and erosion due to migration of fines into voids.

Short-term (primary) compression is generally regarded to occur rapidly (say one month) with little or no pore pressure build-up (Phillips *et al*, 1993; Morris & Woods, 1990). The on-going (secondary) compression is thought to continue indefinitely at a rate which is roughly proportional to the logarithm of time (Sowers, 1973).

The biodegradation components of long-term (secondary) compression is due to a four stage process by which solid organic particles in the waste are solubilised and converted through methanogenesis to methane and carbon dioxide (Wall & Zeiss, 1995). The decomposition step of interest is the conversion of refuse organic solids to liquid. It is thought that this reduction in solids directly may relate to an increase in the magnitude and rate of secondary settlement.

Observations of settlement of final surfaces of MSW landfills are often idealised in the form depicted in Figure 1.

3. MODELS USED

A soil mechanics modelling approach has been generally adopted in landfill engineering practice to predict the projected settlements of a landfill subjected to surface loading. Manaserro *et al* (1996) presented an extended overview of various methods which have been used to analyse the settlement of MSW. Sowers (1973) adopted a behaviour similar to secondary consolidation of soils, in which the settlements were assumed to be proportional to the landfill thickness, H, and to vary linearly with time. Edil *et al* (1990) presented data and analysis procedures using rheological model based upon the power creep law. Edgers *et al* (1992) proposed a biological model for long term settlement based on the rate process theory and the biological growth kinetic. More recently two similar studies were reported by Bjarngard & Edgers (1990), and Fasset *et al* (1994), in which the respective researchers compiled available MSW landfill performance data, evaluated the data and proposed empirical methods for the prediction of settlements in landfills.

The model upon which this paper will focus is that proposed by Bjarngard & Edgers (1990), which is given as:

$$\frac{\Delta H}{H} = C_p \log \frac{\bar{p}_o + \Delta p}{\bar{p}_o} + C_{\alpha(1)} \log \frac{t(2)}{t(1)} + C_{\alpha(2)} \log \frac{t(3)}{t(2)} \quad (1)$$

where: ΔH = settlement; H = initial thickness of waste layer; $\Delta H/H$ = vertical strain; \bar{p}_o = initial average vertical effective stress at the considered depth; Δp = average induced vertical effective stress also due to overburden increase at depth considered; $t(1)$ = time (days) for completion of "initial" compression; $t(2)$ = time (days) for completion of "intermediate" compression; $t(3)$ = period of time (days) for prediction of settlement; C_p = primary compression ratio; $C_{\alpha(1)}$ = intermediate secondary compression index; $C_{\alpha(2)}$ = secondary compression index.

Figure 1 shows the typical sequence of these three phases of settlement.

The model described by Fasset *et al* (1994) is essentially identical to Equation (1) above except that the two secondary compression indices for intermediate and long term phases are combined into one, which will be denoted herein as C_{ae} .

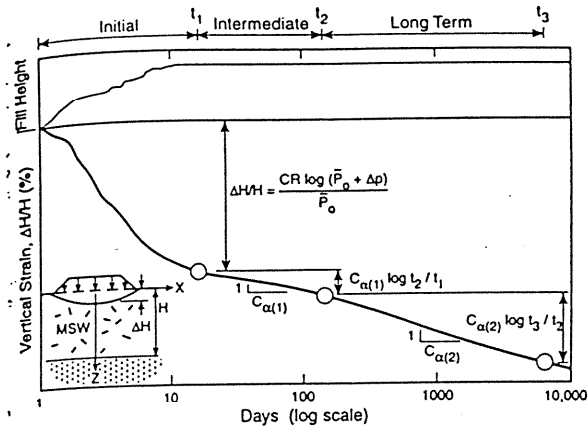


Figure 1. Idealised settlement model (after Bjarngard & Edgers, 1990).

Published settlement-time data of completed landfills indicate that the intermediate phase of secondary compression is often short in duration or not observable at all, which supports that adoption of a single phase of secondary movement.

Hence for all practical purposes:

$$\frac{\Delta H}{H} \approx C_p \log \frac{\bar{p}_o + \Delta p}{\bar{p}_o} + C_{\alpha e} \log \frac{t_f}{t_i} \quad (3)$$

$$= C_p \log \frac{\bar{p}_o + \Delta p}{\bar{p}_o} + (C_{\alpha p} + C_{\alpha b}) \log \frac{t_f}{t_i} \quad (4)$$

In Equation (4), $C_{\alpha e}$ is the sum of secondary compression due to:

- strain due to physical/mechanical creep, described as $C_{\alpha p}$; and
- strain due to biodegradation, fines migration and other physio-chemical and biological decay volume changes, described by $C_{\alpha b}$.

These processes are generally regarded to proceed simultaneously in the long-term and are not usually distinguishable.

Equations (3) and (4) describe the usual behaviour of a landfill over time (and indeed most uncompacted fills), in that settlement under constant effective stress and moisture content shows an approximately linear behaviour with the logarithm of elapsed time.

The parameter $C_{\alpha p}$ can be measured by sustained compression testing in the laboratory using large samples of refuse. Long term settlement monitoring of a completed landfill would permit the determination of $C_{\alpha e}$, but would not allow either of the two components of $C_{\alpha e}$ to be distinguished. The direct determination of

$C_{\alpha b}$ by either laboratory or field monitoring is felt to be impractical, and perhaps unnecessary.

4. COMPRESSIBILITY OF MSW

A review of published settlement and compressibility data reveals typical values of C_p (Table 1). Despite there being a wide variation in discrete values of C_p as expected, median values of C_p for municipal refuse fall into a relatively narrow range for both laboratory samples of refuse and surcharged municipal landfills. A value of C_p of 0.20 ± 0.05 would appear applicable to this range of published studies.

Table 2 summarises a review of published secondary compression data for municipal refuse. On the basis of the data available, $C_{\alpha e}$ is typically about 4% to 8% for average conditions, but can range from about 3% when conditions are not conducive to biodegradation through to about 20% in favourable biodegradation conditions. $C_{\alpha e}$ also appears unrelated to stress level and refuse thickness.

5. PRACTICAL ESTIMATION OF LANDFILL SETTLEMENT

5.1 Empirical Model Proposed

On the basis of the model described in Equation (3), an empirical computing tool, referred to as "FILLS", has been developed by the author to simulate the layer-by-layer, cell-by-cell development of a landfilled airspace (Bouazza & Pump, 1997; Pump, 1994). FILLS is based on an integration of calculated layer thicknesses (post compression under self-weight) to model the 3-dimensional filling of an MSW site.

The programme takes into account:

1. the type of waste, its method of placement and degree of compaction;
2. the short and long-term compressibility of waste;
3. the thickness and compaction of soil cover;
4. the staged filling of a site in cells;
5. the period allowed, following cell capping, for subsidence to take place; and
6. the topography of both the site to be filled and the desired long-term surface of the completed landfill.

Although one dimensional tools have been previously proposed (Morris & Woods, 1990), FILLS enables a landfill-wide assessment of waste compression and surface settlement and their influence on site tipping capacity. The author is not aware of any other published model which provides equivalent information.

Table 1 Typical primary compressibility of municipal refuse.			
Data Source	Measured C_p		Reference
	Range	Median	
1. Surcharged Landfills			
Settlement records of 21 landfills	0.13 - 0.47	0.26	Sowers (1973)
Settlement records of 10 landfills	0.05 - 0.26	0.14	Bjarngard & Edgers (1990)
Surcharging of 5-15 yr old landfill, 2-9m thick.	0.05 - 0.25	-	Burlingame (1984)
Surcharging of 0-4yr old landfill, 8-37m thick.	0.05 - 0.52	0.17	Edil et al (1990)
Surcharging of fresh landfill, 15m thick.	0.14	0.14	Edil et al (1990)
Settlement Records at Greek site, 4m thick	-	0.26	Manassero et (1996)
Full Scale Test Cell	-	0.15	Rao et al (1977)
Field Test Cell	-	0.10	Rao et al (1977)
2. Laboratory Tests: Confined Compression Tests on Large Samples			
US Refuse	-	0.23	Rao et al (1977)
Australian Refuse (i) $e_o > 3.5$ (ii) $e_o < 3.5$	0.11 - 0.30 0.02 - 0.34	0.16 0.03	Moore & Pedler (1977)
UK Refuse	0.10 - 0.66	0.50	Beaven & Powrie (1995)
-	0.15 - 0.22	0.17	Gabr & Valero (1995)
Canadian Refuse	0.21, 0.25	-	Wall & Ziess (1995)
Canadian Refuse	0.17 - 0.22	0.21	Landva & Clarke (1990)
German Refuse	0.18 - 0.23	0.22	Jessberger & Kockel (1993)

5.2 Information Provided

By integration of the layer-by-layer filling of an MSW landfill site, the model provides rational estimates of:

- the site's airspace capacity, necessary volumes of cover materials, and active tipping life;
- the rate of post-capping settlement; and
- vertical profiles of estimated overburden pressure, bulk density, void ratio and porosity, and layer thicknesses.

FILLS also represents a means to conduct parametric studies of the respective influence of type of waste stream; degree of refuse compaction; etc.

5.3 Assumptions Inherent in FILLS

The following assumptions have been used to develop the tool :

1. the landfill is built up by the area fill method or by a staged (cellular) development;
2. wastes placed are uniform in specific gravity, moisture content and compressibility;

3. despite inevitable inhomogeneity of the wastes over short distances laterally and vertically throughout the landfilled mass, MSW properties are regarded as being sufficiently uniform to describe geotechnical behaviour of the landfill as a single entity;
4. each layer of waste, and daily cover, is placed to the same lift height and compacted to the same initial density throughout the landfill;
5. the landfill is free-draining, or alternatively saturation occurs after the time of interest (ie after commencement of the post-closure land-use);
6. both daily cover and final cover are placed to the same compacted density and are considered to be relatively incompressible (at least compared to that of the refuse);
7. primary settlement of each layer of refuse is complete within one month and is the result of the weight of overlying layers and of the final cover layer;
8. secondary settlement of each layer is independent of the initial void ratio of the compacted refuse and of the mass of the overlying materials;
9. to account for ravelling and the migration of fines into voids into the decomposing refuse, it is

Table 2 Typical secondary compressibility of municipal refuse.				
Data Source	Measured Secondary Compression			Reference
	Creep Comp't C_{cp} (%)	Gross Secondary Compressibility C_{ac} (%)		
		Range	Median	
1. Landfills				
Load tests by:				
(i) Sand filled skip: Site 1	2	-	-	Watts & Charles (1990)
(ii) Surcharging by fill: Site 1	-	19	-	
	-	6	-	
Settlement records of 9 landfills.	-	3 - 8	4	Sowers (1973)
Settlement records of 24 landfills.	-	0.3 - 5.1	2.5	Bjarngard & Edgers (1990)
Surcharging of 0-4 yr old landfill, 8m - 37m thick.	-	2.4 - 7.5	-	Edil et al (1990)
Settlement records of 3 landfills, 8.5 to 9.5 m thick, up to 2yrs old:				Gasparini et al (1995)
Landfill No.3	-	3.5 - 16.1	9.0	
Landfill No. 6	-	6.7 - 23.1	11.2	
Landfill No. 7	-	3.1 - 6.0	4.2	
Settlement records of landfill, 10-34 m thick	-	10.8, 11.1, 13.5	11.1	Di Stefano (1995)
Settlement records of 2-4 yr old landfill, 8-20m thick.	-	0.7 - 20	9.0	Grisolia et al (1993)
Settlement records of 3 landfills, 6-38m thick, 1-7 yr old:				Yen & Scanlon (1975)
< 12m thick	-	2 - 4	3.7	
12-24m thick	-	1.5 - 5.5	2	
25-31m thick	-	2.6 - 5.9	3.9	
> 31m thick	-	2.7 - 6.1	3.5	
Field Test Cell (1.5m thick)		9.0	-	Rao et al (1977)
Full Scale Test Cell (3.3m thick) - old refuse		7.2 - 17.5	8.5	
Surcharging of 7-22 yr old landfill, 5m thick.				Geidans et al (1983)
Surcharge thickness: 1m	-	3	-	
3m	-	1.5	-	
6m	-	5.8	-	
2. Laboratory Tests: Confined Compression Tests on Large Samples				
Canadian Refuse				Wall & Zeiss (1995)
Applied Pressure (kPa): 10	3.3 - 5.6	-	-	
10	3.7 - 4.9	-	-	
US Refuse				Rao et al (1977)
Applied Pressure (kPa): 44 - 1553	2.7 - 4.0	-	-	
German refuse:				Jessberger & Kockel (1990)
Applied pressure (kPa): 50 - 650	0.6 - 1.0	-	-	

assumed that the thickness of each layer of daily cover eventually reduces to 25% of that initially placed.

6.0 CASE STUDY

Few case studies have been published which provide comprehensive monitoring data on the performance of an MSW site. Application of the FILLS approach can be nevertheless demonstrated by reference to data relating to the Rio Vigne landfill in Italy (Grisolia *et al*, 1993).

A 2.6ha, valley-fill MSW landfill, Rio Vigne operated between July 1983 and October 1988, accepting a total of about 250,000 tonnes of wastes comprising 65% MSW, 23% urban sludges and 12% industrial sludges. Waste were placed in 0.15m layers and compacted in lifts of 2.5m, over which was placed clay soil cover of 0.20m. Settlement was monitored after final capping of the site for a period of 50 months through to 1993 using 23 surface markers. The authors also presented data on the topography of the original site and the final capped surface.

Based on waste compressibility of $C_p=25\%$ and $C_a=5.5\%$, which is within the expected ranges for MSW (Tables 1 and 2), application of the FILLS tool for the site provides a good agreement with actual site characteristics, as shown in Table 3.

Table 3. Rio Vigne MSW Landfill, Italy - Predicted and actual landfilling conditions.

Item	Actual Value	FILLS Computed Value
1. Site Waste Capacity	250,000t	244,000t
2. Airspace	300,000m ³ (approx.)	361,000m ³ at capping; 311,000m ³ after 4yrs.
3. Av. Bulk Density of Waste	800kg/m ³ (approx.)	676kg/m ³
4. Settlement after 4.1yrs at location of thickest point of waste	1.76-1.86m	1.88m
5. Settlement as above as % of waste thickness	8.6-9.2%	8.7%
6. Active Life of Site	63mths	62mths
7. Capping Date	Oct-88	Sept-88

Actual and predicted settlements of the capped surface are compared in Figure 2, which also shows good agreement.

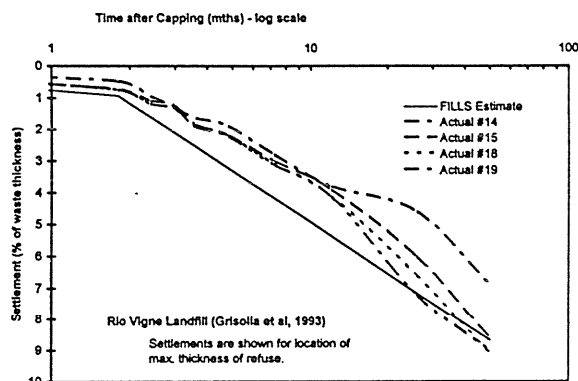


Figure 2 Predicted and actual data, Rio Vigne landfill, Italy.

7.0 CONCLUSIONS

A range of alternative approaches have been published that describe the compressibility of municipal solid wastes and the settlement behaviour of MSW landfills. Empirical equations consistent with soil mechanics principles are felt to represent a reasonable technique for estimation of landfill settlements. Nevertheless, models that derive from adoption of such equations should be applied carefully and conservatively. Inherent inhomogeneity of municipal wastes should not be overlooked. Presently there is also a limited understanding of the effects on long term settlement of factors that directly influence rates of MSW biodegradation (including the rate of landfill gas formation and the solubilisation of the carbon constituents).

Despite these limitations, an empirical tool has been developed by the author which provides an integrated basis for incorporating predictions of landfill settlements directly into the process of landfill planning and design. Based on soil mechanics principles and secondary consolidation parameters, the approach warrants further development and calibration.

A review of published waste compressibility parameters, upon which the tool is based, reveals a reasonable degree of consistency in monitored landfills and laboratory compression tests.

Application of the tool compares well with published data in terms of landfill settlements, and estimates of site tipping capacities. Such a comparison appears to validate adoption of the Sowers secondary consolidation type of approach.

A better understanding of integrated compressibility behaviour of municipal wastes is required, especially its relationship with waste degradation, and the formation of leachates and landfill gas. Settlement monitoring data from fully engineered bioreactor test cells, where decomposition is enhanced, should clarify these questions. It is important that monitoring of such cells continue over some years (say > 5yrs) to clarify the affect of organic decomposition on secondary settlement.

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