Simulation of landfill leachate and gas: application to leachate recirculation and landfill gas-to-energy projects.

V. O. Okereke
King County Solid Waste Division, Seattle, U.S.A.

Abstract

A one-dimensional coupled landfill leachate and gas model (LLGM) is developed for the continuous and simultaneous simulation of post-closure leachate accretion, gas generation, and to study the effects of leachate recirculation. A fully implicit finite difference scheme of the Fokker Planck equation is used to simulate moisture transport and distribution in the temporal and spatial domains, and then is coupled to a two-stage landfill gas first order rate equation to simulate landfill gas. This latter equation is uniquely correlated to moisture transport and distribution with a substrate utilization equation. The effects of the variation of key hydrologic parameters on leachate simulation are examined. A leachate treatment cost sub-model is also developed by non-linear Simplex regression analysis for the prediction of average long-term secondary leachate treatment costs. The economic viability of leachate recirculation in horizontal and vertical wells is evaluated for a hypothetical landfill gas-to-electrical energy project. Disproportionate volumes of leachate are simulated for concurrent increases in moisture content and gas. The use of vertical wells for leachate recirculation yielded a higher net economic benefit than horizontal wells for the tested hypothetical energy project. Moisture transport and retention are demonstrated to be dependent on the antecedent moisture content, refuse saturated moisture content and saturated hydraulic conductivity.
1 Introduction

Landfill gas (gas) is an energy resource and may be useful for the generation of energy. It is well documented by Pohland[1] that moisture is the essential parameter affecting refuse decomposition, therefore, the viability of a Landfill Gas-to-Energy (LFGTE) project may be improved by enhancing gas production through moisture addition. Although the decomposition of refuse and transport processes which occur in landfills produce leachate and gas simultaneously, a preponderance of existing mathematical models are designed to simulate either leachate or gas. The concurrent simulation of leachate and gas would provide a cost-effective alternative approach to LFGTE project developers for evaluating the enhancement of gas production with leachate recirculation.

Zanten and Scheepers[2] provided a critical review of empirical methods for gas simulation in landfills. Numerical and mechanistic approaches of variable degrees of complexity have been developed by others[3][4]. These approaches do not explicitly correlate gas generation with the distribution of moisture content in the landfill. Al-Yousifi and Pohland[5] developed a mechanistic model (PITLEACH-2) for the simulation of leachate, leachate recirculation, methane, microbial and biokinetic products of refuse decomposition. The hydrological water balance method [6] is commonly used for leachate simulation, and was adopted by Schroeder et al [7] in the HELP model for the computation of vertical and lateral flow of leachate flow at the bottom of the landfill. A representative and typical numerical leachate simulation model was developed by Ahmed et al [8].

This landfill gas and leachate model (LLGM) is distinguished from others by the inclusion of a subroutine for the recycling of leachate through vertical and horizontal wells, simulation of the one-dimensional spatial and temporal distribution of moisture content and its correlation with gas generation, and the development of an empirical relationship for estimating associated leachate secondary treatment costs. The coupled model was calibrated and tested using data for cells 4 and 5 of the Cedar Hills Regional Landfill, and published data by El-Fadel [4] for cell 7 of the Mountain View Experimental Landfill (MVLF) in California, USA. The cost sub-model was calibrated with data from two other landfills in the USA. This paper summarizes the key features of the model and discusses an example of its application. Complete details of model development, calibration and sensitivity analysis was presented by Okereke[9].

2 Assumptions and Model Equations

A review of the literature indicated that to minimize excessive leachate accretion, especially in wet climates, leachate recirculation is preferably implemented after the landfill is filled and capped. This model simulates leachate and gas generation, and the effect of leachate recirculation in a
completed refuse cell, and is not suitable for modeling leachate recirculation during the operating phase of a landfill. Since these processes occur simultaneously in real landfills, the generation of leachate and gas occurring at earlier times is assumed to be adequately modeled by the initial values of selected model parameters.

The layered structure of modern landfills cause the percolating leachate to have vertical and horizontal components. However, over the long term, the vertical component tends to dominate, enabling the accumulation and removal of the accreted leachate. The impact of these layers is neglected for the long term simulation of the vertical one-dimensional flow of leachate through the refuse cell. It is implicitly assumed that the transport and distribution of moisture at different landfill depths will catalyze the generation of gas by mechanisms that can be simulated with a first-order kinetic equation. The effects of bacteria, nutrients, and other factors are modeled by the magnitude of the refuse decomposition constants used in the model. The model was specifically developed as an alternative cost-effective approach for municipal landfill management and for the assessment of the economic viability of leachate recirculation in LFGTE projects.

The simulation of evapotranspiration was based on the Penman method presented by Schroeder et al[7]. Infiltration was estimated as net precipitation during unsaturated boundary daily time steps. Surface runoff was computed by the SCS[10] method, in a modified form to account for the sloping landfill surface and to, enable the implementation of continuous simulation. Lateral flow over the liner, and a constant leakage, were computed with a special form of the Darcy's equation under constant head and during saturated surface boundary time steps. Leachate accretion and recirculation, moisture transport and distribution were simulated with eqns (1) and (2). The simulated moisture content was integrated into eqn (3) and then coupled with eqns (4) and (5) to simulate gas generation. A discretionary module was used for the addition of recycled leachate at different depths using horizontal wells. Recycled leachate was added in proportion to the subcell surface area in the vertical wells. Secondary leachate treatment cost was simulated with eqns. (6) and (7) that was developed by non-linear Simplex regression analysis with historical leachate treatment data for the Cedar Hills Regional Landfill. The primary model equations include:

\[
\frac{\partial \theta}{\partial t} = - \frac{\partial k(\theta)}{\partial z} + \frac{\partial}{\partial z} \left[ D(\theta) \frac{\partial \theta}{\partial z} \right] + \frac{q_{mc}}{\partial z} \tag{1}
\]

This equation (without \(q_{mc}/\partial z\)) is commonly known as the Fokker Planck equation and is the one dimensional, \(\theta\) - based form of the Richards [11] porous media flow equation. Separate finite difference equations were formulated for nodes at the partitioned surface and bottom layers, and for several nodes for the interior of the landfill cell.
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\[ LAR = \sum \left( \frac{K(\theta) - D(\theta) \partial \theta}{\partial z} \right) i * Ai \]  

(2)

\[ Gr_{i(1,2,3)} = Gr_{\text{max}} * \theta_i / K_{\text{e}(1,2,3)} + \theta_i \]  

(3)

\[ G_{\text{lf}_g(1)} = \sum_{j=0}^{m} \sum_{i=1}^{n} Gr_i *Mi * \exp(-K_{t=0} * t) \]  

(4)

\[ G_{\text{lf}_g(2)} = \sum_{j=0}^{m} \sum_{i=0}^{n} Gr_i *Mi * \exp(-K_{t=0} * t) \]  

(5)

\[ LTC($) = AQf * \exp(-B/Q) \]  

(6)

\[ \text{LEUAC} = (\text{capital cost} * \text{CRF}) + \text{operating cost} + \text{LTC} \]  

(7)

\[ MW = \text{MMCF/day} * \% \text{CH}_4 * (1 \text{day}/24 \text{hrs}) * (1000 \text{BTU}/\text{CF}) * (1,000,000 \text{CF/MMCF}) * (\text{KWh}/13,000 \text{BTU}) * (\text{MW}/1000 \text{KW}) \]  

(8)

\[ \text{KWh/yr} = \text{installed KW} * \text{operating hrs/year} \]  

(9)

\[ \text{Gross Revenue} ($) = \text{Available KWh} * \text{$0.1175/KWh}(2006 \text{cost}) \]  

(10)

**Notation**

- \( \theta_i \): moisture content, \( L^3 / L^3 \)
- \( q^* \): moisture input (rainfall or recycled leachate), \( L / T \)
- \( LAR \): leachate accretion rate, \( L3 / T \)
- \( K(\theta) \): unsaturated hydraulic conductivity, \( L / T \)
- \( D(\theta) \): hydraulic diffusivity, \( L^2 / T \)
- \( Ai \): surface area of refuse cell, \( L^2 \)
- \( G_{\text{lf}_g} \): rate of gas generation, \( L^3 / T \)
- \( K_s \): specific initial rate constant of methanogenesis, \( 1 / T \)
- \( t^* \): refuse age, \( T \)
- \( n \): number of phases of decomposition (3)
- \( m \): number of refuse elements
- \( t_{\text{max}} \): time to reach maximum gas generation rate, \( T \)
- \( Mi \): fractional mass of refuse, \( M \)
- \( Gr_{i(1,2,3)} \): moisture adjusted unit mass gas generation rate, \( L^3 / M \)
- \( K_{\text{dt}} \): refuse decay rate for second stage gas generation, \( 1 / T \)
- \( K_c \): empirical moisture utilization constant for fast(i), moderately(2), and slowly decomposing refuse(3)
- \( Gr_{\text{max}} \): maximum gas generation rate for three refuse fractions, \( L^3 / M \)
- \( \text{LTC} \): secondary leachate treatment costs, \( S \)
- \( A, f_B \): calibration constants
- \( Q \): leachate quantity, \( L^3 \)
- \( \text{LEUAC} \): equivalent unit annual leachate treatment costs, \( S \)
3 Simulation of leachate, gas and leachate recirculation

Figure 1 shows a comparison of the year 2001 simulated and recorded gas generation profiles for capped cell 4. The average simulated annual gas generation rate was higher than the actuals by about 3%. Model proficiency to simulate gas was further investigated (Figure 2) with data reported by El-Fadel [4]. The reported moisture content was 0.26 (0.30 for LLGM). The simulated gas yield was 1.43 cf/dry-lb (0.09 m³/dry-kg) compared to 1.31 cf/dry-lb (0.08 m³/dry-kg) for the actual data. Due to paucity of calibration data to validate the model for the simulation of leachate accretion rates, simulated results (Figure 3) were compared to that obtained with the HELP model. The results predicted with the HELP model were about 35% higher than those with the LLGM.

![Figure 1: Simulated and recorded gas generation profiles in cell 4.](image-url)
Figure 2: Measured and simulated gas generation in MVLF cell 7. 
Source of MVLF data: El-Fadel et al [4].

Figure 3: Predicted post-closure leachate accretion in cell 4.

Figure 4 show results of a ten year simulation of leachate recycling in cell 5 for horizontal wells. Increases of 34%, 21% and 9,000% in moisture content, gas and leachate generation respectively, were simulated in the horizontal wells at a maximum leachate recirculation rate of 240,000 gpd (908 m³/day). The equivalent values for vertical wells were 29%, 19% and 10,500%, at a maximum leachate recirculation rate of 49,500 gpd (187 m³/day). For a constant model average saturated moisture content of 0.55, the average refuse moisture content increased from an initial value of 0.30, to 0.36 and 0.33 respectively for the horizontal and vertical wells respectively.
4 Sensitivity Analysis

Figures 5 and 6 illustrate results of sensitivity analysis performed to evaluate the relative impacts of saturated moisture content and saturated hydraulic conductivity, at an average model antecedent moisture content of 0.25. Moisture contents generally increased as the saturated hydraulic conductivity and saturated moisture content (MCSAT) increased, but showed a declining trend for a MCSAT value of 0.60 (Figure 5). The latter trend is attributed to the exhaustion of the moisture capacity.

Leachate accretion rates generally increased with increasing saturated hydraulic conductivity, but declined by several orders of magnitude as the saturated moisture content increased (Figure 6). This trend suggests that the saturation state of the refuse matrix is critical in the minimization of leachate accretion in landfills that employ moisture recycling as a method of enhancing gas generation. Additional testing showed that leachate accretion rates increased as the antecedent moisture content increased[9]. This latter observation does suggest that landfills in drier climates may be more suitable for a leachate recirculation process. The effects of the fineness of spatial discretization for nodal distances between 1.5ft (45.7cm) to 20ft (610cm), and antecedent moisture contents between 0.15 to 0.45 were also investigated and the results documented by Okereke[9]. It was shown that, the finer the discretization the faster leachate accretion rates approached equilibrium, otherwise, there were no discernable differences in leachate accretion rates for the range of nodal distances tested.
5 Application to gas-to-electrical energy project

Figure 7 shows the results of a cost-benefit analysis for a hypothetical LFGTE project that utilizes a gas turbine (heat rate of KWh/13,000 BTU) and gas generated from Cell 5 enhanced with recycled leachate, added through vertical wells. This analysis was based on incremental costs of leachate treatment and revenues derived from the sale of net electricity generated. It was assumed that a decision has been made to develop a LFGTE facility irrespective of leachate recirculation. Capital and operating costs were assumed to be Sunk costs, except
that the operating costs for the leachate recirculation facility was assumed to be 5% of the capital cost. All other costs were assumed unchanged. Capital cost of the leachate recirculation facility was estimated at $15,000/acre ($6,000/ha). Net annual optimum economic benefits of $51/year/gpd or $13,600/year/m³-day was obtained for the vertical wells at a leachate recirculation rate of 3,500 gpd (13 m³/day). Equivalent values were $16/year/gpd or $4,200/year/m³-day at 19,200 gpd (73 m³/day) for the horizontal wells.

![Figure 7: Comparison of costs and revenues.](image)

### 6 Summary and Conclusions

A one-dimensional coupled numerical leachate and empirical gas model is presented as a viable tool for evaluating the economic viability of leachate recirculation for LFGTE projects. Results show that the proposed leachate recirculation schemes could increase gas generation. Moisture distribution (and by inference, gas generation) and leachate accretion are demonstrated to be dependent on saturated moisture content, saturated hydraulic conductivity and antecedent moisture content. Maximum simulated increases in moisture content and gas were slightly higher in horizontal wells than vertical wells. However, the relative leachate accreted for each percentage increase in gas generation was also higher for the horizontal wells, leading to higher economic benefits for the vertical well application. Moisture uptake of about 24% (horizontal well) and 12% (vertical well) of the theoretically available moisture capacity was facilitated by the recycled leachate. Since the test landfill is located in a wet region, a LFGTE project that utilizes leachate recirculation is expected to be more economically viable in dry or moderately wet climates. The veracity of model results depends on actual costs and revenues associated with the
development of the particular LFGTE facility. These results indicate that the full benefit of leachate recirculation may be unattainable in modern landfills due to compaction and soil cover application practices. Possible improvements include a shortened operating life, improved porosity in daily cover materials, and lower refuse compaction rates. Bioreactor landfills offer the best approach for attaining these benefits. Planned improvements to the model include; addition of two-dimensional simulation, real time simulation of leachate recirculation during the active landfill life and additional testing with data from drier climatic regions.

7 References