Numerical Model to Predict Settlements Coupled with Landfill Gas Pressure in Bioreactor Landfills

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Abstract
Prediction of landfill gas generation and settlements are of concerns in design and maintenance of a bioreactor landfills. Accurate settlement prediction is essential for design of piping systems used for the delivery of re-circulated leachate and recovery of collected gases. Landfill settlement takes place as a result of change in overburden stresses and biodegradation of waste. Biodegradation-induced settlement is a direct result of rearrangement of waste skeleton in response to the conversion of waste mass into landfill gases. A comprehensive model for settlement analysis of a bioreactor landfill should be able to capture both mechanisms. Traditionally compressibility index is defined similar to that of clays, to explain the general settlement behavior of waste. Literature review showed that modeling of gas generation and transport has been attempted as a separate problem and there is limited research to explain landfill gas generation and transport as integral parts of the landfill settlement. This research describes a model which couples settlement behavior of a bioreactor landfill with the generation and transport of landfill gases. In the absence of a closed-formed analytical solution a computer program was developed to numerically predict the settlements as well as gas pressures in a bioreactor landfill using landfill geometry and waste properties. The mass balance of the landfill gas was used to link settlement and gas pressures. Explicitly computed settlement values were then used to predict the pressure profile implicitly. Satisfactory trends were observed in the settlement and the landfill gas pressure profiles when a simple hypothetical bioreactor landfill, a -10 lift - single cell landfill was analyzed using the proposed model.

Keywords: Settlement, Bioreactor landfills, Biodegradation, Mechanical compression, Modeling

1. Background
In a bioreactor landfill enhanced microbiological activity occurs to transform and stabilize the decomposable organic waste. Fast degradation rates in bioreactor landfills have given this innovative technology much attention. Enhancement in the biodegradation is usually achieved by re-circulating the leachate collected from the bottom of the landfill. Recirculation of leachate helps the landfill to maintain a wet environment in addition to the supply of nutrients needed for the biodegradation.

Prediction of waste settlement in a landfill is difficult since the density is dependent upon the waste type, moisture content, depth and time of placement. The changes in density with respect to landfill depth are due to a number of factors, which includes the increased strain in the waste layers due to the weight of the overlying layers (Bleiker et al., 1995). The waste at the bottom of a deep landfill compacts both immediately upon placement and over time as waste decomposition occurs vertically. This results in a much higher density values of the waste at the bottom when compared to that at the top of the landfill.

For years concepts borrowed from soil mechanics were used to model the settlement behavior of landfill waste. Sowers (1973) was the first to report the similarity of waste settlement to that of peat, with large initial

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consolidation followed by substantial secondary compression. Edil et al. (1990) also confirmed that solid waste compressibility properties were rather close to those of organic soils. However, landfill waste is inherently heterogeneous and anisotropic and is more difficult to characterize than soils.

When landfills are operated as bioreactor landfills, where collected leachate is pumped back into the waste matrix, waste decomposition and gas production are accelerated making them different from traditional ‘dry’ landfills. Waste begins to show a high compressibility and fast degradation rate. This is manifested in significant changes in waste properties and hence stability and settlement behavior of landfills. Accurate prediction of this change in volume is of special importance to effective operation of leachate recirculation systems and gas collection pipe networks, and to estimate air space, and designing both intermediate and final covers.

One of the objectives of settlement computations for a traditional dry landfill is to establish the space that can be recovered in the future with the end of the degradation process. Therefore, frequently landfill designers use only total settlement (or in some cases, a rough estimate of time dependent settlement) for planning purposes. With this type of settlement computations the whole landfill is treated as a single waste mass (i.e., the landfill was completed at once), and no attention is paid to the initial construction period. But the settlement behavior during construction becomes a key factor when the landfill is operated as a bioreactor landfill because of the impact of rapid degradation on the components of the bioreactor landfill itself such as the leachate recirculation systems and the gas collection pipe networks. Rapidly settling waste mass can impose a significant load causing distortion or damage to the pipe networks. Therefore, proper construction planning is crucial from the beginning and it is essential to know how the waste mass behaves and settles during the period of construction and subsequent operation of the bioreactor landfill.

Waste typically shows an immediate settlement upon placement followed by a time dependent settlement. The settlement that takes place immediately is believed to be due to re-arrangement of the waste skeleton caused by the self-weight or any other applied loads and usually defined as initial settlement. Decomposition of waste with time contributes to the major constituent of time dependent settlement.

Current practice of modeling landfill settlement processes is predominantly empirical. These methods heavily depend on measured laboratory and field parameters. El-Fadel and Khoury (2000) classified existing settlement models into four broad categories: soil-mechanics based models; rheological models; empirical models; and the models accounting for the decay of waste on settlement. Only few attempts of modeling time dependent settlement behavior of bioreactor landfills are reported in the literature. Almost all of them are either direct or adjusted versions of soil mechanics based models that have been originally proposed for the dry landfills.

Heterogeneity of the waste prevents use of any simple equations to adequately describe the rate of biodegradation and gas generation. Qualitative models such as Farquhar et al. (1973) have been proposed to describe stages of gas generation based on experimental observations. Quantitatively the rate of gas generation can be predicted by considering the landfill as a batch reactor. The Monod model or a modified version of it remains the most widely used microbial growth model. Such a model relates variation of microbial population to substrate concentration (El-Fadel and Khoury, 2000).

Most landfill gas transport models are based on the assumption that the landfill can be treated as a porous medium and the gas velocity is given by Darcy’s law (El-Fadel et al, 1989; Findikakis and Leckie, 1979). Gas extraction models rely on pressure change between the landfill gas pressure and atmospheric pressure during static or dynamic pumping conditions. Young (1989) developed a more complete model that describes transport of gas in a rectangular cross section of a landfill. Arigala et al. (1995) improved Young’s model by incorporating a more realistic description of waste biodegradation. In this model waste is represented by three classes of waste having different degree of biodegradability, as originally suggested by Findikakis and Leckie (1979).

2. Proposed numerical model

Waste changes its volume mainly due to the load (or stress) acting on it or the mass loss due to decay, hence the mechanisms of waste settlement can be included in two broad categories: mechanical compression and biodegradation-induced settlements. Even though biodegradation creates voids in the waste mass, the subsequent settlements takes place as a result of stress acting on it. Thus the total settlement has to be modeled as a combined process of mechanical compression and biodegradation-induced settlements. This is achieved with the help of a phase diagram. The proposed model keeps track of the changes in the volume in each phase.

\[
\Delta V = \Delta V_s + \Delta V_w + \Delta V_g
\]
This change in volume is converted to strain which is then used in the mass balance equation to compute the landfill gas pressure.

In this manuscript it is assumed that the waste mass is comprised of layers of waste that are infinitely extended and horizontally parallel to each other. Movement of gas and moisture is assumed to occur in the vertical direction. Under leachate recirculation conditions the waste is assumed to be always at its field capacity. Gas is expected to reach the top surface where it is mixed with outside air which is at the atmospheric pressure. Mechanical compression occurs due to compression of voids and solids due to the weight of the overlying waste. Since the strain is essentially a function of stress, mechanical compression at a given depth also remains a function of stress. While addition of new waste increases stress, loss of mass due to biodegradation can cause in swelling or rebound. This behavior makes the stress at a given depth a function of time (see Figure 1).

![Diagram of stress at kth layer as a function of time](image)

**Figure 1. Stress at kth layer as a function of time**

In this research the relationship between mechanical compression and stress was established through a series of laboratory compression tests. As far as the compressibility of waste remains a constant, a given level of stress always ensures a certain level of strains. Unloading tends to follow a curve with a shallower gradient showing that the loading produces both elastic and plastic deformations in the waste structure. Figure 2 was obtained based on a series of laboratory compression tests (Hettiarachchi et al., 2004) and it demonstrates the basic stress-strain relationship of fresh waste. Both curves well fit into straight lines in the logarithmic time scale. Change in strain corresponding to a change in stress can be expressed by the following equation.

\[
\delta \varepsilon = C^* \log \left( \frac{\sigma + \delta \sigma}{\sigma} \right) \quad \text{where,} \quad C^* = \begin{cases} C_c^* ; \delta \sigma > 0 \\ C_s^* ; \delta \sigma < 0 \end{cases} \tag{2}
\]

\(C_c^*\) is the compression ratio (slope of the graph strain vs. log of loading stress) and \(C_s^*\) is the swelling ratio (slope of the graph strain vs. log of loading stress). Equation (2) is useful in determining the initial mechanical compression followed by the placement of the waste as well as the in computing the release of strain (or swell) due to decomposition.

Similar to soils, waste also comprises of three phases; solids, water, and air. But decay of solids mass in waste makes it different from soils where solids mass always remains unchanged. Since waste solids are highly heterogeneous use of average properties could produce wrong and misleading estimations. Therefore in this manuscript, solids fraction of waste is divided in to four groups depending on the degradability. They are non-degradable waste, slowly degradable waste, moderately degradable waste and rapidly degradable waste.

Throughout this manuscript \(V\) and \(M\) denote volume and mass. The subscripts \(g\), \(w\), \(s\), and \(j\) denote gas, water (or leachate), solids and the number of the solids group respectively.
It is believed that the decomposition rate of a biodegradable matter can be estimated by first order kinetics. The first order decay equation applied to the \( j \)\(^{th} \) group of waste solids and its solution, are presented by equations (3) and (4) respectively where \( \lambda_j \) = the first order kinetic constant for the \( j \)\(^{th} \) group (\( \lambda_i = 0 \)).

\[
\frac{dM_{sj}}{dt} = -\lambda_j M_{sj} \tag{3}
\]

\[
M_{sj} = M_{sj,0} \exp(-\lambda_j t) \tag{4}
\]

If the initial solids fraction for each waste group is \( f_{sj} = \left( \frac{M_{sj,i}}{M_{sj,j}} \right) \), then the total solid waste mass can be expressed as:

\[
M_s = M_{sj,0} \sum_{j=1}^{4} f_{sj} \exp(-\lambda_j t) \tag{5}
\]

The volume of the decayed waste (\( \delta V_s \)) can be computed as shown in equation (6), where \( w_j \) and \( G_{sj} \) are gravimetric water content and specific gravity of the \( j \)\(^{th} \) group of the waste solids and \( \rho_w \) is the density of water.

\[
\delta V_s = \frac{M_{sj,0}}{\rho_w} \sum_{j=1}^{4} \frac{f_{sj}}{G_{sj}} \left[ 1 - \exp(-\lambda_j t) \right] \tag{6}
\]

Definition of volumetric water is used to determine the change in the liquid phase while the equation (2) is used to estimate the changes that occur in the gas phase as suggested in an earlier section.

Considering the amount of gas present in a unit volume of landfill the overall mass balance can be established in the following manner.

\[
\left( \text{Rate of change of gas mass in the waste element} \right) = \left( \text{Gass flux through the element} \right) + \left( \text{Rate of gas generation} \right)
\]

\[
\frac{1}{V} \frac{\partial M_g}{\partial t} = -\frac{\partial}{\partial z} \left( \rho_g v - D \frac{\partial C}{\partial z} \right) + G(t) \tag{7}
\]
Where, $V$ is the volume of the waste element at time $t$, $\rho_g$ is the density of the landfill gas in the element, $v$ is the gas velocity, $D$ is the diffusion coefficient, $C$ is the concentration of landfill gas, and $G(t)$ is the rate of generation of gas per unit volume of waste.

Since the only source of gas generation is degradable mass, the rate of degradation should be equal to negative rate of gas production.

$$G(t) = -\frac{1}{V} \frac{\partial M_0}{\partial t}$$

3. Numerical Solution

Proposed sequence for numerical computations is given in Figure 3. Strain is first computed using waste properties and geometry. Leachate recirculation is not expected to commence until the filling is complete, hence up to that time ($t \leq t_0$) biodegradation-induced strain is computed using a lower first order constant for each waste group. For each time step, once the strain is computed the mass balance equation for gases is solved for gas pressure. Then the stress is updated for possible mass loss due to biodegradation as well as for increase in stress due the addition of new layers. Once the leachate recirculation is in operation ($t > t_0$) the appropriate values should be selected for first order kinetic constants. This procedure is repeated for each layer and the time dependent strain from each layer is finally summed up to find the spatial and temporal variation of waste settlement.

With the help of the ideal gas law equation (7) is finally brought to the following form.
Here \( P_{atm} \) stands for the atmospheric pressure which is considered as a constant, and \( p \) is the pressure beyond the atmospheric pressure (relative pressure). \( R^*, T, k_g \) are individual gas constant, landfill temperature in Kelvin and unsaturated gas conductivity respectively.

Equation (9) is a modified version of a parabolic partial differential equation (parabolic PDE). It should be noted that the most of the coefficients are not constants due to the changing volume of the waste. Therefore, it has to be solved using non-uniform lengths of the grid and the change in the location of the top boundary with time should also be taken into consideration. Although the volumes (or heights) are computed explicitly the final equation is solved implicitly to retain the unconditional stability of the solution.

A simple hypothetical bioreactor landfill was analyzed to demonstrate the efficiency and the capacity of the proposed model. A 10 -lift single cell landfill was taken into consideration. Each lift was 0.5 m high at the placement. To keep this demonstration simple, no time delay was assumed between the construction of two lifts. It was assumed that the landfill gas generated in each layer was moved up and eventually escaped from the top surface. Hence the effect from a top cover was not a concern. The waste properties, initial conditions, and other constants used in the computations are listed in Tables 1-3.

**Table 1. Group properties of waste solids**

<table>
<thead>
<tr>
<th>Group</th>
<th>Non-degradable waste (1)</th>
<th>Slow degradable waste (2)</th>
<th>Moderately Degradable waste (3)</th>
<th>Highly degradable waste (4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial fraction (( f_s ))</td>
<td>0.35</td>
<td>0.25</td>
<td>0.25</td>
<td>0.15</td>
</tr>
<tr>
<td>Specific gravity (( G_s ))</td>
<td>3.0</td>
<td>2.0</td>
<td>1.2</td>
<td>1.0</td>
</tr>
<tr>
<td>Decay constant (( \lambda, 1/\text{days} ))</td>
<td>0.0</td>
<td>0.000005</td>
<td>0.0005</td>
<td>0.0005</td>
</tr>
</tbody>
</table>

**Table 2. Initial conditions and landfill geometry**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Atmospheric pressure</td>
<td>101 kPa</td>
</tr>
<tr>
<td>Dry density of waste at the placement</td>
<td>600 kg/m³</td>
</tr>
<tr>
<td>Layer thickness at the placement</td>
<td>0.5 m</td>
</tr>
<tr>
<td>Number of layers</td>
<td>10</td>
</tr>
</tbody>
</table>

**Table 3. Constants used in the analysis**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Landfill temperature (( T ))</td>
<td>315 K</td>
</tr>
<tr>
<td>Diffusion coefficient (( D ))</td>
<td>0.6 m²/d</td>
</tr>
<tr>
<td>Individual gas constant (( R^* ))</td>
<td>518.3 J/kg/K</td>
</tr>
<tr>
<td>Volumetric moisture content (( \theta_v ))</td>
<td>0.3</td>
</tr>
<tr>
<td>Gas conductivity (( k_g ))</td>
<td>3.0 m/d</td>
</tr>
<tr>
<td>Compressibility ratio (( C_C ))</td>
<td>7.8</td>
</tr>
<tr>
<td>Swelling ratio (( C_s ))</td>
<td>2.8</td>
</tr>
</tbody>
</table>

4. Analysis
Settlement behavior and variation of landfill gas pressure were simulated for this bioreactor landfill for 10,000 days (25 years) using the computer program. Total average strain profile and the variation of strain in the 1st, 5th, and 9th waste lifts are given in Figure 4. Variation of relative pressure (pressure beyond atmospheric pressure) at the top of the 1st, 5th, and 9th waste lifts and the pressure profiles at the end of 1 month 1 year, 10 years, and 25 years are given in Figures 5.

When additional waste lifts are added the existing lifts gets compressed due to the weight of the added layers. This initial compression should be different from layer to layer depending on the location. It is evident from Figures 4 that the proposed model is capable of capturing this ‘sudden hike’ in strain due to initial compression. The total settlement reached 26 % after 25 years. In order to maintain numerical stability simulation time step had to be chosen as 1 day. This resulted in less details of the initial pressure build-up (Figure 5a). However the dissipation of pressure is well demonstrated in Figure 5 (a) and (b). The magnitude of relative landfill gas pressure was in range of 0 -16 kPa throughout the simulation period which is possible in a bioreactor landfill due to rapid biodegradation. Less settlements in middle and bottom (see layers 1 and 5 in Figure 4b) layers compared to that in top layers of waste (see layer 9 in Figure 4b) could be due to the build up of pressure at the bottom of the landfill. However the magnitudes of pressure and settlement are highly dependent on the waste and other properties selected for this simulation hence they are not discussed in detail.

5. General Discussion

The methodology presented in this paper demonstrates a few promising features over other available settlement models despite the fact that it is still in the developmental stage. Mechanical compression is modeled with the help of laboratory simulations. In the absence of a proper theoretical explanation, laboratory simulations are perhaps the best possible alternative to study the mechanical compression behavior of waste. To model the settlements due to biodegradation, it is assumed that waste degradation obeys the first order kinetic equation. Even though there is no direct evidence to prove its validity, many have recognized the first order equation’s
ability to give better results (Edgers et al, 1992; Kang et al, 1997; Oweiss and Khera, 1998; Hettiarachchi et al., 2003). When predicting the contribution from mechanical compression, the model is sensitive not only to the increase in strain caused by an increase in stress but also to decrease in strain due to possible swelling as a result of mass lost during biodegradation.

A phase diagram was introduced to define masses and volumes of each phase. Waste comprise of material which may range from very highly degradable solids to non-degradable solids. Therefore, use of average material properties could be misleading and also could produce erroneous results. In order to have a better representation, solids phase was further subdivided into four groups based on degradability. Number of subdivisions can be increased or decreased considering the nature of the waste to be analyzed.

In computations, each layer is considered separately starting from placement of waste until end of its biodegradation. Total time dependent strain from each layer is summed up to calculate the total landfill strain and hence settlement. By starting computations since placement, the proposed model could predict settlement behavior during the construction phase too. Since time dependent settlement behavior is a concern in a bioreactor landfill (especially during construction phase) an improved version of the current model could be a helpful tool during design and construction stages. Total strain is expected to be increased by various other minor mechanisms that are active during the process of rearrangement followed by degradation, such as arching actions, raveling, and change in particle sizes. Although the contribution from each minor mechanism may not be significant, it may sum up to a considerable amount of settlement. Identification of each of these minor mechanisms is difficult and hence modeling them is almost impossible. Therefore the current attempt is only limited to modeling the two major mechanisms which are responsible for the major component of the settlements.

Figure 5. Variation of average relative pressure in the 1st, 5th, and 9th waste lifts (a) and pressure profiles at the end of 1 month 1 year, 10 years, and 25 years (b). Note: nodes 1 & 11 represent the bottom and the top surface of the landfill respectively.
The work presented here is only focused on solids and gas phases of waste. Any contribution or influence from the remaining phase i.e. water (or leachate) in the total strain, was not taken in to consideration. Moisture profile of a bioreactor landfill is highly site specific due to the arrangement and frequency of leachate recirculation available at the site. Authors understand the importance of making the moisture phase as an integral part of the settlement mechanics and hence they are currently developing an advance model where settlement is coupled with gas generation and dissipation as well as distribution of moisture.

6. Summary

A new methodology was proposed for settlement predictions in bioreactor landfills. The major mechanisms of waste settlement were identified as mechanical compression and biodegradation-induced strain. Then a procedure was proposed to compute settlements due to mechanical reasons in a bioreactor landfill by separating that from the biodegradation. A new conceptual framework was also proposed to numerically predict the settlements using waste properties and landfill geometry.

By identifying and employing the major mechanisms in settlement computations, the proposed model can capture the major contributors of the settlement of waste. A phase diagram was also introduced to define masses and volumes of each phase more effectively and the solids phase was further subdivided into four groups based on degradability in order to have a better representation and hence the model can select appropriate values for waste properties depending on the degradation phase.

The proposed model was used to analyze a simple hypothetical bioreactor landfill, a -1 lift - single cell landfill. Settlement and the landfill gas pressure profiles were generated with the help of a computer program and satisfactory trends were observed.

References


