Stability Analysis for a Landfill Experiencing Elevated Temperatures

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ABSTRACT

This paper describes input parameters and stability analyses for a municipal solid waste (MSW) landfill experiencing elevated temperatures due to an aluminum waste reaction. The scenarios analyzed to investigate slope stability include elevated temperatures and increased gas and liquid pressures. The input parameters are discussed including strength parameters for MSW before and after being impacted by elevated temperatures, inclusion of gas pressures, and possible leachate levels. The MSW that was thermally degraded at this site was modeled using an effective stress cohesion and friction angle of zero and 20 degrees, respectively.

INTRODUCTION

Aluminum production wastes can be disposed of in MSW landfills because this waste is not categorized as hazardous under 40 CFR §§ 261, subpart D which explicitly lists the materials that are defined as hazardous. Aluminum waste products, e.g., dross, salt cake, baghouse fines, etc., are not listed under 40 CFR §§ 261, subpart D so are not a hazardous waste under this code section. Under 40 CFR §§ 261, subpart C, if a waste exhibits one of the following four characteristics of a hazardous waste, i.e., ignitability, corrosivity, reactivity, or toxicity, the waste is categorized as hazardous and cannot be disposed of in an MSW landfill. Calder and Stark (2009) recommend new testing protocol that may result in aluminum wastes being classified as "reactive" or even "ignitable".

Aluminum waste is usually in the form of what the industry calls aluminum dross or baghouse fines (BHF). The aluminum production waste usually contains metallic aluminum, aluminum oxides, salts, and aluminum carbides, and nitrides (Hwang et al. 2006). Generally, disposal of these wastes has not been problematic, but incidents of reaction, combustion, and/or pyrolysis from these materials upon contact with liquid within landfills have been reported (USEPA 1994). Such a situation can develop when aluminum wastes have been previously deposited and then leachate recirculation is initiated in areas of the aluminum waste. Thus, initiation of leachate recirculation in an existing landfill should be carefully considered before initiation. Hazardous and potentially explosive gases, including hydrogen, methane, acetylene and ammonia can be generated via the highly exothermic reaction with metallic aluminum, aluminum carbides, and aluminum nitrates and water (Ohio EPA 2006, Calder and Stark 2009). These reactions are capable of generating heat at temperatures between 200° F and 300° F within the landfill. Excessive heat and/or gases within a landfill generated as result of a subsurface aluminum reaction can result in the surrounding MSW being partially or fully combusted. This can result in "glowing" or "smoldering" combustion of MSW itself and can cause stability, odor, and/or safety issues (Ohio EPA 2006).

This paper presents a stability analysis for a hypothetical MSW landfill subjected to elevated temperature and increased gas and liquid pressures due to aluminum reaction and subsequent thermal degradation. Field observations and published shear strength test data are used to provide recommendations for MSW strengths to be used in static and seismic slope stability analysis of landfills that have been subjected to elevated temperatures.

STABILITY ANALYSIS INPUT PARAMETERS

There is an increasing need for estimating the shear strength of MSW because of the requirement of stability analysis by governmental and regulatory authorities after a number of landfill slope failures. In addition, the trend to increase landfill capacity by increasing landfill slope inclination and height up to 180 m (Stark et al. 2008) also requires a more careful consideration of slope stability. The selection of MSW strength, liquid and gas pressure, and geometry for static and seismic stability analyses is vital to these analyses and discussed below.

MSW Shear Strength

Shear strength parameters are a major input parameter for any slope stability analysis. Although shear strength testing of MSW can be performed to provide a better understanding of the strength of MSW, this may not be feasible especially for a preliminary analysis or in an emergency situation involving a landfill undergoing an elevated temperature event. Shear strength testing of MSW may also pose difficulties because of its heterogeneous composition, difficulty in sampling, specimen preparation, testing, compaction, and time dependent properties, such as age of the MSW and decomposition state due to biological processes, thermal degradation, chemical reaction, strain incompatibilities between the MSW and underlying materials, etc.

Eid et al. (2000) and Stark et al. (2008) provide recommendations for the MSW strength to be used in static and seismic slope stability analysis for landfills that have not experienced elevated temperatures. However, observation of MSW that has experienced elevated temperatures shows that this MSW strength can be reduced significantly due to thermal degradation by removal of the reinforcing materials in the MSW.

There is a wide range of effective stress strength parameters for MSW reported in the literature (Stark et al. 2008). Values reported for effective stress friction angle (ϕ') range from 10° to 53° while effective stress cohesion (c') ranges from 0 to 67 kPa. For example, Zekkos (2005) and Bray et al. (2009) recommend a strength envelope for MSW with c' = 15 kPa and atmospheric pressure, P_0, of 1 atm (101.3 kPa or 2115.7 psf) as follows:

$$\tau = 15\text{ kPa} + \sigma_n^{'}\tan\left[36^o - 5\log\left(\frac{\sigma_n^{'}}{P_o}\right)\right] \quad 1$$

Eid et al. (2000) compiled measured and back-calculated shear strength parameters of MSW for effective normal stresses (σ'_n) less than 400 kPa and suggest that the shear strength of MSW can be defined by a narrow band with an effective stress friction angle, ϕ', of approximately 35°, and cohesion, c', that ranges from 0 to 50 kPa. Eid et al. (2000) also recommend that average values of c' and ϕ' of 25 kPa and 35°, respectively are appropriate for the design of MSW containment facilities that have not experienced elevated temperatures. The relatively high shear strength of MSW is likely caused by interconnection of plastic and other materials (Eid et al. 2000). The high shear strength recommended for MSW is supported by the fact that nearly vertical cuts and scarps in landfills have been observed to remain stable for months to years (Stark et al. 2008).

Eid et al. (2000) recommend a linear envelope because the data considered is limited to normal stresses of 400 kPa. Stark et al. (2008) evaluated the stress dependent nature of the Mohr-Coulomb strength envelope for MSW for normal stresses greater than 400 kPa. Figure 1 shows that the strength envelope is stress dependent even for normal stresses less than 500 kPa. A normal stress of 500 kPa corresponds to a waste depth of only 40 m based on a typical waste unit weight of 12.6 kN/m^3. A waste depth of 40 m is considerably smaller than depths of 180 m, which are currently being proposed. To accommodate the increasing demand for vertically expanding existing landfills and the interest in mega-landfills, Stark et al. (2008) also provide guidelines for selecting stress dependent envelope of MSW for effective normal stresses up to 1,800 kPa. Figure 2 presents the compiled data for normal stresses up to 1,800 kPa, which corresponds to a waste height of 145 m based on a typical waste unit weight of 12.6 kN/m^3.

The stress-dependent MSW shear strength shown in Figure 2 can be modeled using a non-linear failure envelope which can be utilized directly in slope stability software. Figure 2 shows for an effective normal stresses less than 200 kPa, a c' and ϕ' of 6 kPa and 35°, respectively, are recommended. For effective normal stresses greater than or equal to 200 kPa, a c' and ϕ' of 30 kPa and 30°, respectively, are recommended. This stress dependent failure envelope can be modeled in slope stability software using the following four combinations of normal and shear stresses: 0 and 6 kPa; 200 and 146 kPa; 600 and 376 kPa; and 1200 and 723 kPa, respectively.

For comparison purposes, Figures 1 and 2 include the linear strength envelope proposed by Eid et al. (2000) in terms of c'= 25 kPa and ϕ'=35°. These figures show that the linear strength envelope in Eid et al. (2000) over predicts the stress dependent failure envelopes in Figures 1 and 2 from Stark et al. (2008) especially at normal stress greater than 500 kPa because Eid et al. (2000) considered data to normal stresses of 400 kPa.

Shear Strength of Thermally Degraded MSW

The interconnecting plastics and other reinforcing materials that contribute to the high shear strength of MSW shown in Figures 1 and 2 are most likely consumed, degraded, burnt, and/or decomposed by elevated temperatures. This results in a reduction of shear strength parameters of MSW which has been observed in samples obtained during gas well drilling and excavations in MSW landfills experiencing elevated temperatures. Figure 3(a) shows thermally degraded waste obtained in a 100 mm diameter sample from an MSW landfill that experienced elevated temperatures.

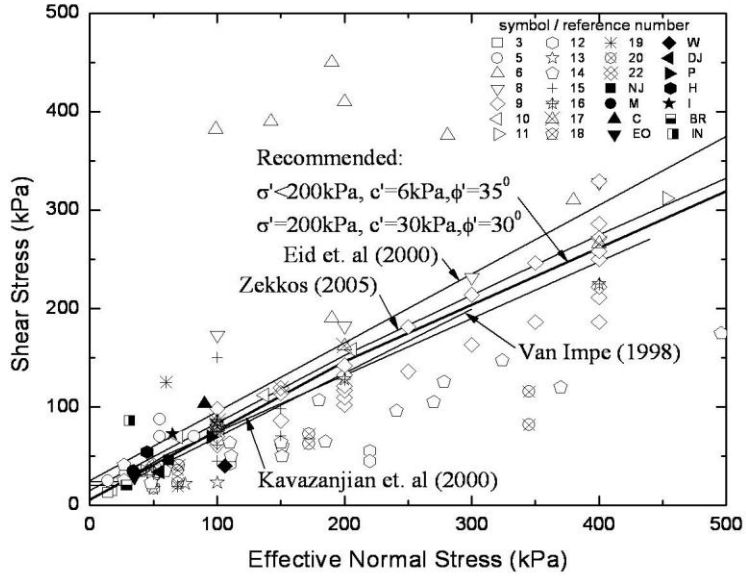

Figure 1. MSW shear strength envelope for normal stresses less than 500 kPa (from Stark et al. 2008).

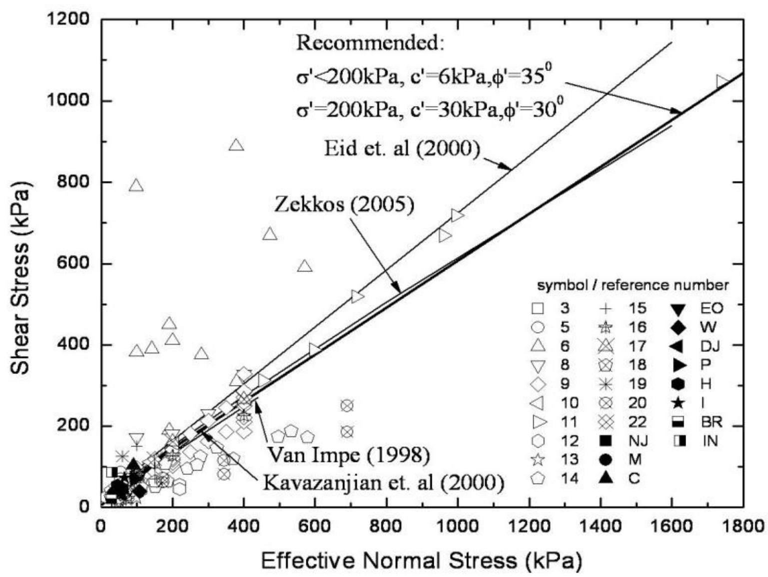

Figure 2. MSW shear strength for effective normal stresses less than 1,800 kPa (from Stark et al. 2008).

Figure 3(b) is a close-up of the thermally degraded waste in Figure 3(a) which is essentially ash. When the ash was handled it fell apart and thus did not exhibit any cohesion. In addition, the ash compressed significantly when a normal stress was applied to it by hand or in a laboratory direct shear device. The thermally degraded

MSW compressed so much that there was insufficient material in the upper and lower shear boxes to conduct a shear test with the sample at hand. Based on these observations, it appears that an effective stress shear strength envelope with an effective stress cohesion of zero and a maximum friction angle of 20° can be used to represent the shear strength parameters of the thermally degraded MSW at this site. These shear strength parameters are probably not applicable to other MSW landfills because of differences in waste constituents, the use of leachate recirculation, the presence of an aluminum waste reaction, and thermal degradation caused by combustion or pyrolysis at this site.

The strength parameters recommended for this site (c' and $\phi'$of 0 kPa and 20°, respectively) are considerably lower than those shown in Figures 1 and 2 which can lead to a reduced factor of safety. This friction angle is also substantially less than degraded friction angles suggested by others, e.g., 30° (Kavazanjian 2008) for decomposed waste, because most of the components of the MSW are reduced to ash including the reinforcing materials. Therefore, facilities that have experienced an aluminum reaction, combustion, or pyrolysis could be less stable simply because of a large reduction in MSW strength even if elevated gas and liquid pressures are present.

(a) **(b)**

Figure 3. Thermally degraded waste from 100 mm diameter sample

Liquid Pressure

The level of leachate in the MSW can also have an effect on slope stability. In general, increased leachate decreases the effective normal stresses and corresponding shear strength of MSW which can lead to a reduction in stability. One facility that has experienced elevated temperatures experienced a ten-fold increase in the leachate collected from 2.5 to 3.5 million gallons/year to 35 to 40 million gallons/year. At this facility, about 23 million gallons of leachate were re-circulated over about five years. This initiated an aluminum reaction that consumed the surrounding MSW. The site is now generating about 35 million gallons of leachate per year after the reaction and fire started. Specifically, in 2004 the landfill generated 3.1 million gallons of leachate. In 2005 when the reaction/fire was first reported, the leachate volume was 12 million gallons. The leachate volume increased significantly afterwards with about 30 million gallons in 2006, 40 million gallons in 2007, and 36 million gallons in 2008. The “black leachate”, which has a viscosity similar to used motor oil, is high in dissolved solids, organic material, and ammonia. The sources of the additional leachate at this site include injection by the facility, precipitation, groundwater infiltration, and the initial moisture content of the waste. This increase in leachate quantity and possibly level should be modeled in the stability analysis along with a reduced MSW strength.

Slope stability software packages are capable of modeling liquid pressures using a variety of methods including a phreatic surface, piezometric surface, pore pressure coefficient (r_u), constant pore water pressure, or pore pressure grid. Because there is usually not a steady state seepage condition in a lined landfill, i.e., the leachate is simply ponding above the liner system, use of a piezometric surface for modeling the leachate level is recommended. An important factor in assessing the piezometric surface is whether or not the leachate is perched or the landfill is actually filled with leachate like a bathtub. If the level is perched, use of a piezometric surface may be conservative because the unsaturated nature of some of the MSW will not be modeled correctly.

Gas Pressure

Landfill gas is continuously generated during the reaction or thermal MSW degradation. Thiel (1998) provides a procedure for incorporating gas pore pressure (u_g) at the geomembrane-soil interface in an infinite-slope analysis that calculates factor of safety (FS) using the following expression:

$$FS = \frac{a' + (h\,\gamma\cos\beta - u_g)\tan\phi'}{h\,\gamma\sin\beta} \qquad 2$$

where a′ is effective stress geomembrane-soil interface adhesion; β is slope angle from the horizontal; h is thickness of cover soil normal to the slope; γ is average total unit weight of soil; and ϕ' is effective stress geomembrane–soil interface friction angle. Inspection of this equation shows that gas pressure reduces the effective normal stress on the geomembrane-soil interface which reduces the frictional resistance of the interface and eventually FS.

A similar approach can be applied for modeling gas pressure in MSW landfills. For example, slope stability software e.g., XSTABL (Sharma 1996), allows a user to define pore water pressure in a soil unit using a "Pore Pressure Parameter, r_u", which relates the pore pressure to the static total vertical stress or a "Constant Pore Pressure", where the pore pressure is constant at all locations within the entire soil unit. If a leachate level is also assigned to the same material unit (in this case, MSW) the pore pressures calculated by r_u or constant pore pressure are added to the pore pressures calculated from the piezometric surface used to model the leachate level. In the subsequent hypothetical study, pore water pressures are modeled using a piezometric surface, while gas pressures were incorporated using a constant pore pressure. If the gas pressure is measured as a pressure head, the pressure head can be converted to a pressure by multiplying it by the unit weight of landfill gas, $\gamma_g = 12.8$ N/m^3 as suggested by Thiel (1998).

HYPOTHETICAL ANALYSIS

A hypothetical slope stability analysis is presented below to illustrate the effects of MSW thermal degradation on slope stability. The stability analysis was performed using slope stability software XSTABL (Sharma 1996) and both rotational and translational failure surfaces. Based on the slope movement that has occurred in facilities experiencing elevated temperatures, the following two modes of movement are possible:

- Movement in the waste above the perimeter berm
- Movement through the waste and perimeter berm

Slope stability analyses for the mode of movement in the waste above the perimeter berm is considered herein because it is assumed that the liner system is intact so the perimeter berm is not saturated, has not softened, and still exhibits shear strength parameters of c' equal to 0 kPa and ϕ' equal to 35° as shown in Table 1. If the liner is compromised and the perimeter berm becomes degraded, movement through the waste and perimeter berm may be possible. Due to space constraints this analysis is not included herein.

Movement above the perimeter berm involves a failure surface developing in the waste and exiting the slope at or near the top of the perimeter berm. The first analysis focuses on movement through the waste before thermal degradation and a normal leachate level and gas pressures. The stability of the slope is then evaluated with elevated liquid and gas pressures and reduced MSW strength to reflect thermal degradation. Figure 4 shows the cross section of the hypothetical slope and different leachate levels considered in the analysis.

Stability before thermal degradation

The stability of the hypothetical 3H:1V slope before thermal degradation caused by an aluminum reaction, combustion, or pyrolysis was investigated using the cross section and liquid level labeled "Initial leachate level" (long dashed line) in Figure 4.

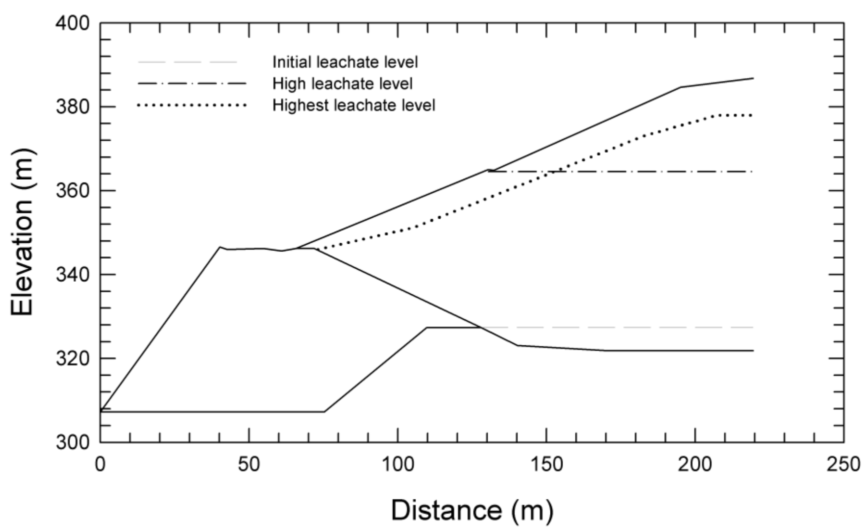

Figure 4. Possible leachate levels in hypothetical slope

Analyses using MSW shear strength parameters from Eid et al. (2000) and Stark et al. (2008) (see Table 1) are performed to evaluate the effect of MSW strength on the factor of safety. The strength parameters from Stark et al. (2008) that correspond to an effective stress less than 200 kPa are used because of the shallow nature of the failure surface. The resulting factors of safety for movement above the perimeter berm using Eid et al. (2000) and Stark et al. (2008) MSW shear strength parameters are 3.3 and 2.75, respectively, which indicates the hypothetical slope is stable before thermal degradation. The factors of safety also suggest that neglecting the stress dependent nature of MSW may over estimate the factor of safety because the Eid et al. (2000) parameters yield a higher factor of safety than the Stark et al. (2008) parameters.

Table 1: Engineering properties to reflect before thermal degradation

Material Name	Total/Saturated Unit Weight, (kN/m^3)	Effective Stress Cohesion, *c*' (kPa)		Effective Stress Friction Angle, ϕ' (degrees)	
		Eid et al. (2000)	Stark et al. (2008)	Eid et al. (2000)	Stark et al. (2008)
MSW	11/12.6	25	6	35	35
Perimeter Berm	18.9/19.7	0	0	35	35
Bedrock	23.6/23.6	190	190	30	30

Stability with elevated leachate and gas pressures

Figure 4 shows the cross-section and liquid level (High leachate level) in the waste assumed for this case based on leachate outbreaks. Gas pressures measured in gas wells at different facilities experiencing elevated temperatures indicate gas pressure heads ranging from 1 to 22 meters. Assuming a unit weight of landfill gas of 12.8 N/m^3 (Thiel 1998) and using the worst case gas pressure head (22 m), a gas pore pressure, u_g, of 281.6 N/m^2 was estimated and used in the analysis as a worst case. A constant pore pressure of 281.6 N/m^2 in the MSW was included in XSTABL (Sharma 1996) in addition to the piezometric surface discussed below to model the gas and leachate effects. The resulting factors of safety for this leachate level using Eid et al. (2000) and Stark et al. (2008) MSW shear strength parameters are 1.5 and 0.9, respectively. Therefore, elevated leachate and gas pressures can significantly reduce slope stability.

Stability after thermal degradation

The stability of the hypothetical slope after thermal degradation was also investigated. To represent the worst impact of thermal degradation on the hypothetical slope, the following two input parameters were changed: the liquid level and MSW strength. The liquid level in the waste was raised to reflect the maximum liquid level observed in similar sites and shown in Figure 4 as “Highest leachate level”. This is essentially the highest liquid level that could possibly occur because it is near the surface of the slope and near the top of the perimeter berm. The shear strength parameters for the MSW were reduced to *c*' of 0 kPa and ϕ' of 20° because the plastics and other reinforcing materials have been removed by the elevated temperatures as discussed above.

A constant liquid pressure of 281.6 N/m^{2}in MSW was included in the analysis to model the gas pressure as well as a piezometric surface to model the highest leachate level shown in Figure 4. It is assumed for the purposes of this analysis that the liner system on the perimeter berm is not compromised so the berm material is not degraded. The stability analyses indicate a factor of safety of about 0.6 for circular and non-circular failure surfaces through the MSW and exiting at the top of the berm.

Table 2 summarizes the stability analyses conducted for the hypothetical slope shown in Figure 4 and failure surfaces through the MSW only, i.e., above the perimeter berm. The resulting factors of safety show the impact that elevated temperatures and gas and liquid pressures can have on slope stability.

Table 2: Stability analyses with elevated leachate and gas pressures

MSW Strength	Liquid Level	Gas Pressure	Factor of Safety	
		(N/m^2)	(Eid et al. 2000)	(Stark et al. 2008)
Not degraded	El. 327 m	0.0	3.3	2.7
Not degraded	El. 364 m	281.6	1.5	0.9
Degraded	Gas Wells	281.6	0.6	

CONCLUSIONS

The following conclusions are based on field observation and a stability analysis of a hypothetical MSW landfill slope experiencing an aluminum reaction and elevated temperatures:

- It is recommended that a stress dependent strength envelope be used to represent the shear strength of MSW prior to elevated temperatures using:
  - For normal stresses less than 200 kPa, c' of 6 kPa and ϕ' of 35°.
  - For normal stresses greater than or equal to 200 kPa, c' of 30 kPa and ϕ' of 30°. This stress dependent failure envelope can be modeled in slope stability software using the following four combinations of normal and shear stresses: 0 and 6 kPa; 200 and 146 kPa; 600 and 376 kPa; and 1200 and 723 kPa, respectively.
- Thermal degradation can consume, burn, degrade, and/or remove the plastics and other reinforcing material from MSW, thereby reducing the shear strength of MSW. At the site considered herein, a c' of 0 kPa and ϕ' of 20° appears reasonable to represent thermally degraded waste which experienced an aluminum reaction, combustion, and/or pyrolysis.
- Leachate naturally present and/or increased by the thermal event should be modeled in the stability analyses. This can be accomplished using a piezometric surface
- Gas pressure developed as a result of MSW biological and thermal decomposition, combustion, pyrolysis, and/or aluminum reaction should be incorporated in the stability analysis because it reduces the effective normal stresses which reduces the shear resistance of the materials

involved. This can be accomplished using a constant pore pressure that reflects measured gas pressure or gas pressure head.

ACKNOWLEDGEMENTS

The contents and views in this paper are the authors and do not necessarily reflect those of any landfill owner/operator, regulatory agency, or any other entity or person.

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