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Comparison of slope stability in two Brazilian municipal landfills

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Abstract

The implementation of landfill gas to energy (LFGTE) projects has greatly assisted in reducing the greenhouse gases and air pollutants, leading to an improved local air quality and reduced health risks. The majority of cities in developing countries still dispose of their municipal waste in uncontrolled 'open dumps.' Municipal solid waste landfill construction practices and operating procedures in these countries pose a challenge to implementation of LFGTE projects because of concern about damage to the gas collection infrastructure (horizontal headers and vertical wells) caused by minor, relatively shallow slumps and slides within the waste mass. While major slope failures can and have occurred, such failures in most cases have been shown to involve contributory factors or triggers such as high pore pressures, weak foundation soil or failure along weak geosynthetic interfaces. Many researchers who have studied waste mechanics propose that the shear strength of municipal waste is sufficient such that major deep-seated catastrophic failures under most circumstances require such contributory factors. Obviously, evaluation of such potential major failures requires expert analysis by geotechnical specialists with detailed site-specific information regarding foundation soils, interface shearing resistances and pore pressures both within the waste and in clayey barrier layers or foundation soils.

The objective of this paper is to evaluate the potential use of very simple stability analyses which can be used to study the potential for slumps and slides within the waste mass and which may represent a significant constraint on construction and development of the landfill, on reclamation and closure and on the feasibility of a LFGTE project. The stability analyses rely on site-specific but simple estimates of the unit weight of waste and the pore pressure conditions and use "generic" published shear strength envelopes for municipal waste. Application of the slope stability analysis method is presented in a case study of two Brazilian landfill sites; the Cruz das Almas Landfill in Maceio and the Muribeca Landfill in Recife. The Muribeca site has never recorded a slope failure and is much larger and better-maintained when compared to the Maceio site at which numerous minor slumps and slides have been observed. Conventional limit-equilibrium analysis was used to calculate factors of safety for stability of the landfill side slopes. Results indicate that the Muribeca site is more stable with computed factors of safety values in the range 1.6–2.4 compared with computed values ranging from 0.9 to 1.4 for the Maceio site at which slope failures have been known to occur. The results suggest that this approach may be useful as a screening-level tool when considering the feasibility of implementing LFGTE projects.
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1. Introduction

The assessment of waste mass stability is a critical step in reducing the risk to the landfill operatives and the general public. Major slope failures can occur, as demonstrated by the July 10, 2000, Payatas Landfill Failure, Quezon City, Philippines (Merry et al., 2005) and the subsequent slide at the Bandung landfill in Indonesia (Kolsch et al., 2005). In both of these cases, major failures led to significant loss of life. The largest slope failure in a North

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American municipal solid waste (MSW) landfill occurred on March 9, 1996 and involved 1.2 M m^3 of waste, providing the industry with lessons for the operation, expansion, and stability of existing landfill slopes (Eid et al., 2000). One of the largest, previous waste slope failures involved 500,000 m^3 in Maine, USA (Richardson and Reynolds, 1991). A number of researchers have concluded that major landfill failures are usually associated with site-specific factors such as excessive pore pressures or weak foundation soils (Koerner and Soong, 2000; Kavazanjian, 2001). The purpose of this paper is to discuss the use of simple, generic stability analyses for shallow failures which occur completely within the waste mass, i.e., which do not involve factors such as weak foundation soils. Analyses involving such site-specific and non-generic factors require, in any event, substantial additional site information.

A secondary consideration is minimizing the risk to the environment by reducing the chances of slope failure and damage to the landfill infrastructure such as lining elements, leachate control systems and landfill gas collection systems. It is these relatively smaller failures within the waste mass that are the subject of this paper.

Methane is both a primary constituent of biogas generated from landfilled refuse and also an important greenhouse gas. Therefore, reducing emissions to the atmosphere by capturing the landfill gas (LFG), and using the LFG as an energy source can yield substantial energy value, economic opportunities, and environmental benefits. As a consequence, there is extensive interest in the implementation of landfill gas to energy (LFGTE) projects which involve collection of LFG and combustion for their energy value.

While potential energy projects in developed countries have been largely captured (e.g., McBean et al., 2002 indicate there are hundreds of such projects already in operation), the situation is not the same in the developing world. For example, the Latin American Caribbean (LAC) region is highly urbanized with nearly 75% of its 500 million inhabitants living in large cities. Many of these LAC cities still dispose of their MSW in uncontrolled open dumps. Due to the absence of any barrier system, the leachate and biogas emanating from decomposing waste contaminates the surrounding environment.

Lately, a few prosperous cities in the developing world have begun to improve disposal practices and some have even commenced operation of engineered landfills (Johannessen and Boyer, 1999). For instance, many landfills in South Africa have started collecting tipping fees, have weigh scales (for landfills receiving more than 1000 tonnes of waste per day), have compactors to grade and compact waste in 2 m lifts and are applying daily cover soil (Johannessen and Boyer, 1999). In China and Indonesia, a number of solid waste projects have recently been implemented to upgrade open dumps to engineered landfills. Nevertheless, while there are improvements, a substantial number of large municipalities in the developing world still dispose of their wastes in open dumps.

Landfill gas in these open dumps is generally managed, if at all, through installation of vertical gas wells for passive ventilation. Such practice results in the release of large quantities of methane directly into the atmosphere, thereby promoting global warming through the greenhouse effect (Johannessen and Boyer, 1999). Although Brazil has been active in implementing improved gas management at some sites, many countries in the LAC still adhere to the bare minimum protective measures stipulated in their legislations, which require only passive venting of gas from wells located in the waste body (Johannessen and Boyer, 1999).

A compounding problem at open dumps is due to the limited space remaining for refuse disposal, and the siting for new landfills is extremely challenging. As a result, the depths and slopes at these open dumps are increasing as a means of keeping the sites functioning for longer times. Managing the landfills in this matter has led to the stability of slopes being a major concern (Singh and Murphy, 1990).

The issue of slope stability is critical for: (i) the safety of on-site workers; (ii) the safety of people living near the base slopes of the landfill; (iii) protection of investments made in improving the level of engineering of the landfill, such as on-site equipment to collect the LFG; and (iv) prevention of large remediation costs. At these open dumps, attention is seldom paid to the subsurface and related conditions, and therefore complete and reliable data are rarely available with respect to the depth and geometry of subsurface formations, pore pressures in foundation soils and the waste mass, leachate head, shear strength of solid waste and underlying native soil.

Therefore, stability with respect to deep-seated failure may only be evaluated by a geotechnical engineer familiar with local ground conditions and, as provided with often-extensive data regarding the various contributing factors which may, as discussed above, trigger instability. The purpose of this paper is not to consider such major and complex potential failures, but rather to evaluate the potential application of a very simple generic approach to relatively small slumps and slides which are contained entirely within the waste mass and which represent an operational hazard and a threat to buried landfill infrastructure such as LFG collection facilities. The authors propose that simple analyses such as those carried out herein might be useful to identify potential problem areas during planning and feasibility studies for LFGTE projects at existing MSW landfills, particularly in developing countries.

Two case studies are employed; the first site is an open dump at which waste is end-dumped with little or no compaction other than that provided by self-weight. The second site has some level of engineering and is constructed in lifts by compactors (approximately 37,000 kg), resulting in an increase in the unit weight of the material. Given the importance of unit weight in influencing the stability of landfill slopes, selection of a reasonable value for this parameter is very important. In the absence of reliable, site-specific data, the reader is directed to Zekkos et al. (2006) and Dixon and Jones (2005) for guidance on the

selection of an appropriate value for the unit weight of landfilled waste.

2. Slope stability analysis

Considerable efforts have been focused toward ensuring design integrity of slopes for sanitary landfills in the developed world, although slope instability has still occurred. For evaluating the stability of slopes, it is required to have an accurate and reliable estimate of in situ shear strength of the waste. The shear strength of MSW has been evaluated using triaxial compression tests and direct shear tests, or by conducting limit-equilibrium back analysis of failed landfill slopes. The shear strength of MSW has most commonly been described using the Mohr–Coulomb failure criterion as commonly applied in geotechnical engineering and written as

$$\tau = c' + \sigma' \tan \phi' \quad (1)$$

where τ is the shear strength of MSW, σ' the effective normal stress, and c' and ϕ' are termed as cohesion and angle of shearing resistance (or angle of internal friction), respectively. The parameters c' and ϕ' are collectively called the shear strength parameters of MSW. The shear strength of MSW has been evaluated by various researchers using large and small direct shear apparatuses, large triaxial apparatus, in situ tests, and back analysis of landfill slope failures.

This approach has been applied as a simple and reasonable model for many years, despite the fact that the applicability of the Mohr–Coulomb model of shear strength to MSW has never been conclusively established. In fact, it must be acknowledged that some fundamental principles have not been conclusively established – such as the degree to which Terzaghi's principle of effective stress or the theory of consolidation might hold in a material such as MSW in which the solid particles are not incompressible. Of course there is substantial evidence that pore pressures do play a role in waste stability (for example the failure in Bogota, Colombia followed the injection of leachate into wells within the waste mass), but fundamental work remains to be done with respect to the essential mechanics. Table 2 summarizes some published values for the shear strength parameters of MSW and provides some context regarding the varying materials and test methods used to obtain the various results.

Determination of shear strength properties for MSW is difficult due to the heterogeneity of disposed wastes, the difficulty in obtaining and testing representative samples, time-varying properties, and strain incompatibility between the MSW and underlying material(s) (Eid et al., 2000). Landva et al. (1984) and Landva and Clark (1990) conducted direct shear tests with a 434 mm × 287 mm shear box on recompacted MSW samples collected from different landfills in Canada. The cohesion and the angle of internal friction were found to vary between 0 and 23 kPa and 24° and 41°, respectively. Direct shear tests were also conducted on individual components of the MSW, such as paper, plastics and wood waste and on a mixture of wood waste and miscellaneous refuse to better understand the role of the main components on the characteristics of typical solid waste compositions.

Siegel et al. (1990) conducted direct shear tests under consolidated drained conditions on a 7.6–10.2 cm high, and 13 cm diameter specimen of MSW. No clear failure was observed in these tests and shear strength was taken as shear stress mobilized at 10% shear displacement. Assuming zero cohesion, these authors interpreted angle of internal friction values between 39° and 53°, suggesting lower and upper boundaries of the shear strength envelope. It should, however, be noted that these samples are smaller then most of the other studies.

Singh and Murphy (1990) observed large scatter in results obtained from the attempts of various investigators to determine reliable shear strength parameters for municipal waste (Fig. 1). Several factors are believed to have contributed to the spread of values. These factors include the highly heterogeneous composition of the refuse, the sampling methods, and the small sample sizes which poorly represented the refuse characteristics. All of these factors have led to variations in laboratory shear strength data.

Grisolia et al. (1995) conducted triaxial compression tests on artificial (synthetic) waste samples of diameter 250 mm and height 650 mm. The sample components and moisture content were chosen so as to represent nearly field conditions of a freshly dumped waste. The compacted unit weight of the samples was 6–7.4 kN/m^3. Even at 35–45% axial strains, failure conditions could not be observed. Consequently, the authors obtained shear stress parameters using various arbitrary values of axial deformations. For axial deformation of 10–15%, the value of ϕ' was calculated to be 15–25°. The value of c' and ϕ' was found to increase progressively to around 40° for deformations between 20% and 35%. Similarly, the value of c' was esti-

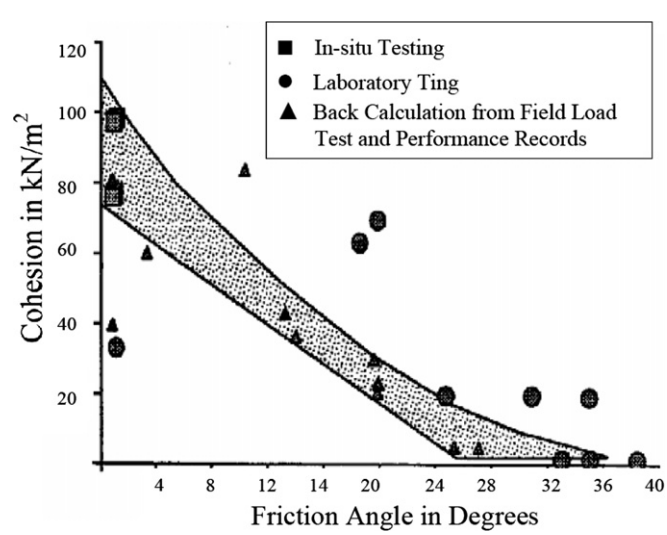

Fig. 1. Experimental values of apparent cohesion and angle of internal shearing resistance for municipal waste (from Singh and Murphy, 1990).

mated to be around 2–3 kPa at 10% axial deformation and increased rapidly up to around 10 kPa in the 10–20% axial deformation range. The authors suggest that the presence of deformable and relatively resistant materials in the waste and their tendency to progressively arrange themselves so as to resist the applied stresses more effectively might be the possible reason for increase in cohesion values at higher axial deformations.

Triaxial compression tests conducted by Jessberger et al. (1995) made use of waste samples of different composition and ages (1–3, 7–10, and 15–20 years old). The waste was regarded as a composite material consisting of a basic matrix comprised of fine and medium grained mostly 'soil-like particles' and a 'reinforcing matrix' (non-soil-like material) comprised of large fibrous components like plastics, textiles, etc. In these experiments, failure of samples could only be observed at very large strains of about 40–50%. Values of c' between 41 and 51 kPa and ϕ' between 42° and 49° were obtained. These authors suggest that at vertical strains greater than 20%, the shear strength depends on the reinforcing matrix and may be defined as cohesion due to tensile strength of the reinforcing components.

Houston et al. (1995) conducted in situ direct shear tests for estimating the dynamic shear strength of MSW as a percentage of its static shear strength. The shear box used by these authors has three compartments each with internal dimension of $1.22 \times 1.22 \times 1.52$ m and height of about 0.76 m. Only two such tests were conducted, and the values obtained for cohesion and angle of internal friction were approximately 4–5 kPa and 33–36°, respectively. Other authors such as Kolsch (1995) and Kavazanjian et al. (1999) have also used large direct shear boxes for obtaining the shear strength parameters from recompacted MSW samples. However, the samples in many of these studies did not undergo shear failure even at large strains.

Mazzucato et al. (1999) conducted a comparative study on intact and recompacted MSW samples using a large cylindrical shear box of 0.81 m diameter and height 0.44 m. For testing intact samples, the shear apparatus was placed on top of the landfill and pushed down into the MSW to fill the shear box with the MSW sample and then sheared. Values of $c' = 22$ kPa, $\phi' = 17°$ and $c' = 24$ kPa, $\phi' = 18°$ were obtained for recompacted and intact samples, respectively.

In the context of the investigation of the failure at the Rumpke landfill in Ohio, USA (Stark et al., 2000), shear strength parameters from large-scale experiments on MSW were summarized by Eid et al. (2000), as illustrated in Fig. 2, in which the average of the lower and upper bounds represents a cohesion of 25 kPa and angle of internal friction equal to 35°.

Due to the limited availability and wide scatter of shear strength data, researchers (e.g., Kavazanjian et al., 1995; Manassero et al., 1996; Bouazza and Van Impe, 1998) have proposed different shear strength envelopes. One such bilinear shear strength envelope proposed by Kavazanjian et al. (1995) depends on the magnitude of applied normal stresses (σ') (Fig. 3). This envelope is derived on the basis of back analysis of existing landfill slopes, which are stable and thus the factor of safety of the slope is estimated to be 1.2, together with published data from laboratory testing of recompacted samples. The authors suggest that:

- For $\sigma' < 30$ kPa, MSW behaves like a purely cohesive material with c' of about 24 kPa.
- For $\sigma' > 30$ kPa, MSW behaves like a purely frictional material with ϕ'' approximately 33°.

The model suggests that at the toe of an unlined landfill, cohesion may be a significant factor in shear strength of MSW, but where normal stress is larger than 30 kPa, cohesion is negligible and the angle of internal friction is approximately 33°. Given that the normal stress on an

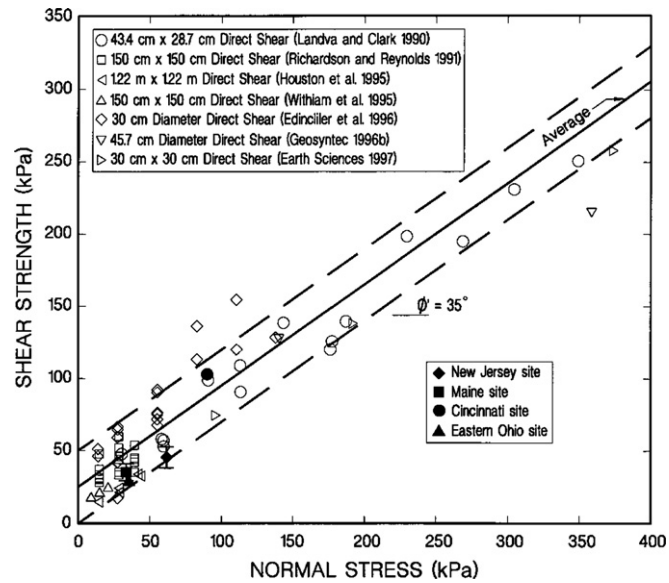

Fig. 2. Range of shear strength envelopes for MSW based on large-scale direct shear tests and back analysis of failed slopes (from Eid et al., 2000).

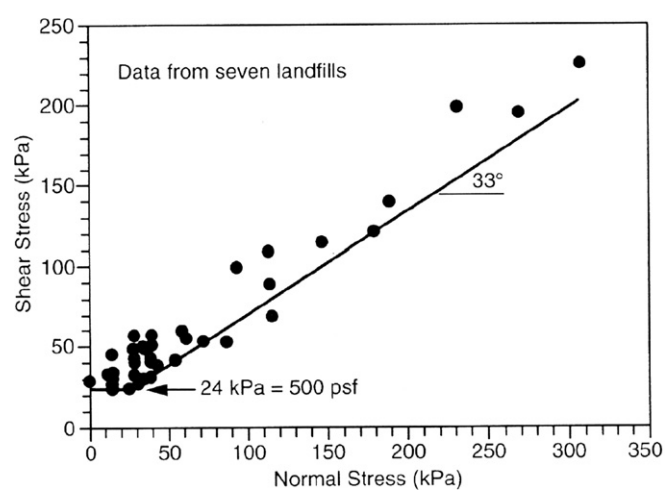

Fig. 3. Shear strength envelope for MSW based on large-scale direct shear tests and back analysis of stable slopes (from Kavazanjian et al., 1995).

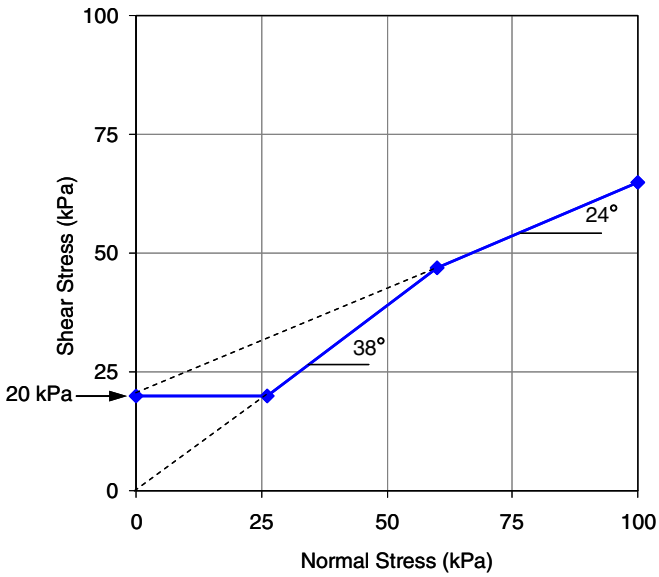

Fig. 4. Tri-linear shear strength envelope for MSW (after Manassero et al., 1996).

inclined surface is 30 kPa or less only within approximately 6 m of the surface, this bilinear model would significantly affect the results only for relatively shallow failures.

A similar but tri-linear shear strength envelope proposed by Manassero et al. (1996) as shown in Fig. 4 suggests that:

- For $\sigma' \leqslant 26$ kPa, MSW behaves like a purely cohesive material, thus showing $c' = 20$ kPa.
- For $26 < \sigma' \leqslant 60$ kPa, MSW is considered to be a purely frictional material with $\phi' = 38°$.
- For $\sigma' > 60$ kPa, it is suggested that $c' = 20$ kPa and $\phi' = 24°$.

A third simple linear failure criteria (Eid et al., 2000) proposes that $c' = 40$ kPa and $\phi' = 35°$.

3. Case study

Two Brazilian landfill sites, namely Cruz das Almas Landfill and Muribeca Landfill, were examined for slope stability. The photograph in Fig. 5 illustrates the method of determining the geometry of side slopes exhibited at various slope locations of the two landfill sites. Fig. 6 shows a typical side slope at Muribeca landfill site.

(i) Cruz das Almas Landfill (Site 1): This landfill site is located in Maceio in the State of Alagoas on the northeast coast of Brazil and has been operating since 1936. It is presently about 40 m in height with a gross tonnage of approximately 6 million. At this site, there have been at least two slope failures during the past 5 years and the failures prior to this have never been recorded. The waste is placed without compaction and no daily cover soil is used. In general, unit weight for waste depends on composition, placement methods, moisture content and leachate levels (Dixon and Jones, 2005). The apparent density of the waste at this site was 450–600 kg/m^3 and a representative in situ unit weight has been estimated to be 8.8 kN/m^3. The waste at this site appeared to be at saturated or near-saturated conditions. Photographs were taken for seven different slopes. The height and the slope angle (β) for these slopes ranged between 8–35 m and 28–43°, respectively.

(ii) Muribeca Landfill (Site 2): This site is a partially engineered landfill and is also located on the northeast coast of Brazil in Recife. The landfill is 70 m high and contains approximately 40 million tonnes of waste. Currently, the waste at this landfill is being received at the rate of 6 million tonnes per year. Compactors are used and the apparent density of the waste is approximately 850 kg/m^3. There are arrangements to collect and treat leachate on-site. There have been no known slope failures at this site.

Fig. 5. Northern edge of the Cruz das Almas landfill in Maceio, Brazil.

Fig. 6. Muribeca landfill located in Recife, Brazil.

Table 1
Brazilian municipal solid waste landfill parameters

Parameter	Landfill site name and location	
	Cruz das Almas Maceio	Muribeca Recife
Average height of fill (m)	40	75
Average annual precipitation (mm/year)	1650	1650
Porosity of solid waste material	0.3	0.3
Typical degree of saturation of solid waste	100%	100%
Saturated unit weight of MSW (kN/m^3)	8.8	14.7

Photographs were taken for five different slopes ranging in height from 2 to 23 m and with the slope angle (β) ranging from 23 to 38°.

The estimated properties of the waste for both sites are listed in Table 1. Due to the high annual precipitation, and inattention to water management, both sites have extensive leachate mounds within the refuse, to the extent that the mounds are within several meters of the refuse surface.

4. Stability analyses

The shear strength parameters used in this approach were identical for both the sites, and the effect of additional compaction on the shear strength parameters was assumed to be negligible. Two alternative shear strength envelopes were used in the analyses: the bi-linear envelope proposed by Kavazanjian et al. (1995) and a tri-linear envelope proposed by Manassero et al. (1996). Shear resistance of MSW has been reported to have an approximately linear

Table 2
Shear strength values of waste from literature

Reference	Shear Strength Parameter		Method of estimation
	c' (kPa)	ϕ' (°)	
Cowland et al. (1993)	10	25	Back analysis of deep trench cut in waste
Eid et al. (2000)	25	35	Large DS and also back calculation from four failed slopes
Gabr and Valero (1995)	17	34	Small CU triaxial (values at 20% axial strain)
Grisolia et al. (1995)	2–3	15–20	Large triaxial (at 10–15% axial strain)
	10	30–40	Large triaxial (at 10–15% axial strain)
Houston et al. (1995)	5	33–35	Large DS on undisturbed samples
Jessberger et al. (1995)	0	31–49	Both large and small triaxial
Kavazanjian et al. (1995)	24	0	For normal stress upto 30 kPa
	0	30	For normal stress more than 30 kPa
Landva and Clark (1990)	0–23	24–41	DS
Landva and Clark (1986)	10–23	24–42	DS on waste from various canadian landfills
Pelkey et al. (2001)	0	26–29	Large DS
Siegel et al. (1990)	0	39–53	DS. At 10% shear displacement, and cohesion assumed zero
Vilar and Carvalho (2002)	39.2	29	At natural water content (20% strain)
	60.7	23	Saturated sample (20% strain)
Withiam et al. (1995)	10	30	Large DS

Note: DS, Direct Shear test; CU, Consolidated undrained triaxial test.

Table 3
Comparison of computed factors of safety for measured slope heights and inclinations at the Cruz das Almas and Muribeca landfills using two published sets of shear strength parameters for municipal waste

Photo No.	Height (m)	Slope angle β (°)	Kavazanjian et al. (1995) FOS			Manassero et al. (1996) FOS			Eid et al. (2000) FOS		
			$Ru = 0$	$R_{u,max} = 0.2$	$R_{u,max} = 0.3$	$Ru = 0$	$R_{u,max} = 0.2$	$R_{u,max} = 0.3$	$Ru = 0$	$R_{u,max} = 0.2$	$R_{u,max} = 0.3$
Site 1 Maceio – Cruz das Almas landfill γ = 8.8 kN/m^3											
1	15	43	1.222	1.131	0.979	1.684	0.989	0.845	3.451	3.039	2.908
2	30	38	1.031	0.773	0.649	1.209	0.928	0.829	2.200	1.830	1.641
3	35	36	1.068	0.779	0.670	1.282	0.958	0.813	2.120	1.760	1.580
4	8	45	1.741	1.613	1.479	1.606	1.372	1.291	7.765	6.589	5.893
5	25	43	0.973	0.737	0.620	1.075	0.792	0.656	2.216	1.913	1.671
6	25	40	1.043	0.788	0.672	1.160	0.861	0.714	2.321	1.931	1.790
7	20	28	1.565	1.245	1.087	1.728	1.341	1.153	3.158	2.707	2.459
Average FS_{MIN} of seven slopes			1.23	1.01	0.83	1.39	1.03	0.90	3.32	2.82	2.56

Photo No.	Height (m)	Slope angle β(°)	Kavazanjian et al. (1995) FOS		Manassero et al. (1996) FOS		Eid et al. (2000)	
			$Ru = 0$	$R_{u,max} = 0.3$	$Ru = 0$	$R_{u,max} = 0.3$	$Ru = 0$	$R_{u,max} = 0.3$
Site 2 Recife-Muribeca landfill γ = 14.7 kN/m^3								
1	8.5	30	1.576	1.124	1.717	1.632	4.477	4031
2	10	28	1.617	1.120	2.060	1.483	3.782	3.536
3	7	38	1.432	1.332	1.784	1.063	4.526	3.280
4	23	28	1.384	0.884	1.514	1.139	2.422	1.789
			1.50	1.12	1.77	1.33	3.80	3.16

Kavazanjian et al. (1995)	Manassero et al. (1996)	Eid et al. (2000)
(i) for $\sigma' < 30$ kPa, $c' = 24$ kPa; $\phi' = 0$ (ii) for $\sigma' > 30$ kPa, $c' = 0$ kPa; $\phi' = 33$	(i) for $\sigma' < 26$ kPa, $c' = 20$ kPa; $\phi' = 0$ (ii) for $26 < \sigma' < 60$ kPa, $c' = 0$ kPa; $\phi' = 38$ (iii) for $\sigma' > 60$ kPa, $c' = 20$ kPa; $\phi' = 24$	$c' = 40$ kPa; $\phi' = 35$

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relationship with increasing normal stress (Kavazanjian et al., 1995; Eid et al., 2000). These shear strength envelopes, as shown in Figs. 3 and 4, were used in a limit-equilibrium analysis using GeoStudio (2004) (GeoSlope International Ltd.). All analyses were carried out using the Morgenstern-Price method with half-sine interslice force functions for factor of safety (FS) calculations.

Since the bi-linear and tri-linear strength envelopes cannot be directly applied to a single material type in SLOPE/W, it was required to input the first portion of Kavazanjian et al. (1995) envelope to a thin layer corresponding to effective stress less than or equal to 24 kPa with the second portion of the envelope applied to the deeper material. A similar approach was used for the tri-linear Manassero et al. (1996) strength envelope. Accordingly, the application of these models to the two sites may be considered to be only an approximation.

Pore pressure conditions are not known within these landfills, although there is existence of a significant leachate mound at each site. Because pore pressure conditions within the waste are not known with any reliable level of detail, the pore pressure ratio (Ru) was used for the stability analyses. The Ru parameter relates the pore water pressure to the overburden stress as follows:

$$Ru = \frac{u}{\gamma_B H_S} \tag{2}$$

where u is the pore pressure, γ_B the bulk unit weight of the overlying material, and H_S is the height of the overlying material. To encompass the range of conditions that might be encountered a range of pore pressure conditions were reflected by Ru values.

For each site, analyses were carried out with zero pore pressure as a lower bound ($Ru = 0$ in Table 2). Assuming hydrostatic conditions with phreatic surface at the ground surface, simple application of Eq. (2) yields upper bound values of $Ru = \gamma_W/\gamma_B$, corresponding to a value >1 for Site 1 and 0.67 for Site 2. An Ru value greater than unity is not reasonable, and simply reflects the low unit weight of the waste at Site 1. In any event, such a situation is not reasonable, particularly near the side slopes of the landfill, given that seepage will occur, reducing the pore pressure.

Pore pressures have been measured in the field in such a situation at a slope with saturated waste at the Brock West Landfill site in Ontario, Canada by Dewaele et al. (2005). At that site, a strong vertical hydraulic gradient was shown to exist within the waste and pore pressure conditions corresponding to Ru values of approximately 0.2. Values of 0 and 0.2 for the pore pressure ratio were therefore used in this analysis to bound the problem for the Recife site, with $Ru = 0$ representing zero pore pressure and $Ru = 0.2$ representing a reasonable upper bound. For the Cruz das Almas site, because the waste unit weight is substantially lower than at the Muribeca site or Brock West (both around 14 kN/m^3), additional analyses were carried out using an upper bound Ru value equal to 0.3. However, unit weight for waste depends on composition, placement methods, moisture content and leachate levels, and higher Ru values can be expected during extreme rainfall events (see Table 3).

For each of the two case study sites, the height and inclination of the various photographed slopes were used with each of the two shear strength envelopes (i.e., the bi-linear envelope of Kavazanjian et al. (1995) and the tri-linear envelope proposed by Manassero et al. (1996))to estimate a factor of safety against slope failure. The failure surfaces were constrained to pass through the waste, given the lack of reliable information about the foundation soils at each of the sites. The results of these analyses are summarized in Table 2. It is immediately apparent that the computed FS values for Site 1 (0.9–3.3) are lower than those of Site 2 (1.1–3.8) using all three strength envelopes. Considering that Site 1 has had slope failures in the past, this finding is to be expected. It is also apparent that the bi-linear envelope of Kavazanjian et al. (1995) yielded somewhat lower FS values than did the tri-linear envelope of Manassero et al. (1996), with the linear envelope of Eid et al. (2000) producing the highest calculated FS values. The bi-linear envelope of Kavazanjian et al. (1995) may therefore represent a more conservative approach for use at sites where there is little or no reliable site-specific data regarding the mechanical properties of the waste.

The identification of potentially weak foundation soils is of fundamental importance to any stability analysis to assess the critical failure mechanism. In addition, the potential for temporary cover soil layers and layers of weaker waste to aid formation of preferential shear planes must be recognized. This analysis was limited in scope and assumed that the failure surface remains within the waste mass and any interpretation of the conclusions reached herein must be made bearing in mind this limitation.

5. Conclusions

A very approximate evaluation of slope stability for municipal landfills may be useful despite limited or missing data regarding geometry, piezometric leachate pressure, solid waste material shear strength, and/or subsurface soil information. Such a screening-level analysis may be useful when considering the feasibility of LFGTE projects at existing MSW landfills, particularly in developing countries.

Simple slope stability analysis was applied to two Brazilian landfill sites: the Cruz das Almas Landfill in Maceio and the Muribeca Landfill in Recife. Three different published shear strength envelopes for municipal waste were used in the analysis, along with a reasonable range of pore pressure conditions and the best estimates of the unit weight of the waste in situ.

The sites examined in this study differ in waste management practice. Cruz das Almas Landfill located in Maceio, Brazil is merely an urban waste 'dump' where little effort is exerted to manage the side slopes. Muribeca Landfill located in Recife, Brazil, on the other hand, is a better-maintained site where there have been zero slope failures on record to date.

The limit-equilibrium analyses suggested that on average, the observed side slopes at the Cruz das Almas landfill were less stable than those of Muribeca landfill. This is not surprising due to the maintenance of the site and its lower unit weight.

If site-specific MSW material strength property data are not readily available, use of the bi-linear shear strength envelope proposed by Kavazanjian et al. (1995) may be useful as an approximate first step in evaluating the potential for problems. Caution must be taken when assuming pore pressure conditions and in assigning a unit weight to the waste material since the factor of safety depends to a great degree upon the value assigned to these parameters.

Selection of appropriate shear strength parameters is a key aspect of the slope stability analysis that relies on information on waste composition, particle size, degree of degradation, and moisture content. With estimates of waste shear strength parameters and using the methodology described in this study, one can provide the landfill operator with information on the critical slope angles, slope heights, and leachate levels to operate the site in a safe manor.

References

Bouazza, A., Van Impe, W.F., 1998. Liner design for waste disposal sites. Environmental Geology 35 (1), 41–54.

Cowland, J.W., Tang, K.Y., Gabay, J., 1993. Density and strength properties of Hong Kong refuse. In: Proceedings of the Fourth International Waste Management and Landfill Symposium, Sardinia 1993, pp. 1433–1446.

Dewaele, P.J., Fleming, I.R., Ciardullo, L. 2005. Engineering geology and hydrogeology at the Brock West Landfill, Ontario: a case history. In: Proceedings of GeoSask2005, 58th Canadian Geotechnical Conference, Saskatoon, Canada, September, 2005.

Dixon, N., Jones, D.R.V., 2005. Engineering properties of municipal solid waste. Geotextiles and Geomembranes 23 (3), 205–233.

Eid, H.T., Stark, D.T., Evans, W.D., Sherry, P.E., 2000. Municipal solid waste slope failure: waste and foundation soil properties. ASCE Journal of Geotechnical Engineering 126 (5), 397–407.

Gabr, M.A., Valero, S.N., 1995. Geotechnical properties of municipal solid waste. Geotechnical Testing Journal 18 (2), 241–251.

GeoStudio, 2004. Geo-slope International Ltd., Canada.

Grisolia, M., Napoleoni, Q., Tancredi, G., 1995. The use of triaxial test for the mechanical characterization of MSW. In: Proceedings of the Fifth International Waste Management and Landfill Symposium, Sardinia 1995, pp. 761–768.

Houston, W.N., Houston, S.L., Liu, J.W., Elsayed, A., Sanders, C.O., 1995. In situ testing methods for dynamic properties of MSW landfills. In: Proc. Specialty Conf. Earthquake Des. Perf. of Solid Waste Landfills, vol. 54. Geotech. Spec. Publ., ASCE, New York, pp. 73–82.

Jessberger, H.L., Syllwasschy, O., Kockel, R., 1995. Investigation of waste body behaviour and waste structure interaction. In: Proceedings of the Fifth International Waste management and Landfill Symposium, Sardinia 1995, pp. 731–743.

Johannessen, L.M., Boyer,G., 1999. Observations of Solid Waste Landfills in Developing Countries: Africa, Asia and Latin America, Urban & Local Government. Working Paper Series No. 3, World Bank, 1999.

Kavazanjian Jr., E.K., 2001. Mechanical properties of municipal solid waste. In: Proceedings of the Sardinia 2001, 8th International Waste Management and Landfilling Symposium, Sardinia, Italy, vol. 3, pp. 415–424.

Kavazanjian Jr., E., Matasovic, N. Bachus, R.C., 1999. Large diameter static and cyclic laboratory testing of municipal solid waste. In: Proceedings of the Seventh International Waste Management and Landfill Symposium, Sardinia 1999.

Kavazanjian Jr., E., Matasovic, N., Bonaparte, R., Schmertmann, G.R., 1995. In: Evaluation of MSW Properties for Seismic Analysis Geoenvironment 2000, vol. 46. Geotechnical Special Publication, ASCE, pp. 1126–1141.

Koerner, R.M., Soong, T.Y., 2000. Stabililty Assessment of Ten Large Landfill Failures. ASCE Geotechnical Special Publication Advances in Systems Using Geosynthetics, pp. 1-38.

Kolsch, F., 1995. Material values for some mechanical properties of domestic waste. In: Proceedings of the Fifth International Waste Management and Landfill Symposium, Sardinia 1995, pp. 711–729.

Kolsch, F., Fricke, K., Mahler, C., Damanhuri, E., 2005. Stability of landfills – The Bandung dumpsite disaster. In: Proceedings of the Tenth International Waste Management and Landfill Symposium, Sardinia 2005.

Landva, A.O., Clark, J.I., 1986. Geotechnical testing of wastefills. In: Proceedings of the 39th Canadian Geotechnical Conference, Ottawa, pp 371–385.

Landva, A.O., Clark, J.I., 1990. Geotechnics of waste fill. Geotechnics of waste fills—Theory and practice. In: Landva, A., Knowles, D. (Eds.), ASTM STP 1070. ASTM West Conshohocken, PA, pp. 86–103.

Landva, A.O., Weisner, W.R., Burwash, W.J., 1984. Geotechnical engineering and refuse landfills. In: Proceedings of the Sixth International Conference on Waste management in Canada.

Manassero, M., Van Impe, W.F., Bouazza, A., 1996. Waste disposal and containment. In: Proceedings of the Second International Congress on Environmental Geotechnics, Osaka, Japan, vol. 3, pp. 1425–1474.

Mazzucato, A., Simonini, P., Colombo, S., 1999. Analysis of block slide in a MSW landfill. In: Proceedings of the Seventh International Waste Management and Landfill Symposium, Sardinia 1999.

Merry, S.M., Kavazanjian, E., Fritz, W.U., 2005. Reconnaissance of the July 10, 2000, Payatas Landfill Failure. J. Perf. Constr. Fac. 19 (2), 100–107.

McBean, E., Mosher, F., David, A., 2002. Energy from Landfill Gas Utilization in Canada. In: Grover, V.I., Grover, V.K., Hogland, W. (Eds.), Recovering Energy from Waste Various Aspects. Science Publishers Inc., Plymouth U.K. (Chapter 11).

Pelkey, S.A., Valsangkar, A.J., Landva, A., 2001. Shear displacement dependent strength of municipal solid waste and its major constituents. Geotechnical Testing Journal 24 (4), 381–390.

Richardson, G.N., Reynolds, R.D., 1991. Geosynthetic considerations in a landfill on compressible clays. In: Proceedings, Geosynthetics '91, vol. 2. Industrial Fabrics Association International, St. Paul, Minn.

Siegel, R.A., Robertson, R.J., Anderson, D.G., 1990. Slope stability investigations at a landfill in Southern California. In: Landva, A., Knowles, D. (Eds.), Geotechnics of Waste Fill – Theory and Practice, American Society for Testing and Materials (ASTM) STP 1070, pp. 259–284.

Singh, S., Murphy, B.J., 1990. Evaluation of the Stability of Sanitary Landfills. In: Landva A., Knowles, D. (Eds.), Geotechnics of Waste Fill – Theory and Practice, American Society for Testing and Materials (ASTM) STP 1070, pp. 240–258.

Stark, T.D., Eid, H.T., Evans, W.D., Sherry, P.E., 2000. Municipal solid waste slope failure – II: Stability analysis. ASCE Journal of Geotechnical and Geoenvironmental Engineering 126 (5), 408–441.

Vilar, O.M., Carvalho, M.F., 2002. Shear strength properties of municipal solid waste. In: de Mello, L.G., Almeids, M. (Eds.), Proceedings of the Fourth International Conference on Environmental Geotechnics, AA Balkema, Lisse, Netherland, pp. 59–64.

Withiam, J.L., Tarvin, P.A., Bushell, T.D., Snow, R.E., German, H.W., 1995. Prediction and performance of municipal landfill slope. In: GeoEnvironment 2000, vol. 46. Geotechnical Special Publication, ASCE, pp. 1005–1019.

Zekkos, Bray, J.D., Kavazanjian, E., Matasovic, N., Rathje, E.M., Riemer, M.F., Stokoe, K.H., 2006. Unit weight of municipal solid waste. ASCE Journal of Geotechnical and Geoenvironmental Engineering 132 (10), 1250–1261.