Slope and Settlement Movements of an MSW Landfill during Elevated Temperatures

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Abstract: Elevated temperature events are problematic for Subtitle D landfills because they: (1) are challenging to identify and delineate; (2) can remain undetected for a relatively long period of time; (3) are difficult to extinguish; (4) may damage engineered components, (5) direction and rate of movement are not uniform, and (6) produce side effects that may damage a facility enough to warrant permanent closure. In addition, slope instability and movement have occurred at these landfills with elevated temperature, leachate, and/or gas pressures. This paper discusses the mechanisms for slope instability, including elevated gas pressures, perched leachate surfaces, and reduced MSW shear strength. Based on a case study, slopes are found to move outwards of up to 15 m. In addition, the slope can reverse backwards into the settlement bowl if settlement is excessive.

INTRODUCTION

Elevated temperatures have been documented in municipal solid waste (MSW) landfills, construction demolition debris landfills, industrial waste fills, and sanitary dumps (Martin et al. 2013; Sperling and Henderson 2001; Ettala et al. 1996; Øygard et al. 2005; Koelsch et al. 2005; Frid et al. 2009). The presence of elevated temperatures, particularly in MSW landfills, can impact the integrity of the cover and liner systems, leachate quality, gas composition, slope stability and differential settlement, odor mitigation, and abatement operations (Øygard et al. 2005; Jafari et al. 2014; Stark et al. 2012). In addition, they present a significant threat to the environment by emitting to the atmosphere incomplete combustion by-products, reduced sulfur compounds, and particulate matter (Ruokojarvi et al. 1995).

MSW landfills with a gas collection and control system used to comply with federal regulations (40 Code of Federal Regulations (CFR), Part 60, Subpart WWW) are required to operate each gas extraction well with a landfill gas temperature less than

55°C (131°F) because methane production from mesophilic bacteria during anaerobic biodegradation can start to significantly decrease above this temperature (Kasali and Senior 1989; Hartz et al. 1982). This paper considers elevated temperatures in MSW landfills to be demonstrated by gas wellhead temperatures above 65°C because anaerobic biodegradation is usually curtailed typical landfill temperatures are below this threshold (Yesiller et al. 2005; Hanson et al. 2010).

Slope instability and movement have occurred at landfills with elevated temperature, leachate, and/or gas pressures (Stark et al. 2012; Stark et al. 2010; Koelsch et al. 2005; Jafari et al. 2013; Hendron et al. 1999; Blight 2008). The objective of this study is to evaluate slope stability input parameters and slope movement observed from a case study experiencing elevated temperatures.

STABILITY ANALYSIS INPUT PARAMETERS

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.

Stark et al. (2009) and Bray et al. (2009) 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. In specific, there is a wide range of effective stress strength parameters for MSW reported in the literature (Stark et al. 2009). 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 biodegrading MSW.

The interconnecting plastics and other reinforcing materials that contribute to the high shear strength of MSW are most likely consumed, degraded, burnt, and/or decomposed by elevated temperatures (see Fig. 1). 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. Fig. 1 shows thermally degraded waste obtained in a 100 mm diameter sample from an MSW landfill that experienced elevated temperatures. 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° are assumed to represent the shear strength parameters of the thermally degraded MSW at this site (Stark et al. 2010). 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.

FIG 1. Thermally degraded (combusted) waste from 100 mm diameter sample

The strength parameters assumed for thermally degraded MSW (c′ and ϕ′ of 0 kPa and 20°, respectively) are considerably lower, 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 et al. 1995) 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 not present.

Elevated Gas and Leachate Pressures

MSW landfills under anaerobic biodegradation typically exhibit pressures up to 3 kPa. Stark et al. (2012) found that gas pressures increased to 45 kPa in areas where aluminum production waste (APW) reactions were occurring. In addition, subsurface combustion is found to display significant gas pressures, in some cases as high as 75 kPa. Several mechanisms can contribute to increased gas pressures. Following the ideal gas law and assuming a landfill is a constant volume boundary, gas temperature and pressure increase simultaneously. For example, landfill gas is approximately atmospheric pressure (101.3 kPa) at a temperature of 40°C (Young 1992; Bogner et al. 1988). If subsurface temperatures increase to 100°C, internal gas pressures would increase by 19.5 kPa and thereby reducing the effective stress acting on the waste. Similar to the APW reaction reported in Stark et al. (2012), elevated temperatures can initiate gas generating processes, such as combustion and pyrolysis. The process of MSW pyrolysis yields about 30 to 50% by weight (wt) of char, 30 to 50% wt of liquid, and 20 to 40% wt of gas (Buah et al. 2007; Rampling and Hickey 1988; Williams and Besler 1993; Lin et al. 1999). This suggests elevated gas pressures could be explained by the increased gas production caused by combustion and pyrolysis. In conjunction with additional gas production, temperatures can damage and/or compromise gas extraction wells and lateral headers. Eventually, the gas collection system can become overwhelmed and lead to elevated gas pressures and reduce slope stability.

When gas and leachate migrate to landfill side slope and are impeded by the cover system (soil or geomembrane), gas pressures and leachate can accumulate and cause leachate outbreaks. The elevated leachate and gas pressures occasionally manifest as "leachate geysers" (Fig. 2) and can eject 9 to 11 m into the air (Stark et al. 2012). These leachate geysers also can be encountered when borings are drilled in the waste for gas wells or exploratory purposes. In some instances, the soil cover system is replaced with a geomembrane to control odors. Although the liner encapsulates the surface, outbreaks can still occur at seams and gas wellhead connections.

FIG. 2 Leachate outbreak of 2 to 4 m at MSW landfill side slope (photo courtesy of Ohio EPA)

CASE STUDY

The case study presented herein is a MSW landfill regulated under Subtitle D regulations. The site is permitted for waste disposal in 178 ha and receives up to 9,000 metric tons of MSW per day. Fig. 3 shows the impacted area in Cells 4 – 7. These cells encompass 26.2 ha and were constructed in phases, with Cell 4 completed in late 1997, Cell 5 in early 1999, Cell 6 in late 1999, and Cell 7 in early 2001. After reaching the permitted elevations in 2005, Cells 4 through 7 were capped with 0.6 m of fine-grained intermediate cover soil and a gas control and collection system was installed. In August 2009, five gas wellheads in Cell 5 experienced temperatures above 68°C and as high as 95°C. Associated laboratory gas sampling from the wellheads reported CO >1,000 ppmv, with a maximum of 10,200 ppmv (Ohio EPA 2010). Based on the Findings and Orders (Ohio EPA 2010), the facility initiated an expanded monitoring program to monitor and delineate the elevated temperatures. The program included installing stability pins into the cover system to monitor changes in northing, easting, and elevation.

Elevated temperatures were first observed in Cell 5, and they migrated to Cells 6 and 7 over the next four years. During the monitoring period, Cell 4 remained unaffected by elevated temperatures. Data collected from the monitoring program is discussed herein to show the spatial trends of settlement and slope movements. Fig. 3 shows the location of stability pins used to monitor settlement and lateral movement. The shaded regions in Fig. 3 delineate areas where elevated temperatures had caused accelerated settlements (red shaded region) and anaerobic biodegradation is assumed to have prevailed during the entire monitoring period (green shaded region).

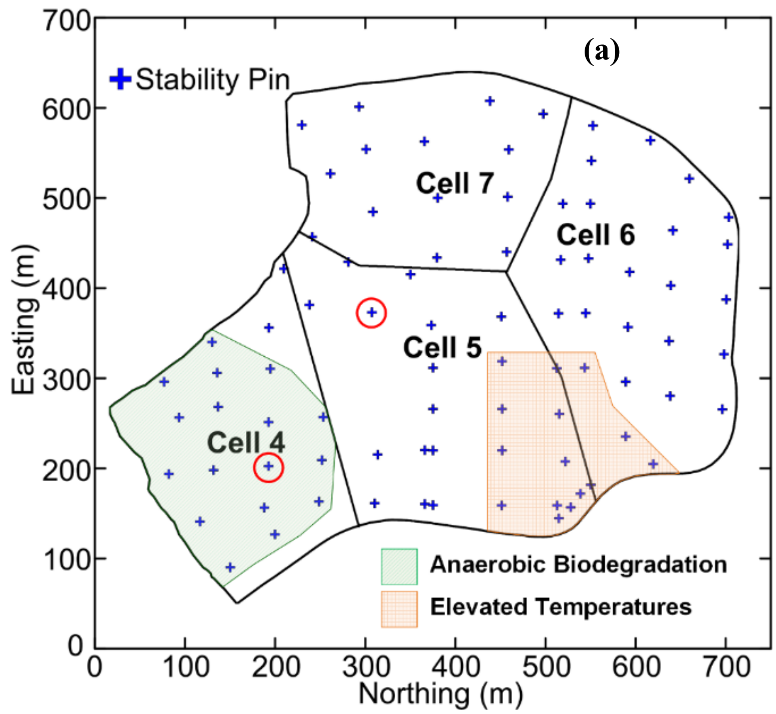

FIG 3. Plan view of Cells 4 through 7 showing the location of stability pins

Slope and Settlement Movement

For this case study, slope movement is preceded and accompanied by forceful gas and leachate outbreaks. Mechanisms for slope instability include elevated gas pressures, perched leachate surfaces, and/or reduced MSW shear strength (Stark et al. 2010). The shearing or tilting of vertical gas wellheads, tension cracks at the slope crest, and bulging of waste near the slope toe can be indications of slope movement.

Fig. 4 shows the cumulative slope movement and settlement obtained from stability pins installed throughout Cells 4 through 7 (locations shown in Fig. 3). The northing, easting, and elevation were measured monthly to evaluate time-lapse slope movement and settlement. The change in elevation is compounded each month to determine the cumulative settlement. Surface movement is represented by vectors that show the direction and magnitude. The vector angle is computed each month from the change in northing and easting values, and the vector length is defined by the total distance travelled from the start of monitoring (September 2009). As an example, if a stability pin had been originally located at northing and easting of 400 m and 500 m, respectively, and then it moved a total of 3 m and 4 m in the positive northing and easting directions, respectively, the the cumulative distance would be 5 m and the angle would be ~325° (reference: 0° points in easting direction; angle increases counterclockwise).

In September 2010 (Fig. 4(a)) and after one year of elevated temperatures, cumulative settlement of ~4 m formed a bowl-like shape in Cell 5. Two years after the onset of elevated temperatures (Fig. 4(b)), the settlement bowl depth increased to 6 m and width expanded radially into Cell 6. From September 2011 to February 2012, settlement significantly increased to 14 m. The settlement bowl extended into Cell 7 for the first time and approached the boundary of Cells 4 and 5. Cumulative settlement in the elevated temperature epicenter continued to rapidly increase through September 2012 and 2013. Fig. 4(e) shows that ~20 m of settlement occurred in Cell 5. In the four year period, i.e., September 2009 to 2013, the average settlement rate in the "bowl" is 5 m/yr. The initial waste height in Cell 5 was 85 m and the corresponding strain is ~24%. The vertical strain is determined from the change in waste height from the initial elevation (ΔH) and initial waste thickness (H_o), i.e., strain= ($\Delta H/H_o$)x100%. During the four years of monitoring, the settlement bowl migrated into Cell 6 before advancing to Cell 7. More importantly, Fig. 4 indicates that the settlement associated with elevated temperatures did not impact Cell 4. The settlement within Cell 4 ranges between 0 and 2 m, which signifies an average rate of 0.5 m/yr.

In September 2010 (Fig. 4(a)), the vectors in Cells 4, 6, and 7 are barely visible, i.e., slope movements are less than 0.15 m. However, vectors in Cell 5 (along cross-section A-A') indicate that ~2 m of slope movement has occurred. In Cells 6 and 7 in Fig. 4(b), the vectors are still small, e.g., cumulative movements are less than 0.5 m, but it is evident that they are pointing out towards the landfill perimeter. The vector arrows in Cell 5 have increased to ~4 m, and they project in the direction of the Cell 5 slope because of the enlargement of the settlement bowl. After significant deepening of the settlement bowl by February 2012, the slope movement can be directly linked to the expansion of the settlement bowl (Fig. 4(c)). For example, the vectors projecting outward of Cell 5 are smaller in Fig. 4(c) because the epicenter of the settlement bowl has settled sufficiently to drag the surface into the "crater". The expansion of the settlement bowl into Cell 7 shows vector arrows projecting out of Cell 7, with slope movements of ~2 m. This trend continues through September 2012 and 2013. In Fig. 4(d) and 4(e), the vectors indicate that the Cell 7 slope has moved about 15 m. Thus, Fig. 4 illustrates the dual nature of slope movement. First, as the settlement bowl expands, gas and leachate pressures exert a force that thrusts the slope outward. Second, if the settlement bowl continues to deepen, the slope can reverse directions and drift backwards into the center of elevated temperature zone. This explains why the vector arrows can increase and decrease in size with time and vector angles can reverse. The comparison of slope movement and settlement in Fig. 4 indicates that the elevated temperature event starts in Cell 5 and expands into Cells 6 and 7. The settlement bowl expands into Cell 6 and the vector arrows indicate cumulative slope movements of ~4 m, but Fig. 4 shows the major thrust from elevated temperatures is primarily towards Cell 7.

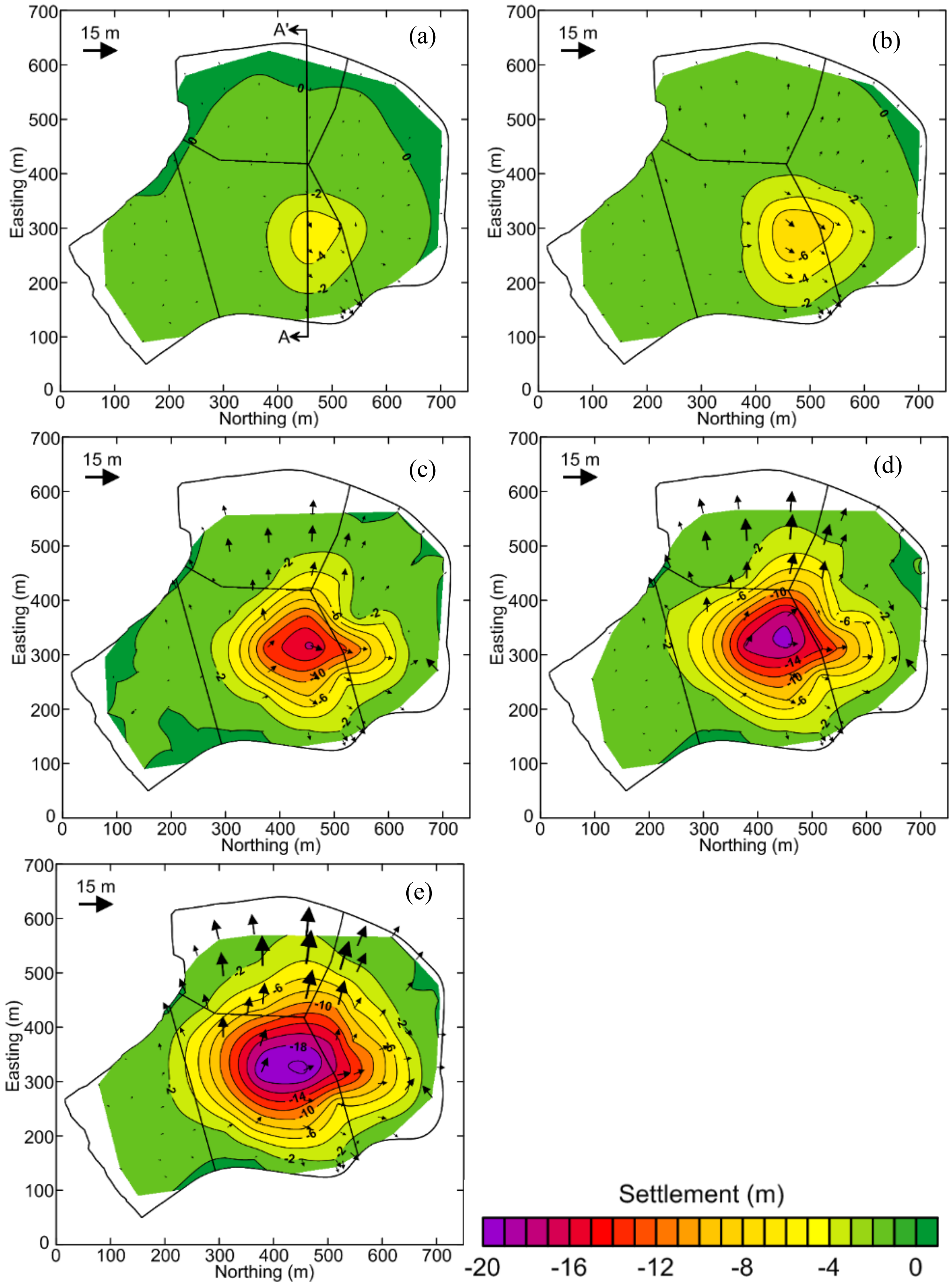

FIG 4. Spatial expansion of settlement and corresponding slope movement for: (a) September 2010, (b) September 2011, (c) February 2012, (d) September 2012, and (e) September 2013

2-D Cross-Section

Cross-section A-A' in Fig. 4(a) provides an opportunity to visualize settlement and slope movement with time. This cross-section, shown in Fig. 5, is chosen because it bisects the settlement bowl and is aligned in the direction of slope movement to and from Cells 5 and Cell 7. Similar to Fig. 4, the stability pins are used to map settlement and slope movement. The 2009 annual topographic landfill survey serves as a baseline for comparing settlements. In Fig. 4(a), the September 2010 surface and vectors indicate that settlement and slope movement was predominantly located in Cell 5. Significant settlement was observed at an Easting 450 m in February 2012, and the vector arrows in Fig. 4(b) increased from no movement in 2010 to a magnitude of 6 m in 2012. This suggests that the settlement bowl is expanding towards Cell 7. From February 2012 to September 2013, the vector arrows continue to grow (2013 slope movements ~15 m). In addition, the landfill surface had settled to an elevation of 260 m across Cell 5. In total, over 20 m of settlement had occurred by September 2013 over the deepest portion of the landfill.

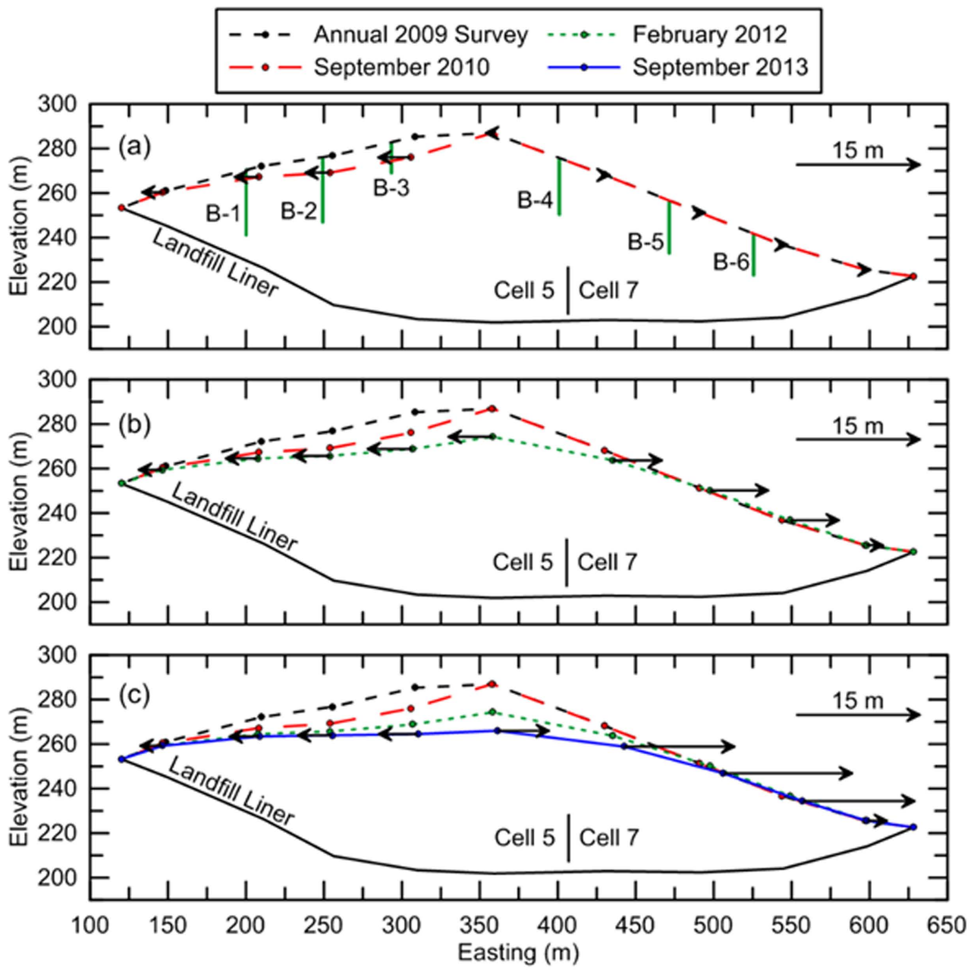

FIG 5. Settlement and slope movement for cross-section A-A' at various months: (a) September 2010, (b) February 2012, and (c) September 2013

SUMMARY AND CONCLUSIONS

Elevated temperature events can significantly impact the behavior and operation of a MSW landfill. If not addressed in an expedient manner, elevated temperatures can result in damage to the landfill infrastructure (i.e., gas extraction, leachate collection, and liner system), slope instability, and environmental conditions that adversely affect health and welfare of the local community. The following is a summary of trends and indicators for identifying the spatial movement of elevated temperatures:

1. Slope movement is preceded and accompanied by gas and leachate outbreaks. Mechanisms for slope instability include elevated gas pressures, perched leachate surfaces, and reduced MSW shear strength. For example, the interconnecting plastics and other reinforcing materials that contribute to the high shear strength of MSW are most likely consumed, degraded, burnt, and/or decomposed at elevated temperatures (see Fig. 1 showing charred waste). The shearing or tilting of vertical gas wellheads, tension cracks at the slope crest, and bulging of waste near the slope toe can be important indications of slope movement.
2. The dual nature of slope movement can involve first the development of a settlement bowl expanding because gas and leachate pressures exert a force that thrusts the slope outward. Second, if the settlement bowl continues to deepen, the slope can reverse directions and drift backwards into center of elevated temperature zone. This explains why the surface can appear to move back in toward the landfill slope.

REFERENCES

Blight, G. (2008). “Slope failures in municipal solid waste dumps and landfills: a review.” *Waste Manag Res.,* 26, 448-463.

Bogner, J., Rose, C., Vogt, M., and Gartman, D. (1988). “Understanding landfill gas generation and migration.” *Proceedings of the 11th annual international landfill gas symposium*, Houston, Texas, GRCDA, Silver Spring, MD, USA, 225-242.

Bray, J.D., Zekkos, D.P., Kavazanjian, E., Athanasopoulos, G., and Riemer, M.F. (2009). “Shear strength of municipal solid waste.” J. Geotech. Geoenvir. Engrg., ASCE, 135 (6), 709-722.

Buah, W.K., Cuncliffe, A.M., and Williams, P.T. (2007). “Characterization of products from the pyrolysis of municipal solid waste.” *Process Safety and Environmental Protection*, 85(5), 450-457.

Ettala, M., Rahkonen, P., Rossi, E., Mangs, J., and Keski-Rahkonen, O. (1996). “Landfill fires in Finland.” *Waste Management & Research*, 14, 377-384.

Frid, V., Doudkinski, D., Liskevich, G., Shafran, E., Averbakh, A., Korostishevsky, N., and Prihodko, L. (2009). “Geophysical-geochemical investigation of fire-prone landfills.” *Environ Earth Sci*., 60(4), 787-798.

Hartz, K. E., Klink, R. E., and Ham, R. K. (1982) “Temperature effects: methane generation from landfill samples.” *J. Environ. Eng. Div.*, 108(4), 629-638.

Hendron, D.M., Fernandez G., Prommer P.J., Giroud J.P., and Orozco L.F. (1999). “Investigation of the cause of the 27 September 1997 slope failure at the Doña Juana landfill.” Proceedings of Sardinia‘99—7th International waste management and landfill symposium, 4–8 October 1999, Cagliari, Italy.

Jafari, N.H., Stark, T.D., and Merry, S.M. (2013). “The 10 July 2000 Payatas landfill slope failure.” *International Journal of Geoengineering Case Histories*, 2(3), 208-228.

Jafari, N.H., Stark, T.D., and Rowe, K. (2014). “Service life of HDPE geomembranes subjected to elevated temperatures.” *Journal of Hazardous, Toxic, and Radioactive Waste*, 18(1), 16-26.

Kasali, G. B., and Senior, E. (1989). “Effect of temperature and moisture on the anaerobic digestion of refuse.” *J. Chern. Tech. Biotechnol.*, 44, 31-41.

Kavazanjian, E., Matasovic, N., Bonaparte, R., and Schmertmann, G. (1995). “Evaluation of MSW properties for seismic analysis.” ASCE Geotechnical Special Publication No. 46, Geoenvironment 2000, Vol. 2, 1126–1141.

Koelsch, F., Fricke, K., Mahler, C., and Damanhuri, E. (2005). “Stability of landfills – the Bandung dumpsite disaster.” *Sardinia 2005, 10th Int. Waste Manag. Landfill Sympm.*, Cagliari, Italy.

Lin, K.S., Wang, H.P., Liu, S.H., Chang, N.B., Huang, Y.J. and Wang, H.C. (1999). “Pyrolysis kinetics of refuse-derived fuel.” *Fuel Processing Technology*, 60(2), 103–110.

Martin, J.W., Stark, T.D., Thalhamer, T., Gerbasi-Graf, G.T., and Gortner, R.E. (2013). “Detection of aluminum waste reactions and associated waste fires.” *J. of Haz., Toxic, and Rad. Waste*, 17(3), 164-174.

Ohio EPA. (2010). “Findings and Orders.” EPA

Øygard, J. K., Måge, A., Gjengedal, E., and Svane, T. (2005). “Effect of an uncontrolled fire and the subsequent fire fight on the chemical composition of landfill leachate.” *Waste Management*, 25, 712-718.

Rampling, T.W., Hickey, T.J. (1988). “The laboratory characterization of refuse derived fuel.” *Report No LR643*, Department of Trade and Industry, HM Government, HMSO, London, UK.

Ruokojarvi, P., Ruuskanen, J., Ettala, M., Rahkonen P., and Tarhanen, J. (1995). “Formation of Polyaromatic Hydrocarbons and Polychlorinated Organic Compounds in Municipal Waste Landfill Fires.” *Chemosphere*, 31(8), 3899-3908.

Sperling, T., and Henderson, J.P. (2001). “Understanding and controlling landfill fires.” *SWANA landfill symposium*, San Diego, California.

Stark, T.D., Huvaj-Sarihan, N., and Li, G. (2009). Shear strength of municipal solid waste for stability analyses. Envir. Geology, 57(8), 1911-1923.

Stark, T.D., Akhtar, K., and Hussain, M. (2010). “Stability analyses for landfills experiencing elevated temperatures.” *Proceedings of Specialty Conference GeoFlorida 2010: Advances in Analysis, Modeling and Design*, ASCE, Orlando, FL, March, 2010, 1-8.

Stark, T.D., Martin, J.W. Gerbasi, G.T., and Thalhamer, T. (2012). “Aluminum waste reaction indicators in an MSW landfill.” *J. of Geotech. Geoenvir. Engrg.*, 138(3), 252-261.

Williams, P.T., Besler, S. (1993). “The pyrolysis of rice husks in a thermogravimetric analyzer and static bed reactor.” *Fuel*, 72, 151.

Young, A. (1992). “Application of computer modelling to landfill processes.” *DoE Rep. No. CWM 039A/92*, Dept. of Environment, London.