SANITARY LANDFILL MINING – OPERATIONAL INTERIM SLOPE STABILITY ASPECTS

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SUMMARY: During landfill mining operations where the existing cap system is removed and the waste mass is exposed, there is a great concern that excessive infiltration into the waste mass may result especially during rainy seasons where the waste surface is very pervious and does not drain easily. This problem can get worse if the surface run-on and run-off control systems are not in-place or effective. The excess infiltration will find its path of least resistence, moving down by gravity force to the bottom of the lanafill. This will increase the liquid level above the bottom liner system, causing the heads on liner to increase. Conversely, if the infiltration is resisted by presence of layer(s) of relatively low permeable daily cover soils within the landfill, the excess liquid will accumulate on top of these layers causing a perched liquid level above the daily cover soil layers and seeping out at the side slopes. These increased liquid level(s) can result in excessive pore water pressure build-up within the waste mass and thus effectively reducing its shear strength and resulting in slope instability. A slope stability model was developed for this parametric study to evaluate the effect fo this liquid level on the factor of safety, at various typical operational slope angles under consideration. Typical landfill mining operational interim slopes used in the analysis vary between 1(V):2.5(H) and 1(V):3.5(H). The landfill heights considered are at 6 m, 15 m, 24 m, and 37 m. And the liquid levels assumed in the analysis are at 0.0 m, 0.7 m, and 1.5 m, measured above the bottom liner system. The goal of this parametric analysis is to identify any potential instability issues during operations. Visual graphical charts were developed and presented in the paper aiming for the landfill operators to identify any slope configuration with potential instability during waste slope excavation activities at each known liquid level. These charts may also be applicable to approximate the factor of safety of any waste slope excavation with known height and slope angle and with similar shear strength properties assumed, for reasons other than landfill mining projects. The analytical results presented indicate that FS above 1.5 will be achieved for the all slopes modeled provided leachate head levels are less than 0.7 m above the liner. The FS values drop below 1.5 when the liquid level above the liner is at a range of 0.7 to 1.5 m and the waste height is less than 15 m. It is thus concluded that the graphical presentation in this paper can be untilized as an important safety guide for the landfill site manager or operator who may be excavating through waste mass and resulting with a steep and exposed waste slope.

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1. INTRODUCTION

The concept of designing a sustainable sanitary landfill that reuses the existing landfill footprint has gained much attention in recent years. In an article published in the June 2013 MSW Maneagement magazine written by the former chief executive officer of the Delaware Solid Waste Authority and a member of MSW Management's Editior Advisory Board, N.C. Vasuki, he mentions that landfill mining and extraction of select materials is one feasible option and also may be it is time that it would be in our best national interest to seriously consider old landfills as potential mines for recovering enormous quantities of plastics and metals in the United States of America.

One of the earliest documented dump mining in the USA was in Collier County, Florida where about 111,000 m^3 of waste was excavataed from 2-hectare cells between 1986 and 1992. There was no reported issue with the excavated waste slope since the waste depth is only 5.5 m and there was no reported perched leachate level within hte waste mass during excavation. The most recent large-scale waste excavation and relocation project was at the New Doha International Airport in Qatar in 2006 during the construction of the airport project. There were a total of 6,000,000 m^3 of uncomtrolled rubbish removed from the airport site and relocated to a new engineered landfill.

The sustainable landfill consists of multiple cell phasing and development, partial cell closing, landfill gas capturing, landfill mining, waste material sieving and sorting, and reusing of landfill footprint in phases of developement. Landfill mining is a way to reclaim a contaminated old dump or to empty a partially closed cell and thus it becomes an important process of a viable sustainable landfill practice. During landfill mining, many steep slopes will result from waste excavation and relocation.

As the waste mass is exposed, infiltration to the waste mass will increase during seasonal heavy rainfall event(s) where there is no cap system to control excessive infiltration into the waste mass. The liquid level within the landfill may raise to a level that may trigger a slope instability condition. In addition, in order to accelerate the waste decomposition, leachate or liquid may be recirculated or bioreactor procedure may be implemented, causing moisture content within the waste mass to reach approximately 40 percent. At this amount of moisture content within the waste, waste shear strength may be reduced and pore water pressure may be build up to a point where slope stability of the landfill may become a serious concern. Because of this concern, in this paper, a parametric slope stability analysis will be conducted to evaluate the effect of liquid levels on the factor of safety within the waste mass at typical operational landfill slopes.

2. BACKGROUND

2.1 Landfill Mining

Landfill mining is often thought of as one of remediation technologies to remove or relocate existing waste mass from either an old dump or a sanitary landfill. It is applicable to sites:

- That has limited airspace
- That require installation or repair of liner
- That has waste sufficiently degraded
- That contains high-value recycled materials
- That is in high-density areas where the site is being considered for redevelopment

Landfill mining removes and reclaims primarily inorganic materials that have a market value that justifies the expense of the mining operation. As a side benefit, landfill mining removes a certain percentage of used landfill volume, freeing up more air space. Its effects are therefore similar to that of an extreme compaction effort. The primary goal of landfill mining is the extraction of valuable metals, though other recyclables, combustible materials, and soils can also be excavated for reuse.

Designers and regulators often express concern that exposing waste mass during landfill mining will introduce surface water or other run-on liquids into the waste mass and ultimately will enhance the degradation of the waste and reduce the stability of the waste mass. Although the introduction of liquids has several potentially destabilizing effects, they can be mitigated through sound design, construction, and operating practices. This paper reviews few of the key factors that would affect the landfill mining interim landfill slope stability. Based on the information presented in this paper, landfill mining can be conducted safely for a site when a site-specific slope stability chart is developed and used to estimate safe slope angle and waste height during landfill mining operations.

2.2 Liquid Levels

When leachate or other liquids are introduced into the waste mass through surface infiltration or liquid recirculation to enhance waste decomposition, it results in increased moisture content. There are two stability-related technical issues that must be considered to address the introduction of liquids: (1) the impact of the presence of liquids; and (2) the impact of the accelerated degradation of the waste. To understand the impact of the presence of liquids, one must understand the migration of liquids within the landfill. The migration of introduced liquids into relatively non-homogeneous waste is often thought to result in random (and uncontrolled) migration of liquids through preferential flowpaths in the waste. Detailed analyses and field observations indicate that this is not the case. Actually, liquids first are absorbed by the waste until the waste reaches its field capacity and then migrate along the path of least resistance, which is predominantly downward through the waste but with a lateral component if lower permeability layers (e.g., daily cover) are present.

2.3 Slope Stability Overview

When performing a slope stability analysisin landfill waste excavation environment, three issues must be considered especially when liquid is introduced to the waste: (1) increased weight of the waste compared to the "dry" waste; (2) the possibility of perched liquids, causing a localized pore-water pressure build-up; and (3) liquid migration along an impervious layer and breaking out on the face of the slope. The increase in the pore-water pressure can contribute to instability and increasing the potential for sideslope seepage and uncontrolled gas migration. The primary defense against these effects is monitoring of the landfill to confirm that liquids are not building up in the landfill at levels that would cause excessive pore pressures.

2.4 Key Factors Affecting Factor of Safety

The key elements of the stability analysis, and considerations that should be made specific to landfill mining stability are listed as follow:

- Selection of Critical Cross Sections: This involves identifying the sections that have the lowest calculated factor of safety.
- Foundation Conditions: The location and extent of each type of material beneath the ground surface that could affect the stability analysis needs to be identified. In addition, the presence of geosynthetic interfaces must be considered, as geosynthetic interfaces are continuous

interfaces that usually are weaker than other soil materials. It is common to perform circular and non-circular analyses along the most critical interface and through the waste mass itself.

- Unit weight and shear Strength: The selected values of unit weight and shear strength of waste and soils are critical to the calculated factor of safety because stabilizing forces are primarily a function of material shear strength.
- Phreatic surfaces: Although the shear strength parameters of solid waste may be unchanged by the presence of liquids, addition of liquids could raise the phreatic surface, which could decrease the effective normal stress and decrease the shear resistance of the waste. Therefore, consideration of the liquid level within the waste is critical.
- Operating Conditions: Develop project operating plans to control liquids infiltrating into the waste mass.
- Monitoring: Monitor landfill mining performance to confirm that the observed field conditions match those that were assumed in the analysis.

3. SLOPE MODELING

3.1 Methodology

The designer must demonstrate that the landfill mining site should be stable under the permitted operating conditions by performing a comprehensive slope stability analysis. The analysis presented in this paper can be performed using the same analytical tools as those used for typical landfills that are not normally having high liquid levels. The stability analysis typically performed for the waste excavation slope considers the following two potential failure modes: (1) overall global stability of the waste mass, and (2) local and/or deep stability within the waste or along discrete interfaces. The veneer stability of the cover system is not considered since it would be removed during landfill mining. Limiting equilibrium methods that are common in geotechnical engineering practice are used. Some of the commercially available computer programs can be used to analysis slope stability, e.g., XSTABL, PCSTABL, SLIDE, SLOPE/W, etc.

In this paper, the slope stability was evaluated using PCSTABL, a well-accepted and reliable model used widely in the solid waste industry. This program uses two-dimensional limiting equilibrium methods to calculate a factor of safety (FS) against shear failure for slope sections analyzed. This program utilizes an automatic search routine to generate multiple shear failure surfaces for circular failure mode or block-type failure mode until the surface with the lowest FS-value is found. The analytical methods used for the circular and block-type failure modes in the slope stability analysis are the Modified Bishop and Modified Janbu methods, respectively.

A sensitivity study is performed on the results of FS to evaluate the effect of the various liquid levels at different waste slope configurations. Although this study focuses on the stability investigation of a landfill mining excavation slope, the methodology presented can easily be applied to general geotechnical stability investigations.

For this evaluation, the generally accepted industry standard FS of equal to or greater than 1.5 is considered acceptable for static stability analysis for interim waste slopes.

3.2 Parametric Analysis

The goal of this parametric analysis is to identify potential instability issues during landfill mining operations. The graphical charts presented herein can be used to identify a site's potential instability and serve as a proactive measure used by the landfill operators to minimize the potential for slope instability especially during rainy seasons.

A sketch showing a typical interim waste slope profile modeled for this study is presented in Figure 1. The key shear strength assumptions for MSW waste, bottom liner system, and typical soil subgrade materials are provided in Table 1.

Slope modeling included both circular and block failure shear surfaces extending through the waste material and along along the weakest soil/liner interface.

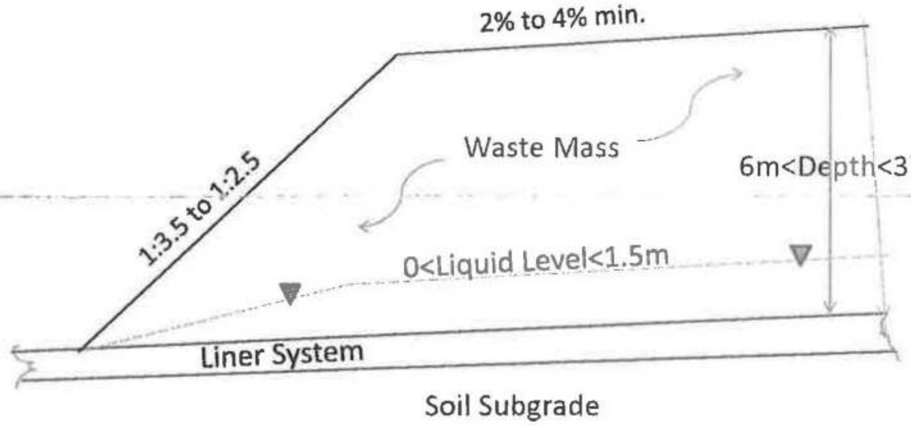

Figure 1. Typical Waste Interim Slope Profile.

3.3 Assumptions on Shear Strength Parameters

The slope stability analysis was performed using the following assumed values (as shown in Table 1):

- Foundation Material and Bottom Liner System: Internal shear strength of the foundation soil layer is assumed to be 96 KN/m^2 cohesion and zero degrees friction angle. Total unit weight was assumed to be 18.85 KN/m^3. Interface shear strength of the bottom liner system is assumed to have 21 degrees friction angle and zero adhesion.
- Waste: Internal shear strength of the waste material is assumed to have zero cohesion and that the shear strength is derived entirely from a friction angle of 33 degrees. In place total unit weight is assumed to be 8.64 KN/m^3.
- Waste heights (vertical distance from bottom liner to top of operating slope) evaluated at 6, 15, 24, and 37 m.
- Interim waste slope angles evaluated are at 1:3.5 (15.9 degrees), 1:3 (18.4 degrees), and 1:2.5 (21.8 degrees).
- The leachate levels above the bottom liner were analyzed for the 0.0 m, ,0.6 m and 1.5 m scenarios. The baseline analysis assumed zero leachate head above the liner.

Table 1. Shear Strength Parameters

Layer	*In-Situ Density (KN/m^3)*	*Shear Strength Parameters*	
		Friction Angle (deg.)	*Cohesion (KN/m^2)*
Waste	8.64	33	0
Bottom Liner System	18.85	21	0
Soil Foundation	18.85	0	96

4. RESULTS AND DISCUSSION

The factor of safety values for waste excavation interim slope stability analyses (under static loading conditions) for the above-mentioned slope section configurations are listed in Table 2; these results are depicted graphically on Figures 2, 3, and 4. Figure 2 represents slopes of 1(V):3.5(H), Figure 3 represents slopes of 1(V):3.0(H), and Figure 4 represents slopes of 1(V):2.5(H). Figure 5 represents all slope conditions on a single chart. These figures indicate that FS values decrease more significantly when leachate heads increase, compared with the scenario of a greater waste height. It is an indication that the leachate head has more of an influence of the critical surface than for the higher waste heights. For the head on liner is zero, the relationship is reversed, as would be expected.

It is notable that all failure surfaces are located within the waste itself and/or alomng the soil/liner interface. The potential for failure surfaces intersecting the bottom liner increases as the strength of the bottom liner decreases.

The analytical results presented indicate that FS above 1.5 will be achieved for the all slopes modeled provided leachate head levels are less than 0.7 m or zero head above the liner. For the 1:2.5 slope, the FS values drop below 1.5 if the liquid level above the liner is greater than 0.7 m and when the waste height is less than 24 m. For the 1:3.5 and 1:3 slopes, the FS values is less than 1.5 when the liquid level above the liner is greater than 0.7 m and the waste height is less than 15 m. This study also concludes that a circular failure mode is more critical than the block-type failure mode in all scenarios except two scenarios when the waste height is at 6 m and the liquid level is at 1.5 m above the liner.

The graphical presentation in this paper can be untilized as an important guide for the landfill site manager who may be excavating through waste mass for wahtever reasons and resulting with a steep and exposed waste slope. The results of this study can be used for the purpose of evaluating in a simple and rapid manner if interim operating slopes and heights are likely to maintain a slope stability factor of safety above 1.5, under various liquid levels that are either measured in the field or by obsesrvation of seep locations. These models and the results discussed herein do not represent an actual site or specific site conditions. More refined, site-specific modeling, taking into account actual slopes, material properties, liquid levels and other factors should be performed if FS values are less than 1.5, or if conditions are materially different from what was modeling in this study. Factor of Safety values will be lower than indicated in Figure 5 chart if shear properties of the materials are less than indicated or if leachate levels are higher than the 1.5 m level modeled.

1. Critical failure surfaces analyzed are located within the waste itself, all in circular modes except for two scenarios as indicated above as in block-type failure modes. FS is calculated using assumed waste shear strength with a friction angle of 33 degrees and 0 cohesion (conservative). The unit weight of the waste is assumed to equal to 8.64 KN/m^3. Liner system: friction angle = 21 degrees and 0 cohesion. Soil Subgrade: cohesion only = 96 KN/m^2 and unit weight = 18.85 KN/m^3.

Table 2. Summary of Waste Interim Slope Stability Analysis

Liquid Head on Liner(m)	*Waste Height (m)*	*Factor of Safety (FS)*		
		1:3.5 Slope	*1:3.0 Slope*	*1:2.5 Slope*
0	6	1.99	1.77	1.56
	15	2.09	1.85	1.60
	24	2.13	1.89	1.64
	37	2.22	1.94	1.66
0.6	6	1.70	1.52	**1.31**
	15	1.99	1.74	1.51
	24	2.04	1.83	1.59
	37	2.17	1.91	1.63
1.5	6	**1.27**	**1.15[1]**	**1.03[1]**
	15	1.78	1.52	**1.36**
	24	1.90	1.73	1.52
	37	2.09	1.83	1.58

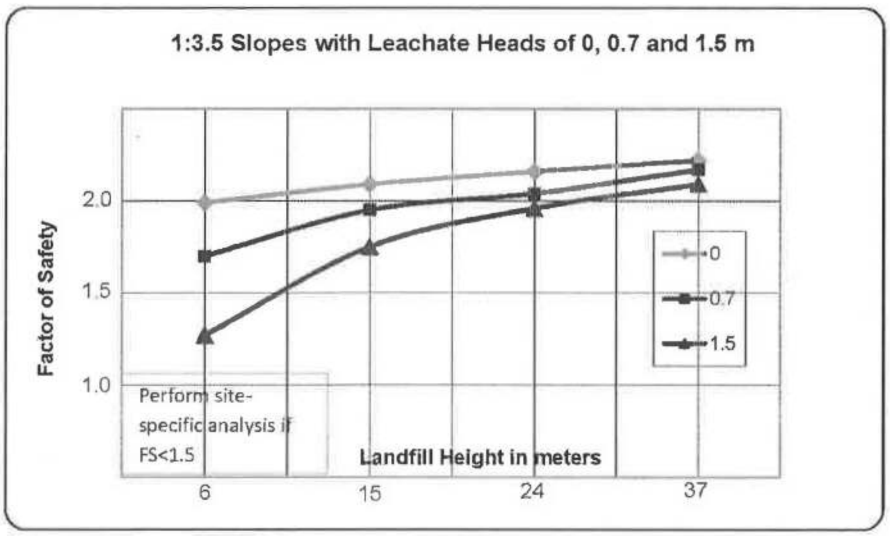

Figure 2. Interim Slope Stability Chart for 1:3.5 Slopes

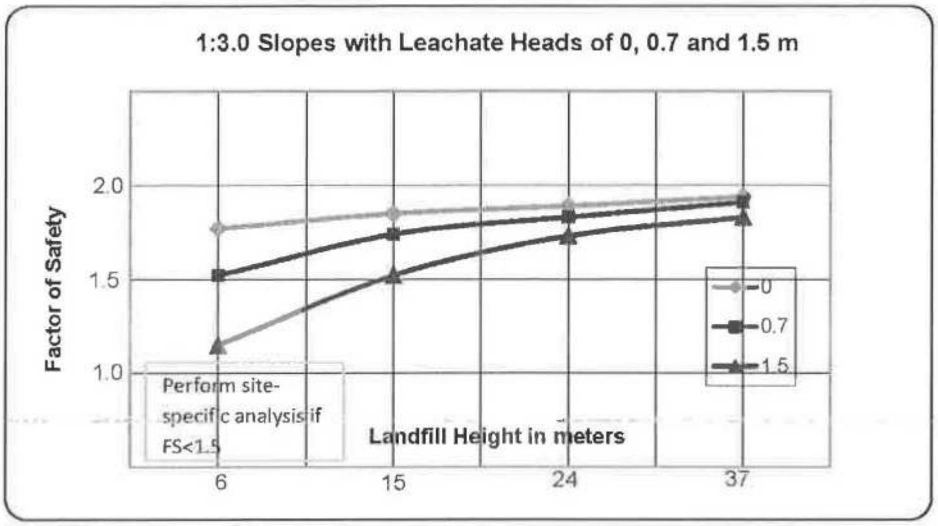

Figure 3. Interim Slope Stability Chart for 1:3.0 Slopes

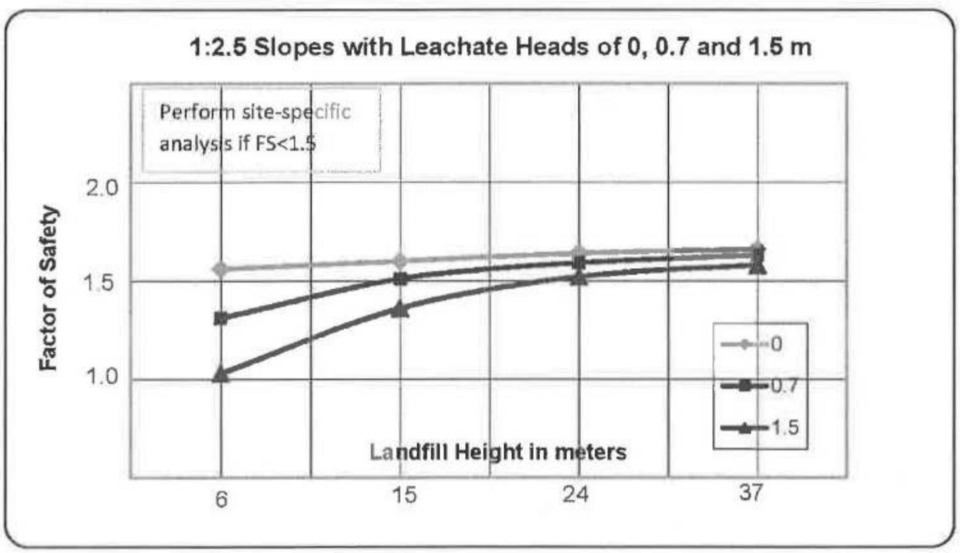

Figure 4. Interim Slope Stability Chart for 1:2.5 Slopes

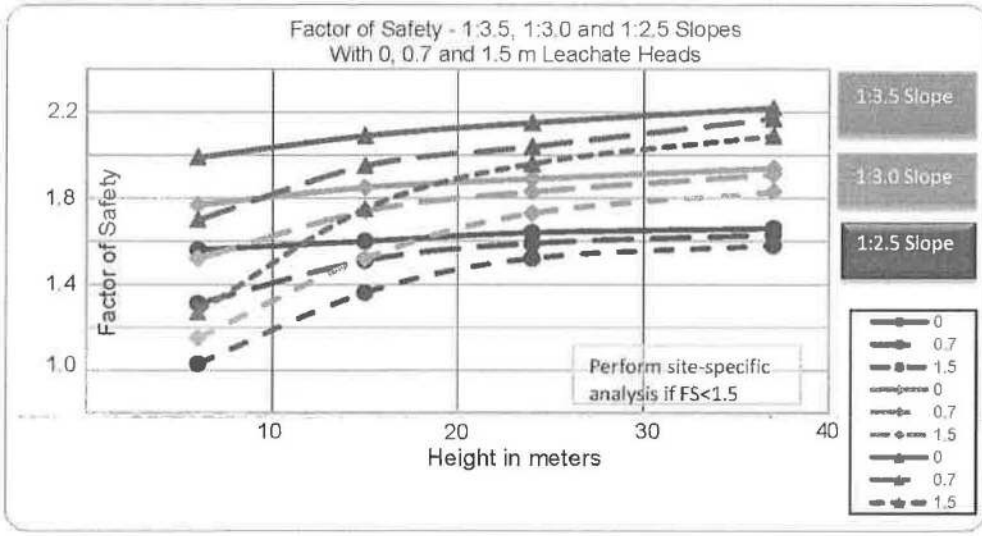

Figure 5. Waste Excavation Interim Slope Stability Chart

5. CONCLUSIONS

This paper was prepared to present the key factors in analyzing slope stability of an interim waste slope during landfill mining operations or waste excavation during liner repair. In summary, these key factors are:

- Stability of a landfill mining excavation slope is controlled by the same parameters that control the stability of typical landfills and non-waste fills, including material shear strength;
- Presence of pore water pressure;
- Unit weight of materials; and
- Slope geometry.

Available data document the range of values of these parameters that allow proper and safe landfill mining operation. Therefore, the stability of landfill mining excavation sites can be evaluated using the same analytical tools as stability of typical landfills. The calculated slope stability factors of safety for landfill mining slopes as presented in this paper are not significantly different from those of conventional, dry landfills.

Landfill mining operations may have a greater impact on stability than a closed landfill site, so additional performance monitoring is recommended, using the current state of the practice for monitoring, to verify that operations are not having an adverse impact on slope stability. The landfill operator should monitor the performance of the mining operations to confirm that the conditions assumed in the stability analyses are present in the site, including liquid level measurements or leachate seep locations in relation with the bottom of the landfill. It is also valuable to monitor the changes of these parameters over time, as they may serve as early indicators of potential problems. Most important, however, is the development and implementation of a site monitoring plan that can detect lateral seepage from the sideslopes and odor problems. Collection and documentation of this information requires a commitment to regular, programmatic inspections by the operator.

REFERENCES

CalRecovery Inc. and Solid Waste Association of North America (SWANA). "Evaluation of the Collier County, Florida, Landfill Mining Demonstration." Prepared for the U.S. Environmental Protection Agency (U.S. EPA), EPA/600/R-93/163. Cincinnati, Ohio: 1993.

Oden, M. W. "Wet Cells – Regulatory Issues for an Emerging Technology." Published proceedings of Wastecon 2002 Conference, Long Beach, Calif., October 2002.

Vasuki, N.C. "*End-of-Life Decisions.*" MSW Management Magaine, June 2013.

Warzinski, J. et al. "Leachate Recirculation Design and Operation." Proceedings of the Waste Tech 2000 Landfill Technology Conference, Orlando, Fla., 2000.

Wilson, V.L., W.D. Evans, and T.D. Stark. "An Interim Slope Failure Involving Leachate Recirculation." Proceedings of the Waste Tech 2000 Landfill Technology Conference, Orlando, Fla., 2000.