

# **DYNAMIC WATER BALANCE ASPECTS OF BIOREACTOR LANDFILLS**

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**SUMMARY:** This paper addresses increases in landfill moisture content that occur during optimized decomposition, both with respect to the overall quantities of liquids which must be managed and geotechnical stability considerations. Controlled laboratory decomposition studies conducted over 400 days with strict control and quantification of moisture content illustrated the dynamic changes in water content that can occur during accelerated decomposition. The ratio of [mass water:mass dry solids] in the controls increased from initial values of 0.73 – 0.75 to the range 0.91 – 0.97 at the end of the study. In “high solids digester” trials evaluated as an end point for optimized decomposition, this ratio increased from 3.3 – 3.4 to the range 5.6 – 9.7 [equivalent to a gravimetric moisture content of 560-970%]. In order to realistically evaluate observed changes in leachate chemistry (e.g., dilution effects) and to design stable slopes, a substantial quantity of additional free moisture needs to be taken into account when designing and maintaining bioreactor systems. Modeling of slope stability indicates that reductions in the shear strength of the waste, resulting from higher moisture contents, can significantly lower factors of safety for the waste and liner slopes during and after waste placement. Thus the development of a dynamic water balance model validated with field data is critically needed for more realistic evaluation of the geochemical and geotechnical effects of high water content in bioreactor landfills.

## **1. INTRODUCTION**

Controlled management of large quantities of landfill liquids is an important aspect of bioreactor design and operation. To date, there has been inadequate study and modeling of the dynamic changes in moisture content that occur during the decomposition process. Existing water balance models (such as HELP, or Hydrologic Evaluation of Landfill Performance; Schroeder et al., 1994a,b; U.S. EPA, 1995) do not consider these dynamic changes. Using controlled laboratory studies and geotechnical modeling, this paper addresses the expected quantities of liquids resulting from bioreactor operation and the effect of increased liquids in lowering safety factors for slope stability considerations.

## 2. MATERIALS AND METHODS

Gravimetric moisture content, biogas production, and leachate/solid chemistry during refuse decomposition were studied in anaerobic laboratory assays over a period of 400 days. A standardized synthetic refuse (paper, grass, food) was used in an experimental design which included two elevated moisture contents and two added soils with either leachate recycle or leachate drainage regimes. The elevated moisture contents were designed to simulate high solids (TS 22%) and low solids (TS 12%) anaerobic digestion conditions in small batch systems to examine end points for optimized decomposition. Four leachate recycle/drainage events were conducted during the experiment. Sufficient replicates (10-20, depending on trial) were included in the experimental design to permit destructive sampling after each recycle/drainage event, and strict control of moisture content was maintained in each trial. Distilled water was added to the leachate drainage assays at quantities equal to the water removed for analysis to maintain assay moisture contents. In addition, based on titration experiments, 1 mL of a neutralizing solution of 101 g KOH and 0.1 g Ca(OH)<sub>2</sub> per 100 mL oxygen-free water was added to each assay (except controls) after recycle/drainage events one and two, and 1 mL of a neutralizing solution of 56.11 g KOH/100 mL oxygen-free distilled water was added after the third event. Anaerobic digester sludge (0.2 mL after second event and 3.0 mL after the third event) was also added to stimulate methanogenesis. All assays were incubated *in vitro* [125 mL serum bottles] at 40 degrees C. At the beginning of the experiment, after each recycle event, and at the end of the experiment, gravimetric moisture content and the chemistry of solid, liquid, and gaseous phases were quantified. See Bogner and Spokas (1995) for additional details of the experimental design and methods.

To demonstrate the effects of higher moisture content on the reduction of waste shear strength, a typical landfill design in Illinois (USA) was analyzed with respect to slope stability under various moisture conditions. Figure 1 shows the proposed design. The liner consists of 0.9 m compacted clay (base) with 1.3 m compacted clay on the side slopes. The compacted clay is successively overlain by a 60-mil smooth HDPE geomembrane, a 30 cm drainage blanket (aggregate) and a geotextile filter. For the stability analysis, the waste is assumed to be 11.9 m thick on top of the bottom liner at a distance of 213 m from the side slopes. Since the higher moisture content in the waste can also effect the post-closure stability of the landfill, Figure 2 depicts the same landfill after closure. Typical properties of various materials including the waste are shown in Table 1. The factors of safety for the waste and liner slopes were determined using the two-dimensional limit equilibrium stability analysis program STABL (Lovell et al., 1984).

## 3. RESULTS

### 3.1 Laboratory assays

Table 2 summarizes the results of the anaerobic assays. Assay performance was evaluated by biogas yield (CH<sub>4</sub> + CO<sub>2</sub> per g dry waste), the percentage of original carbon converted to biogas carbon, and the decline in the cellulose:lignin ratio. In general, after 400 days of incubation, a limited amount of degradation and biogas production had occurred in the controls. On the other hand, the "350" high solids digester assays were characterized by high gas yields, a significant decline in the cellulose:lignin ratio, and fractional carbon conversion of >40%. This percentage

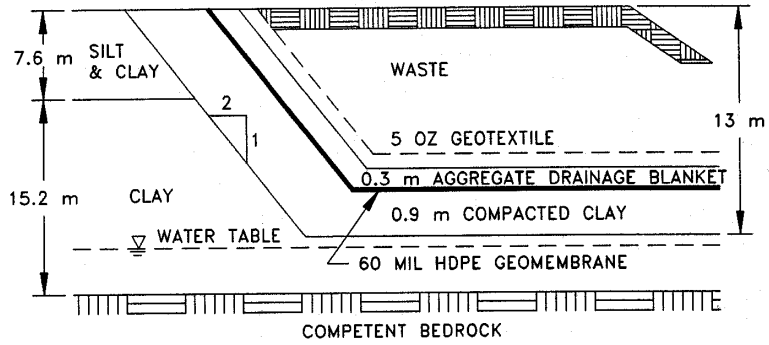


FIGURE 1. TYPICAL LANDFILL WITH COMPOSITE LINER—OPERATIONAL PHASE

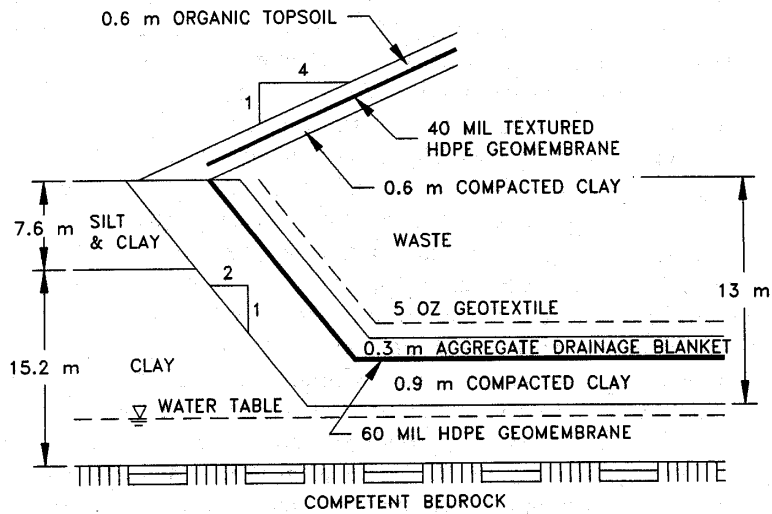


FIGURE 2. TYPICAL LANDFILL WITH COMPOSITE LINER—POST CLOSURE

Table 1. Properties of various materials used for landfill stability analysis

Material Type	Moist Density (g/cm <sup>3</sup> )	Saturated Density (g/cm <sup>3</sup> )	Cohesion (Kpa)	Friction Angle (Degrees)
Compacted Clay	2	2.1	48	0
Silt and Clay (in place)	2.1	2.2	96	0
Clay [Yorkville] (in place)	2.2	2.2	120	0
Drainage Aggregate	1.8	1.8	0	30
Waste	1	1	9.6	30
Organic Topsoil	2.1	2.2	72	0
60-mil Smooth HDPE Geomembrane	0.9	0.9	0	8
40-mil Texture HDPE Geomembrane	0.9	0.9	0	20

of carbon conversion is similar to the maximum values reported from German, Italian, and American studies by Bogner and Spokas (1993) for optimized laboratory assays simulating landfill conditions. The “750” low solids assays yielded intermediate values for gas yields, % carbon conversion, and decline in cellulose:lignin. The performance of the “750” assays was limited by high rates of hydrolysis and carboxylic acid production, resulting in lower pH and lower rates of methanogenesis (Bogner and Spokas, 1995). To suggest a possible range for water contents in operating bioreactor landfills, which would fall at points between the controls and the “350” assays, the initial water contents for the three groups of assays (80, 350, and 750) were plotted vs. the final water contents (Figure 3) and fitted to a linear regression. The regression equation indicates a final moisture content that is approximately double the initial value. Practically, one might expect moisture content increases between the observed changes in the controls (1.24 – 1.28 times initial values) and the observed changes in the “350” assays (1.6 – 1.9 times initial values). The box in Figure 3 suggests an operational definition for optimum moisture contents in bioreactor landfills. The lower end of the box on the x-axis is placed at the maximum observed water content for refuse samples recovered from conventional (non-bioreactor) landfills, approximately 150% (Bogner, 1990). The upper end of the box is placed at about 200% gravimetric moisture content, or about 33% solids; this is a high value for conventional high solids digesters, and it is assumed that this would be an upper boundary for bioreactor operations, with moisture contents at or above this level severely impeding site management activities.

It is also important to evaluate dynamic changes in dissolved constituents during optimized decomposition. However, it is misleading to examine concentrations alone without concurrent evaluation of changing moisture contents. With increased moisture content, for example, a simple dilution effect resulting in a lower observed concentration could be attributed to biodegradation or other processes. Figures 3-4 examine changes in total VFA (volatile fatty acids), chloride (Cl),

Table 2 - Summary of results for laboratory anaerobic assays. Average values for 4 replicates except controls (10 replicates). Initial cellulose:lignin was 4.3. C indicates added clay (C) soil; S indicates added sand (S) soil. The "80" assays had no added water; the "350" assays were amended with water to simulate a high solids digester (about 22% solids); the "750" assays were amended with additional water to simulate a low solids digester (about 12% solids).

Assay	Initial W%	Final W%	% C conversion (% initial C converted to biogas C)	Final cellulose: lignin	Total Biogas mL/g (dry)
Control-80C	75.7	96.6	0.42	0.25	15
Control-80S	73.0	90.8	0.32	0.25	12
350C-Drain	339.0	643	47	0.02	372
350S-Drain	329.3	1025	47	0.02	347
350C-Recycle	339.0	559	27	0.10	257
350S-Recycle	329.3	973	41	0.01	309
750C-Drain	724.4	1673	7	0.04	64
750S-Drain	703.6	1929	10	0.02	72
750C-Recycle	724.4	1216	7	0.09	70
750S-Recycle	703.6	1544	8	0.05	74

dissolved Fe, and dissolved Zn for the "350" assays with added sand soil during the four recycle events. Figure 3 plots the concentration trends (mg/L), while in Figure 4 the concentrations have been recalculated as "loads" based on the product of the concentration (mg/L) and the gravimetric moisture content expressed as a fraction. While the observed concentrations of the VFA's decreased after the third recycle event, the loads of both the VFA's and the Cl increased. Often Cl is used as a conservative ion in aqueous systems because of its high solubility. These results indicate that Cl can continue to be released during the decomposition process—see Figure 5 which shows a linear relationship between Cl loading and VFA loading. In Figures 3 and 4, both the concentrations and the loads of dissolved metals (Fe, Zn) decreased, suggesting that they were solubilized early in the decomposition process and later incorporated into solid phases.

### 3.2 Slope stability analysis

The factor of safety for the waste slope shown in Figure 1 was found to be 2.13. However, reducing the shear strength parameters of the waste by 10, 20, 30, 40 and 50% to simulate the effect of increased moisture content produced the factors of safety of 1.92, 1.67, 1.46, 1.24, and 1.03, respectively. These results show that the factor of safety reduces proportionally to the reduction in shear strength, and a significant reduction in shear strength due to increased moisture can result in unstable slopes. The decreased shear strength of waste does not affect the factors of safety for the composite liner systems; however, the reduced stiffness of the waste is shown to have a significant effect on the shear stress and shear displacements induced within the liner system, particularly in the geomembrane liner. Reddy et al. (1996) analyzed a typical

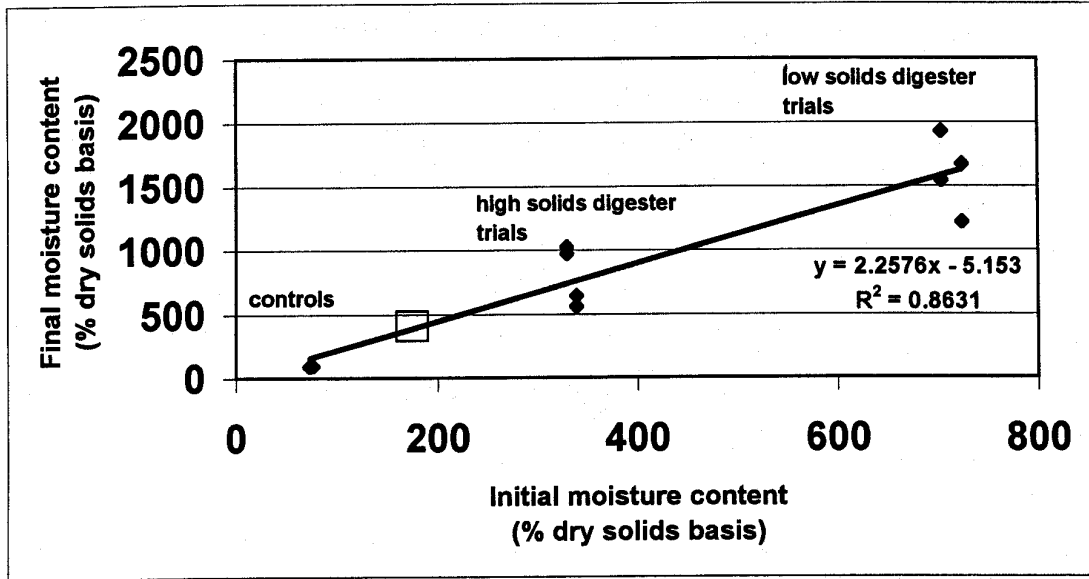


Figure 2. Relationship between initial and final moisture contents in anaerobic assays. Note high final moisture contents and “box” which suggests optimum moisture contents in bioreactor landfills (see text).

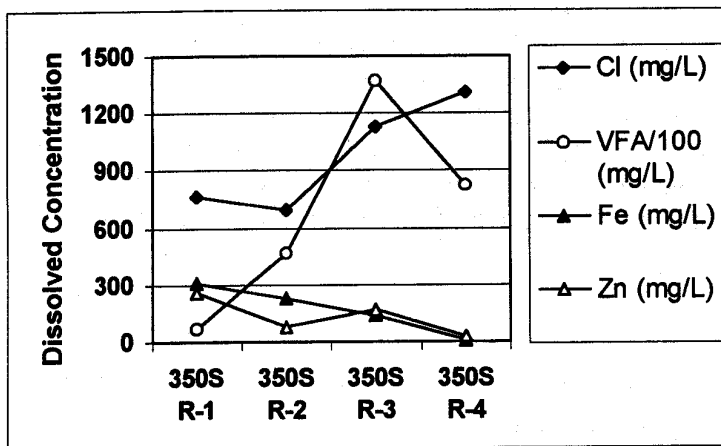


Figure 3. Dissolved concentrations for “350” assays with added sand soil during 4 recycle events.

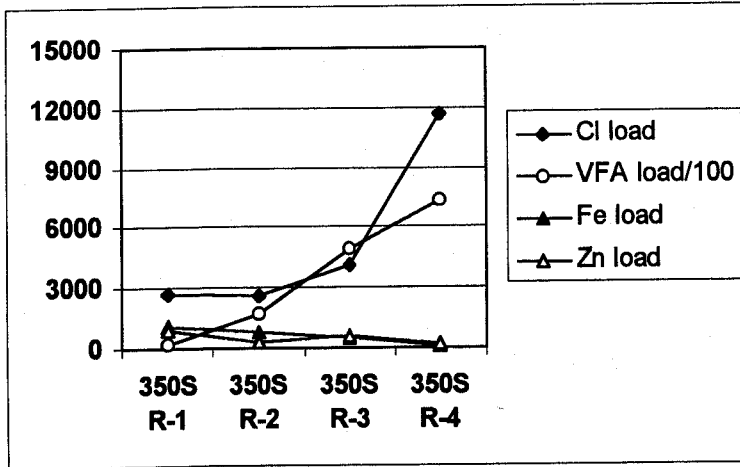


Figure 4. Loads for “350” assays with added sand soil during 4 recycle events. Loads were calculated from the product of the constituent concentration (mg/L) and the moisture content expressed as a ratio (mass moisture/mass dry solids).

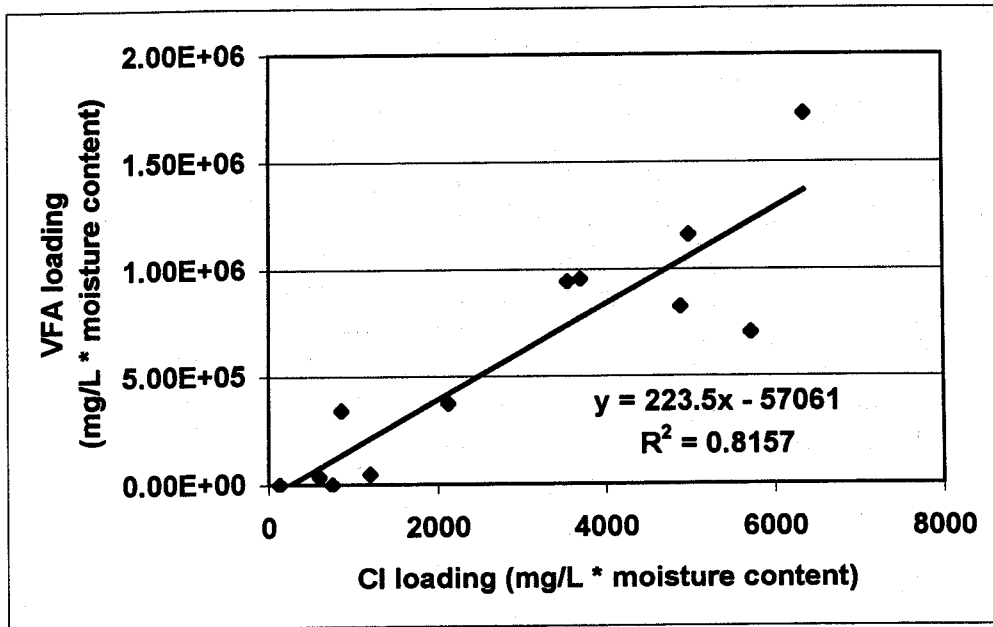


Figure 5. Comparison of VFA loading and Cl loading for the “350” assays. All data combined.

analyzed a typical landfill under operational conditions using a finite element method and showed that reduced stiffness of waste can increase shear stress and displacement in the base liner system. These results demonstrate that it is critical to properly design waste filling operations in bioreactor landfills to insure that the waste and liner slopes remain stable.

For the post-closure condition (Figure 2), the factor of safety for the liner is 1.68. However, reducing the shear strength parameters of the waste by 10, 20, 30, 40 and 50% produced the factors of safety of 1.54, 1.40, 1.26, 1.13, and 1.01, respectively. These results also clearly demonstrate that a reduction in shear strength of the waste can endanger the overall stability of the landfill under post-closure conditions. Therefore, it is very important to determine the reduction of shear strength of the waste as a result of the increased moisture content in bioreactor landfills and take this into account in the design of the landfill slopes.

#### **4. CONCLUSIONS AND RECOMMENDATIONS**

We have demonstrated from laboratory studies and slope stability analysis that very large increases in moisture content in bioreactor landfills are possible and can lead to significant reductions in the shear strength of the waste. With respect to observed concentrations of dissolved constituents, the changes in concentration must be evaluated with respect to the higher moisture contents to separate simple dilution effects from other operational variables. With respect to changes in shear strength, unfortunately, there are no data available on the magnitude of the shear strength reduction in waste due to increased moisture content; these data are needed as the implementation of bioreactor landfills is increasing. Existing geotechnical literature (Lamb and Whitman, 1969) indicates that it is possible to have strength reduced as much as 50 percent for clays and organic soils as a result of increased moisture contents below those discussed herein. Similar reductions in the shear strength of waste can have a profound effect on the stability of waste and liner slopes in bioreactor landfills. Typical landfill design configurations analyzed in this study clearly show that a significant reduction in shear strength due to moisture changes can result in unstable slopes. Recent experience (Wilson et al., 2001), where a slope failure occurred at an Ohio (USA) landfill approximately one year after the initiation of leachate recirculation, indicates that these failures can occur when slope stability is not properly assessed. Therefore, it is critical to determine realistic reductions in the shear strength of the waste due to increased moisture content and then use the proper shear strength values for the design of waste and liner slopes.

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