Measuring landfill-gas emissions from cracked and intact areas of a final soil cover without a synthetic membrane.

In the U.S., nearly half of all solid waste disposed ends up in landfills, where approximately half of the biogas emitted is methane. As a result, municipal landfills are a sustainable resource for landfill gas (LFG) because the supply of waste is renewable, despite efforts to divert waste from entering the landfill via recycling, composting, and combustion. Making an effort to collect LFG has a wealth of benefits and as population and energy prices continue to increase, the feasibility of exploiting this abundant resource becomes more practical. Throughout the U.S., landfills are signing up to participate in the U.S. Environmental Protection Agency's (EPA) Landfill Methane Outreach Program (LMOP), which aims "to reduce methane emissions by lowering barriers and promoting the development of cost-effective and environmentally beneficial landfill gas energy" (EPALMOP 2008). Capturing LFG from landfills is not only a proven method to reduce LFG emissions it is an efficient way to generate energy and revenue for an entire community. Collected gas can be used to generate electricity, used as a replacement or supplementary fuel, or can fuel service vehicles. If enough gas is generated and treated, the gas can be sold to the natural gas pipeline system. In addition, the gas is no longer released out into the atmosphere.

Before LFG can be recovered from a landfill it must be concentrated inside the landfill cell so that recovery pipes can efficiently extract the LFG. To do this, a final soil cover that acts like a cap must be placed over the entire pile of solid waste. Final soil covers not only prevent hazardous gasses from escaping they are necessary to prevent added moisture from entering the landfill cell unit. However, recent studies have shown that shrinkage of soil due to loss of moisture can cause cracking of the final soil cover resulting in a free flow of gas into the atmosphere.

There are few studies which have quantified spatial variability in LFG emissions from mixed-waste landfills with final soil covers vulnerable to cracking. Previous studies have been conducted in labs where seasons were simulated or on thin layers of cover soil in states other than Texas. This study will examine a 10 to 15 foot thick soil layer overlying a 30 acre cell at the City of Denton Landfill over a period of several seasons. The study will determine whether cracking is occurring and whether these cracks significantly influence the flow of LFG emissions into the atmosphere. This study will also contribute to the current literature, by analyzing LFG emissions from cracked and intact sections of landfill cover.

Landfill Covers

According to Texas State Law, landfill owners and operators are required to install an impermeable final cover on landfill units no longer accepting waste. The purpose of an impermeable final cover is to minimize infiltration of liquid into the solid waste pile, to prevent erosion, and promote LFG oxidation. In landfills without a gas recovery system, the U.S. EPA sets a default LFG oxidation estimation of roughly 10% in the landfill cover while the rest is emitted into the atmosphere (U.S. EPA, 1999). Landfill covers are generally comprised of a synthetic or clay barrier overlying the solid waste, which is then covered by a layer of vegetated soil. According to closure requirements for municipal solid waste landfills set by the Texas Commission on Environmental Quality (TCEQ), a final cover system must be composed of either a synthetic membrane or 18 inches of earthen material preferably a clayey soil, sandy clayey (SC) soil or a low plasticity clayey (LC) soil. A soil with high plasticity is permitted, however, since these soils are likely to crack, they must be covered by a minimum of 12 inches of topsoil. Overlying the clay/synthetic layer is a six inch erosion layer which permits the growth of vegetation (TCEQ Rule 330.457). Side slopes for the final cover may not exceed a 25% grade unless controlled drainage pathways such as flumes, diversion terraces, spillways, etc. are accepted by an executive director. A 2.0% to 6.0% grade must be constructed for the top of the landfill cover in order to prevent pooling.

Slopes

Slopes are a distinct feature of landfills. Sloping affects the mass stability of the landfill as well as how soils on the surface can resist erosion due to rainfall. The shear strength of the material used in the cover is important in the stability of the landfill. Shear strength is a measurement used to describe the strength of a material against yield or structural failure which results in shearing (Figure 1). The shear strength of the entire final cover can be determined by the internal friction and cohesion, compressibility, elasticity, permeability and capillarity of the materials used in the final cover. If the shear force applied cannot be supported by the shear strength of the slope, sliding and failure is likely to occur. This is the reason why the sloping surfaces of the landfills are covered with a vegetated soil layer. Root systems of plants increase the shear strength of the sloping surface.

If one side of the slope is less vegetated than the other, it is likely that there will be more erosion on that side. Interestingly, vegetation growth on slopes can be influenced by the direction in which the slope faces. Northern facing slopes receive more moisture and cooler temperatures, while southern facing slopes receiver more sun and higher temperatures. Therefore, northern facing slopes are likely to have more vegetation while southern facing slopes will have less. Accordingly, the direction of slope face will influence the amount of heat and moisture which will reach the surface.

Cracking

Expansion and contraction of soils depends on the size of soil particles as well as the thermal properties of the soil. The thermal properties of the soil are heat capacity, thermal conductivity and thermal diffusivity which are all dependent on water, air and/or soil particles. Soil particle size influences soil porosity, the amount of porous space between soil particles. These pores are either filled with air or water. Thermal conductivity increases with the presence of water because while dry soils conduct heat at a point by point basis, water in the soil will warm several particles of soil at the same time. When the soil surface is warmed the particles expand. Expansion does not happen evenly throughout the surface due to the differences in thermal expansion, this is called differential expansion.

Similarly, freezing temperatures alter the state of moisture inside the soil. When water stored in pores or cracks in the soil freezes the volume of the water increases, expanding the crack or pore space. This process is called frost wedging. When temperatures warm up the ice melts and cracks are left behind, exposing the area to further weathering.

When soils are exposed to repeated wetting and drying cycles their tendency to shrink and swell results in cracking. It is common to observe more cracks in soils with a high amount of fine soil particles. Soil particle size influences soil porosity, the amount of porous space between soil particles. Porous space in the soil stores water. A soil is able to bend freely when water is present, this is called soil plasticity. Soils with a high percentage of fine soil particles and clay tend to have a high plasticity index, silts which are very fine, have low plasticity index. A plasticity index is the range of soil moisture content which allows the soil to exhibit plastic properties. A high plasticity index implies that the soil has a greater range in which the soil can be in a plastic like state. If the moisture content of the soil is above the plasticity index, then the soil will exhibit a liquid state. If the moisture content of the soil is below the plasticity index, then the soil will be hard and eventually reach the shrinkage limit. Soils with high plasticity index, such as clay, are more prone to shrinkage strains during drying. When water from the soil is evaporated, the soil dries creating suction which increases the effective stress of the soil, which in turn decreases the volume of the soil and cracks begin to develop.

Emissions

Cracks in the soil cover not only allow water to percolate down into the waste pile, they also influence the flow of LFG from the landfill cover into the atmosphere. LFG emissions and oxidation both depend on the physical condition of the overlying landfill cover. When pathways are created for gas to escape from the soil, oxidation time within the soil is reduced. LFG oxidation occurs when bacteria within the soil consume the gas and react it with oxygen. When methane gas comes into contact with oxygen the product is carbon dioxide (CO_2) and water ($2H_2O$).

When the porous space between soil particles is occupied by water, pathways for gasses decrease and promote LFG oxidation within the soil. According to Spokas et al. (2003), a soil moisture content of 15% to 30% is optimal for methane oxidation within the soil. Tecle et al. (2008) studied LFG emissions, soil temperature and soil moisture content at an inactive landfill in Kansas City, Missouri. Spatial analysis of moisture content and LFG emissions showed a strong spatial correlation indicating that when the soil was occupied by water, LFG emissions decreased. When soil moisture content is above 40% or below 10%, methane oxidation in the soil decreases. Figure 2 (Tecle et al. 2008, 1140) represents the map showing spatial variability created using the kriging method.

The study conducted by Tecle et al. (2008) also found that soil temperature and methane emission had a strong positive correlation. According to Tecle et al. (2008), methane oxidation in the soil reaches the maximum between 25° to 30° Celsius (77° to 86° Fahrenheit). The study did not observe cracks in the soil as a result of temperature, but made an important conclusion that soil temperature is a "major controlling factor for methane emission" (Tecle et al. 2008, 1142).

Site Description

This study will observe the cover soil of a 30 acre inactive municipal solid waste landfill unit at the City of Denton Landfill. The unit was constructed without a bottom liner and began accepting solid waste in 1984, and stopped receiving waste in 1999. Closure requirements for solid waste units without a bottom liner that receive waste after October 9, 1993 require a clay-rich soil cover layer consisting of a minimum of 18 inches of earthen material with a permeability less than or equal to the permeability of the constructed bottom liner (TCEQ Rule 330.457). The 30 acre unit is covered by 3 feet of clay as well as 10 to 15 feet of overburden soil. The height of the unit is approximately 40 feet above ground surface. Vertical pipes have been inserted through the final soil cover into the solid waste pile.

A Tier 2 NMOC (non-methane organic compound) Emissions Rate test conducted on August 18, 2008 revealed a total emissions rate of 20.9 megagrams per year (Mg/yr) from the entire landfill facility. The threshold for calculated NMOC emissions per NSPS/EG regulations is 50 Mg/yr. The estimated date at which the landfill expects to exceed this amount is 2017. LFG recovery was initiated early simply because LFG was being produced but was not being used.

In 2006, LMOP recognized the City of Denton's Biodiesel Production Facility as "Project of the Year" for its use of LFG as an alternative fuel source for vehicles. As of December 2008, the City of Denton Landfill in partnership with DTE Biomass Energy (DTEBE) will capture

LFG and provide Denton Municipal Electric (DME) with enough energy to supply nearly 1,600 households with electricity (Pegasus News 2008).

The final cover soil has been in place for the last 10 years, weathering severe drought and heavy rain. It is possible that cycles of severe drought, heavy rains, and freezing temperatures have at some point eroded or cracked the surface to some degree. While the final soil cover overlying the inactive landfill unit at the City of Denton Landfill is very thick, it is not immune to some degree cracking. Research conducted at the landfill will determine whether cracking has occurred or is occurring and whether these cracks are flawing the LFG recovery system. This research will either support the effectiveness of the 10 to 15 foot of soil that overlies the final clay cover or encourage renovation of the current design.

Methodology

Before selecting the sampling areas, the final cover will be observed and plotted using a Global Positioning System (GPS) device. The plotted points will then be interpolated in order to create a Digital Elevation Model (DEM) for the entire landfill surface. By using a DEM, slope of the terrain as well as the direction of the slope can be determined (Figure 3). This will supply needed slope information which can then be used to select sampling sites based on the percentage of the slope. Instead of randomly selecting sites throughout the landfill cover without regard to percentage of slope, sites will be selected based on percentage of slope. This is because slope is a major factor testing the strength of the soil. Landfill cover slopes are required by law not to exceed 25%, therefore, sites will be chosen from 3%, 6%, 9%, 12%, 15%, 18% , 21% and 24+% (if present) sloped areas. Sampling sites will be chosen randomly from sites with these slope percentages.

In order to gather data for the cracked areas of the landfill, the final soil cover will be examined thoroughly in order to find cracked areas of the cover. Each crack observed will be investigated and photographed. A ruler will be used to measure the length, width, number of crack segments and intersections and depth of the cracks. It is possible that very few cracks will be found, therefore, every cracked area will be used as a sampling site. The goal of this study is to measure as many cracked areas as possible. Coordinates for cracked and intact areas will be recorded and used to create a map that illustrates the spatial variability of cracks in the cover.

In order to fully understand the physical condition of the final soil cover it is important to determine the type of soil being utilized. First of all, the TCEQ demands that the soil cover must be classified as defined by the Unified Soils Classification System (USCS). The classification will lend an understanding to the soil's permeability and potential to crack and/or self-heal. Figure 4 (Acipco International 2008) is located in the appendixes and illustrates the American Society for Testing and Materials (ASTM) standard soil classification chart. Understanding the type of soil will enable our understanding of how this particular soil will react to environmental conditions such as drought and heavy rain. While a degree of cracking is expected from all soil types, soil with higher fines content will likely have a greater extent of cracking. An approximately 1 lb soil sample will be taken from each sample area and put through a sieve analysis. Grain size, uniformity coefficient, and coefficient of gradation will all be determined using the sieve analysis.

In order to quantitatively observe the effect that environmental conditions have on the final cover, soil moisture content and soil temperature must be measured. Shrinking and swelling, expansion and contraction are caused by both the moisture content of the soil as well as the temperature, and can cause cracks in a variety of different soil. During each site reconnaissance soil temperatures will be measured using soil thermometer inserted at a depth of 6 inches. Soil moisture content will be measured using a Time Domain Reflectometer (TDR), which consists of probes that receive and emit electromagnetic waves and measure the travel time of waves through a porous medium. TDR is a common method for measuring soil moisture content and electrical conductivity. A TDR system consists of a TDR100 Reflectometer which "generates an electromagnetic pulse that is applied to a coaxial system which includes a TDR probe for soil water measurements and (2) samples and digitizes the resulting reflection waveform for analysis of storage" (Campbell Scientific).

Finally, LFG emissions will be measured using surface flux chambers. Figure 5 (Hartman 2003, 15) is an illustration of a surface flux chamber. Surface flux chambers are the best tool for this research because they have been used in studies similar to this study (Abichou et al. 2006; Chiemchaisri et al. 2007; and Spokas et al. 2005) Surface flux chambers are simple and cost effective which enables the use of multiple chambers for longer periods of time in order to obtain an accurate analysis of a sample area and allowing better coverage of the site (Hartman 2001, 16). Collecting data from the flux chambers may become skewed if measurements are not taken at the most optimal times. Measuring should be avoided during periods of extremely high or low barometric pressure. Cziepel et al. (2003) has shown that a barometric pressure decrease of 10 millibars can cause a tripling of methane emissions. Since wet soil also influences the flow of emissions, measurements should not be taken within seven (7) days of rain (Hartman 2001, 18). Finally, for locations with extreme seasonal temperature variations, measuring flux at the same location over a period of several seasons is more appropriate.

Analysis

With the data collected from cracked and intact areas of the landfill cover, two (2) multiple regression analysis will be applied to the data in order to determine whether the dependent variable ((test a.) emissions and (test b.) cracks) can be predicted by the dependent variables ((test a.) cracks, temperature, soil moisture content, slope (percentage and direction), percentage of fines and (test b.) temperature, soil moisture content, slope (percentage and direction), and percentage of fines). From the multiple regression analysis we will be able to determine the correlation, percentage of the variation in (test a.) emissions and (test b.) cracks that can be explained by each of the independent variables, and the significance of each explanation. An Independent T-test will be used to test the difference between the emissions measured from the cracked and intact areas of the final soil cover as well as temperature, soil moisture content and cracking from the north and south facing slopes. A Levene's test will test the null hypothesis which assumes that the variances in emissions from cracked and intact areas and temperature, soil moisture content, and cracking from the north and south facing slopes are equal. If the Levene's test is significant at $p \leq .05$, the null hypothesis will be incorrect and the variances between these sampled areas are significantly different.

Along with the DEM, other maps will be created based on the data collected using Geographic Information Systems (GIS). These maps will include soil temperature maps, soil moisture content maps, and maps showing the location of cracks. By conducting this research over a one year period, the weathering of sites located on the north and south slopes can be compared. The statistical and spatial results of cracked areas will be compared to the results of intact areas over a span of several seasons.

Conclusion

Solid waste has the potential to release gasses even 20 years after it was dumped into the landfill and the estimated amount of LFG released per day is approximately two million cubic feet (approximately 15 U.S. gallons). The State Energy Conservation office has estimated "If the 70 largest landfills in Texas were fully developed for energy production, about 40 billion cubic feet of methane could be put to use generating nearly 200 MW of electricity" (Energy Report, 251). That is nearly 299, 220, 779, 220 gallons of methane that would otherwise be flared or emitted into the atmosphere from Texas alone. Controlling the migration and emission of LFG and protecting the surrounding environment is a worthy endeavor for environmentalist and those interested in alternative sources of energy. With improved cover designs and efficient LFG recovery systems the Texas economy can reap treasure from trash.

Landfills in the North Texas area are increasingly vulnerable to cracking due to the variability of the seasons. Previous studies have shown that soil used as landfill covers are likely to crack after the first wet and dry cycle. While previous studies have observed cracking in thin layers of cover soil (up to 3 feet thick), no studies have been conducted on a layer of soil 10 to 15 feet thick. Other studies have simulated weather and soil thickness in labs in order to model one aspect of a system that is extremely dynamic. What these studies lack is real-time unpredictability of weather and interaction of variables at a macro scale. There are several aspects of this problem which cannot be studied in a lab. The sloping topography of the landfill cover and its shear size and design as well as the underlying processes which create LFG cannot be studied in a lab. While wet and dry, heating and cooling can be simulated through the use of percolators or heating lamps, the unpredictable nature of weather does not consider plasticity index of soil or percentage or direction of slope or even vegetation.

An analysis of this cover design will either find that emissions from cracked and intact areas of the cover are equal or significantly different, and determine what percent of variables such as degree and direction of slope, moisture content, percent of fines and temperature contribute to cracking in the cover soil. The results will decide the effectiveness of the 10 to 15 feet of cover soil and either encourage renovation or promote this design to other landfills with clay covers/liners.

Figures

FIGURE 14-3 A slope's shear strength depends on the slope material's strength and cohesiveness, the amount of internal friction between grains, and any external support of the slope. These factors promote slope stability. The force of gravity operates vertically but has a component acting parallel to the slope. When this force, which promotes instability, exceeds a slope's shear strength, slope failure occurs.

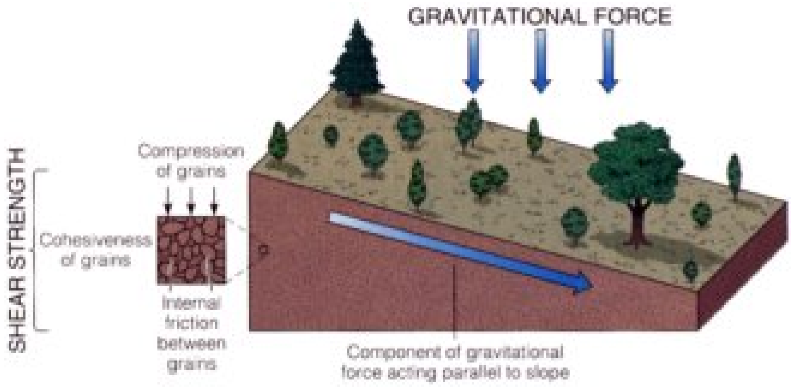


Figure 1: Shear strength of slope.

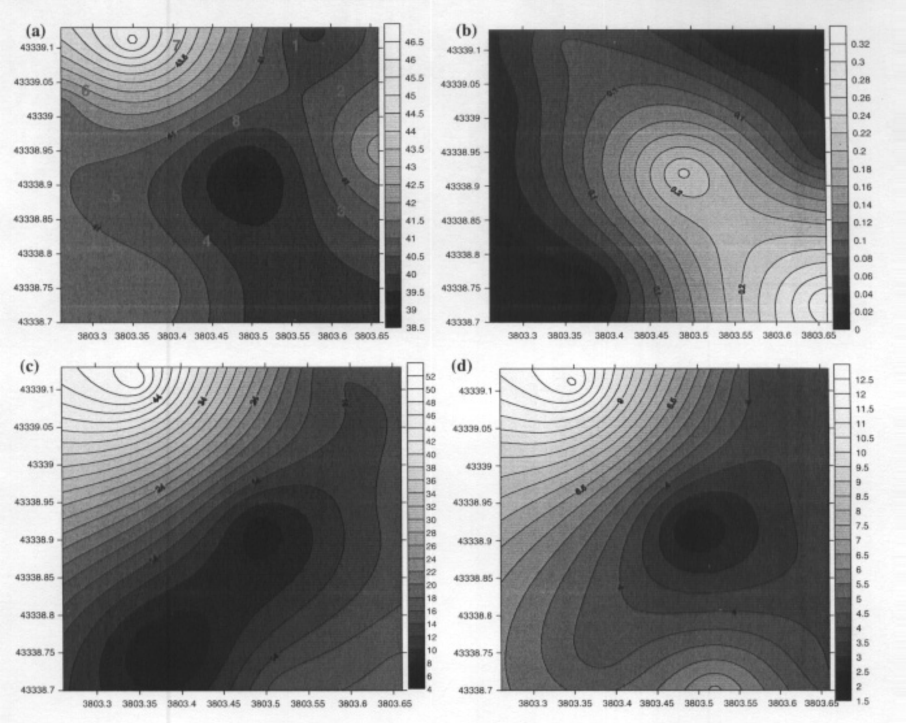


Fig. 3 Spatial maps of variability of; **a** volumetric moisture content, **b** volumetric methane, **c** uniformity coefficient, C_u, and **d** percentage of fines. *Note*: percentage of fines is plotted against UTM Geographic coordinates of Easting and Northing on the *X*-axis and *Y*-axis, respectively. Monitoring station locations are indicated by the numbers from 1 through 8 in Fig. 3a

Figure 2 (Tecle et al. 2008, 1142): created using the kriging method in order to represent the spatial variability of volumetric moisture content (a), volumetric methane (b), uniformity coefficient (c),and percentage of fines (d). The monitoring station locations are also labeled (a).

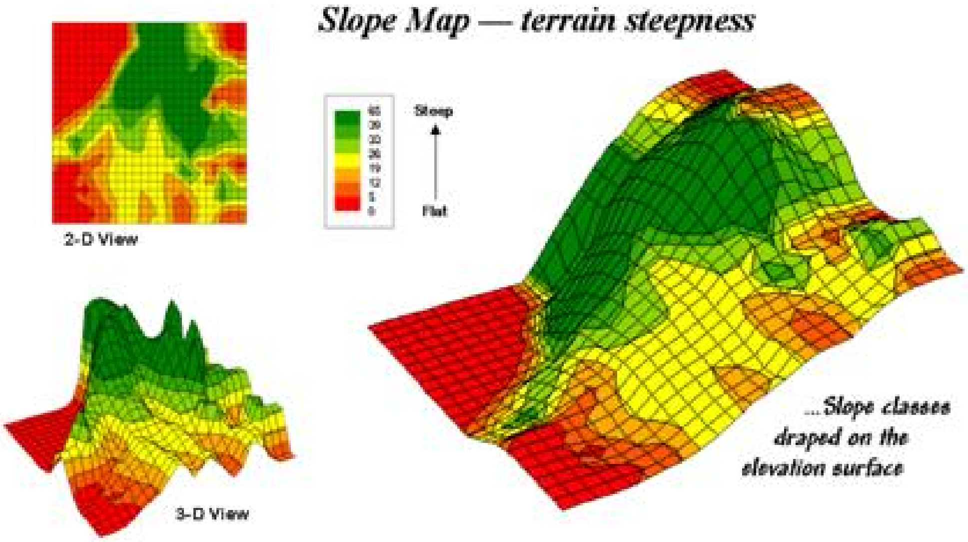
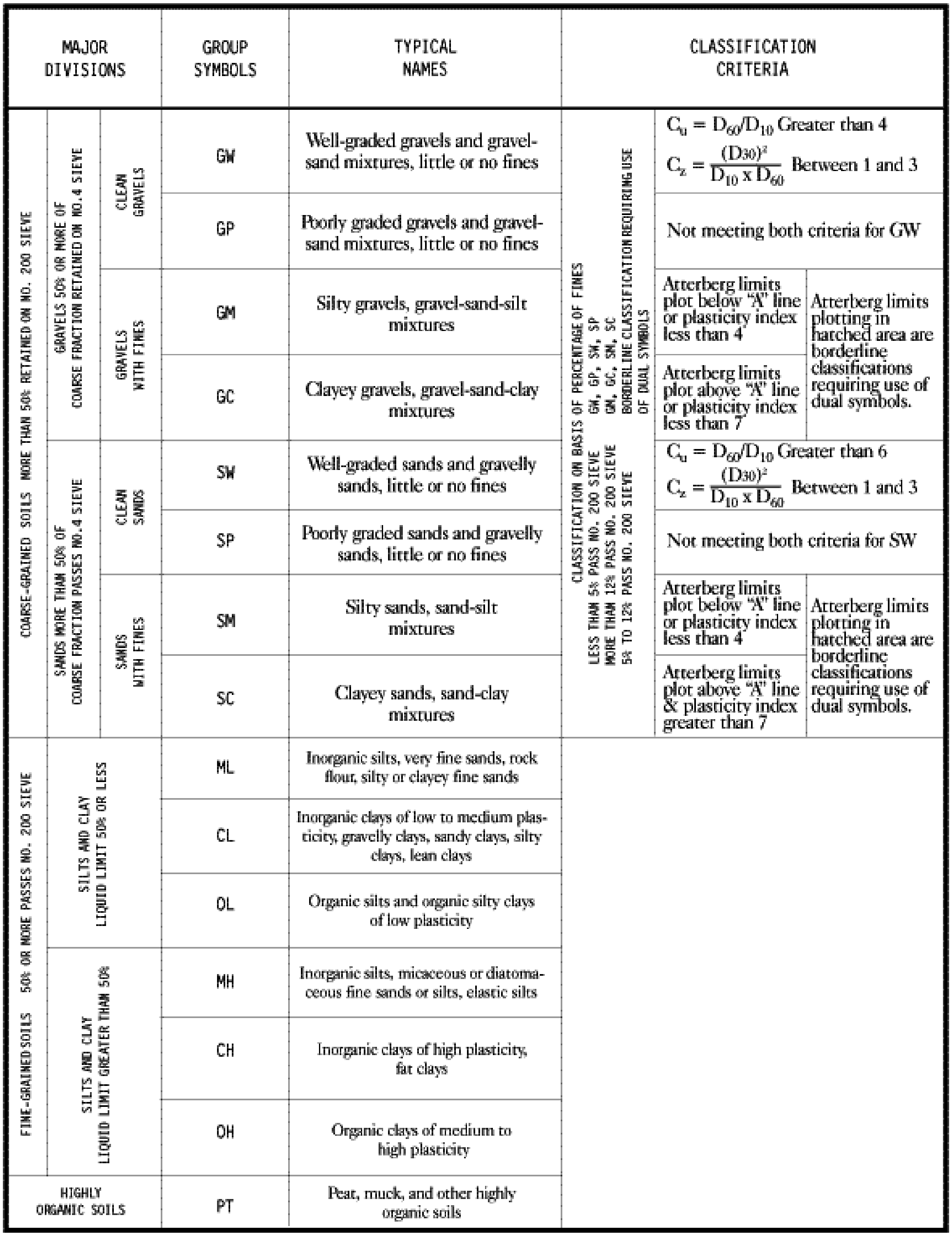


Figure 3: Digital elevation model illustrating terrain steepness.



MAJOR DIVISIONS			GROUP SYMBOLS	TYPICAL NAMES	CLASSIFICATION CRITERIA		
COARSE-GRAINED SOILS MORE THAN 50% RETAINED ON NO. 200 SIEVE	GRAVELS 50% OR MORE OF COARSE FRACTION RETAINED ON NO.4 SIEVE	CLEAN GRAVELS	GW	Well-graded gravels and gravel-sand mixtures, little or no fines	CLASSIFICATION ON BASIS OF PERCENTAGE OF FINES LESS THAN 5% PASS NO. 200 SIEVE GW, GP, SW, SP MORE THAN 12% PASS NO. 200 SIEVE GM, GC, SM, SC 5% TO 12% PASS NO. 200 SIEVE BORDERLINE CLASSIFICATION REQUIRING USE OF DUAL SYMBOLS	$C_u = D_{60}/D_{10}$ Greater than 4 $C_z = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ Between 1 and 3	
			GP	Poorly graded gravels and gravel-sand mixtures, little or no fines		Not meeting both criteria for GW	
		GRAVELS WITH FINES	GM	Silty gravels, gravel-sand-silt mixtures		Atterberg limits plot below "A" line or plasticity index less than 4	Atterberg limits plotting in hatched area are borderline classifications requiring use of dual symbols.
			GC	Clayey gravels, gravel-sand-clay mixtures		Atterberg limits plot above "A" line or plasticity index less than 7	
	SANDS MORE THAN 50% OF COARSE FRACTION PASSES NO.4 SIEVE	CLEAN SANDS	SW	Well-graded sands and gravelly sands, little or no fines		$C_u = D_{60}/D_{10}$ Greater than 6 $C_z = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ Between 1 and 3	
			SP	Poorly graded sands and gravelly sands, little or no fines		Not meeting both criteria for SW	
		SANDS WITH FINES	SM	Silty sands, sand-silt mixtures		Atterberg limits plot below "A" line or plasticity index less than 4	Atterberg limits plotting in hatched area are borderline classifications requiring use of dual symbols.
			SC	Clayey sands, sand-clay mixtures		Atterberg limits plot above "A" line & plasticity index greater than 7	
FINE-GRAINED SOILS 50% OR MORE PASSES NO. 200 SIEVE	SILTS AND CLAY LIQUID LIMIT 50% OR LESS		ML	Inorganic silts, very fine sands, rock flour, silty or clayey fine sands			
			CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays			
			OL	Organic silts and organic silty clays of low plasticity			
	SILTS AND CLAY LIQUID LIMIT GREATER THAN 50%		MH	Inorganic silts, micaceous or diatomaceous fine sands or silts, elastic silts			
			CH	Inorganic clays of high plasticity, fat clays			
			OH	Organic clays of medium to high plasticity			
HIGHLY ORGANIC SOILS			PT	Peat, muck, and other highly organic soils			

Figure 4: illustrates the ASTM standard soil classification chart.

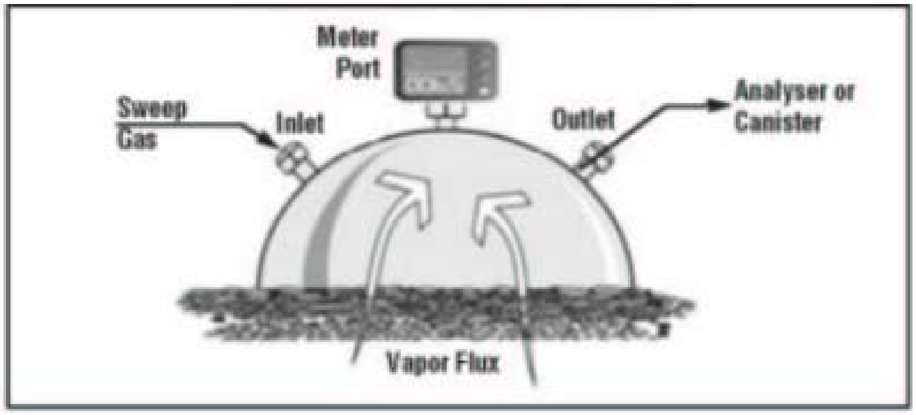


Figure 5 (Hartman 2003, 15): is an illustration of a surface flux chamber was provided in LUSTLine Bulletin.

Works Cited:

Abichou, Tarek J., D. Powelson, J. Chanton, S. Excoriaza, and J. Stern. 2006. Characterization of methane flux and oxidation at a solid waste landfill. *Journal of Environmental Engineering* 132: 220-228.

Abicou, Tarek, J. Chanton, D. Powelson, J. Fleiger, S. Escoriaza, Y. Lei, and J. Stern. 2005. Methane flux and oxidation at two types of intermediate landfill covers. *Waste Management* 26: 1305-1312.

Albrecht, Brian A., and C. H. Benson. 2001. Effect of desiccation on compacted natural clays. *Journal of Geotechnical and Geoenvironmental Engineering* January: 67-75.

Albright, William H., C. H. Benson, G. W. Gee, T. Abichou, E. V. McDonald, S.W. Tyler, and S. A. Rock. 2006. Field performance of a compacted clay landfill final cover at a humid site. *Journal of Geotechnical and Geoenvironmental Engineering* 132: 1393-1403.

American Society of Agronomy. 2009. Landfill Cover Soil Methane Oxidation Underestimated. *ScienceDaily*. http://www.sciencedaily.com/releases/2009/04/090427121637.htm (last accessed 9 May 2009)

Bogner, J.E., K.A. Spokas, and E.A. Burton. 1997. Kinetics of methane oxidation in a landfill cover soil: Temporal variations, a whole-landfill oxidation experiment, and modeling of net CH4 emissions. *Environmental Science and Technology* 31: 2504-2514.

Campbell Scientific, Inc.. Time domain reflectometry: TDR100 reflectometer-based system. 2008. ftp://ftp.campbellsci.com/pub/csl/outgoing/uk/leaflets/tdr100_csi_1-08.pdf. (last accessed 29 March 2009)

Chiemchaisri, C., W. Chiemchaisri, S. Kumar, and J.P.A. Hettiaratchi. 2007. Solid waste characteristics and their relationship to gas production in tropical landfill. *Environmental Monitor Assessment* 135: 41-48.

Chok, Y.H., W.S. Kaggwa, M.B. Jaksa, and D.V. Griffiths. Modeling the effects of vegetation on stability of slopes. Paper presented at 9th Australia New Zealand Conference on Geomechanics, Auckland. http://www.ecms.adelaide.edu.au/civeng/staff/pdf/9ANZ_04_Chok.pdf (last accessed 9 May 2009)

Czepiel, P.M., J.H. Shorter, B. Mosher, E. Allwine, J. B. McManus, R. C. Harriss, C. E. Kolb, and B. K. Lamb. 2003. The influence of atmospheric pressure on landfill methane emissions. *Waste Management* 23, (7): 593-598.

Dec, D. and R. Horn. *Effect of differentiation of soil bulk density due to different tillage systems on thermal soil properties.* http://www.bodenkunde2.uni-freiburg.de/eurosoil/abstracts/id253_Dec_full.pdf (last accessed 9 May 2009)

Denton begins innovative project to transform methane gas from landfill into useable energy. 2009. *Pegasus News Wire* http://www.pegasusnews.com/news/2008/dec/26/denton-energy/. (last accessed 26 December 2008)

Dobson, Kevin. February 2009. *The climate action reserve: Landfill project submittal form.* https://thereserve1.apx.com/mymodule/reg/TabDocuments.asp?r=111&ad=Prpt&act=update&type=PRO&aProj=pub&tablename=doc&id1=434 (last accessed 8 May 2009)

Eigenbrod, K. D. 2003. Self-healing in fractured fine-grained soils. *Canadian Geotechnical Journal* 40: 435-449.

El-Fadel, Mutasem, A. N. Findikakis, and J. O. Leckie. 1996. Estimating and enhancing methane yield from municipal solid waste. *Hazardous Waste & Hazardous Materials* 13: 309.

Energy Information Administration. 2009. http://tonto.eia.doe.gov/state/state_energy_profiles.cfm?sid=TX#related_reports. (last accessed 9 May 2009)

Environmental Protection Agency. 1999. Landfills. *U.S. Methane Emissions 1990–2020: Inventories, Projections, and Opportunities for Reductions*. http://www.epa.gov/methane/reports/02-landfills.pdf. (last accessed 4 May 2009)

Environmental Protection Agency. 2009. Landfill methane outreach program. http://www.epa.gov/lmop/index.htm. (last accessed 16 February 2009)

Field, Andy. 2005. *Discovering statistics using SPSS: (and sex, drugs, and rock 'n' roll).* London: Sage Publications.

Fogel, Mike. City of Denton Landfill. 26 February 2009.

Haahr, Mads. Random.org. 2009. http://www.random.org/ (last accessed 5 April 2009)

Hartman, Blayne. 2003. How to collect reliable soil-gas data from upward risk assessments. Part 2: Surface flux-chamber method. *LUSTLine Bulletin* 44, http://iavi.rti.org/attachments/Resources/Lustline44-chambers_final.pdf. (last accessed 5 April 2009).

Huang, R. and L. Wu. 2007. Stability analysis of unsaturated expansive soil slope. *Earth Science Fronties* 14, (6): 129-133.

Mallwitz, K. *Self-healing properties of clayey soils.* Department of Civil Engineering, Neubrandenburg University of Applied Sciences. Neubrandenburg, Germany.

National Drought Mitigation Center. 2009. U.S. drought monitor. http://drought.unl.edu/dm/index.html (last accessed 5 April 2009)

North Central Texas Council of Governments - SEE Less Trash Program. North Central Texas solid waste facilities - Denton landfill. http://www.nctcog.org/envir/SEELT/disposal/facilities/landfill_details.asp?FacMap_ID=5027#**.** (last accessed 1 April 2009)

Rayhani, M.H.T., E.K. Yanful, and A. Fakher. 2007. Physical modeling of desiccation cracking in plastic soils. *Environmental Geology* 97: 25-31.

Roberts, E. M. 2002. Bioreactor landfill cell feasibility study - Reference to City of Denton Subtitle-D permit #1590A landfill. Master of Science. University of North Texas.

Sadek, S., S. Ghanimeh, and M. El-Fadel. 2006. Predicted performance of clay-barrier landfill covers in arid and semi-arid environments. *Waste Management* 27: 572-583.

Scharff, Heijo, and Joeri Jacobs. 2006. Applying guidance for methane emission estimation for landfills. *Waste Management* 26: 417-429.

Spokas, K., C. Graff, M. Morcet, and C. Aran. 2003. Implications of the spatial variability of landfill emission rates on geospatial analyses. *Waste Management* 23: 599-607.

Spokas, K., J. Bogner, J. P. Chanton, M. Morcet, C. Aran, C. Graff, Y. M. Govan, and I. Hebe. 2005. Methane mass balance at three landfill sites: What is the efficiency of capture by gas collection systems?.*Waste Management* 26: 516-525.

Tang, Chaosheng, B. Shi, C. Liu, L. Zhao, and B. Wang. 2008. Influencing factors of geometrical structure of surface shrinkage cracks in clayey soils. *Engineering Geology* 101: 204-217.

Tecle, Dawit, L. Lee, and S. Hasan. 2009. Quantitative analysis of physical and geotechnical factors affecting methane emission in municipal solid waste landfill. *Environmental Geology* 56: 1135-1143.

Texas Commission on Environmental Quality. 2006. *Title 30: Environmental quality; Part 1: Texas commission on environmental quality; Chapter 330: Municipal solid waste; Subchapter K: Closure and Post-Closure.* http://info.sos.state.tx.us/pls/pub/readtac$ext.ViewTAC?tac_view=5&ti=30&pt=1&ch=330&sch=K&rl=Y (last accessed 8 April 2009)

Themelis, Nickolas J., and Priscilla A. Ulloa. 2007. Methane generation in landfills. *Renewable Energy* 32: 1243-1257.

Villar, M.V., and A. Lloret. 2003. Influence of temperature on the hydro-mechanical behavior of a compacted Bentonite. *Applied Clay Science* 26: 337-350.

Westlake, Kenneth. 1995. *Landfill waste pollution and control*. Chichester, England: Albion Publishing Limited.

Yesiller, N., C.J. Miller, G. Inci, and K. Yaldo. 2000. Desiccation and cracking behavior of three compacted landfill liner soils. *Engineering Geology* 57: 105-121.

Yoon, Joon Sik, S. Moon, J. Young Kim, K. Nam, and M. Chung. 2003. Mass transport of organic contaminants through a self-sealing/self-healing mineral landfill liner. *J Mater Cycles Waste Management* 5: 130-136.