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# A MODEL BASED ON MECHANICS TO PREDICT SETTLEMENTS IN BIOREACTOR LANDFILLS

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## ABSTRACT

Prediction of waste settlement behavior during the construction phase of a landfill is vital to effective functioning of leachate recirculation systems and gas collection pipe network, yet prediction of waste settlement is complex and difficult to perform. Few models, are currently available which can be used to calculate landfill settlement of the entire waste thickness after closure without accounting for variation in density and other parameters with depth. By starting after closure, these models do not account for settlements during construction. The use of entire depth does not allow for the calculation of strains at different depths. When landfills are operated as bioreactors, waste decomposition and gas production are accelerated making the problem more complicated. Rapid degradation results in a significant impact on waste properties, settlement and stability. Accurate prediction of this rapid change in volume is of importance in estimating airspace, planning construction sequence, designing covers as well as planning for expansions. This paper focuses on the behavior of the density and settlements of waste with time and space and proposes a new mathematical model based on mechanics which is capable of computing settlements during construction of landfills. The impact of leachate recirculation and different waste types on settlement behavior of a landfill is also accounted in the proposed model.

## BACKGROUND

Concepts in soil mechanics were used to model the behavior of waste in landfills for years. Sowers (1973) showed that the settlement of solid waste was similar to that of a peat, with large initial consolidation and substantial secondary compression. Edil et al. (1990) indicated 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.

Prediction of waste settlement in a landfill is difficult since the density is dependent upon the waste type, moisture content, depth and time since 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 landfill development progresses vertically. This results in a much greater density of the waste at the bottom as compared to the waste at the top of the landfill.

Bioreactor landfill is an emerging technology which has already gained much attention due to fast degradation. A bioreactor landfill is a landfill that uses enhanced microbiological processes to transform and stabilize the decomposable organic waste. Usual way of achieving fast stabilization is creating an environment, which is favorable for biodegradation by recirculating the leachate produced by the same landfill. Recirculation of leachate helps the landfill to maintain a wet environment in addition to the supply of nutrients needed for the biodegradation process.

## SETTLEMENT ISSUES IN BIOREACTOR LANDFILLS

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 results in a significant impact on waste properties and hence stability and settlement behavior of landfills. Accurate prediction of this change in volume is of special importance in effective functioning of leachate recirculation systems and gas collection pipe network, and for estimating air space, and designing both intermediate and final covers.

Potential for improved raveling is one more feature that bioreactor landfills inherit from the practice of leachate recirculation. Recirculation of leachate helps waste to re-arrange its structure into a compact one by mobilizing the smaller waste particles. But quantification of the contribution of flushing action in the settlement process is a difficult proposition.

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 cessation 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 gas collection pipe network. Rapidly settling waste mass can impose a significant load causing distortion or damage to the pipe network. Therefore, proper construction planning is crucial even during the beginning and it is essential to know how the waste mass behaves and settles during the period of construction of the bioreactor landfill.

## MECHANISMS OF WASTE SETTLEMENT

Mechanisms of waste settlement are many and complex, even more than for a soil due to extreme heterogeneity and large voids in the waste fill. The main mechanisms involved in waste settlement, as identified by Edil et al. (1990) are listed below.

1. Mechanical (Distortion, bending, crushing and reorientation; similar to consolidation of organic soils)
2. Raveling (movement of fines in to large voids)
3. Physico-chemical change (corrosion, oxidation and combustion)
4. Bio-chemical decomposition (fermentation and decay, both aerobic and anaerobic processes

The majority of immediate settlement is due to mechanical mechanisms (Bleiker et al., 1995). Sowers (1973) estimated that these processes are completed in one month for a typical landfill. The last three mechanisms are important for long-term predictions. Edil et al. (1990) further identified initial waste density or void ratio, fraction of the degradable waste, fill height, stress history, fluctuation of leachate level and environmental factors such as moisture content, temperature as factors affecting the magnitude of the landfill settlement.

As discussed by Edil et al. (1990), settlement of a waste cell is characteristically irregular. Initially, there is a large settlement within one or two months of completing construction, followed by a substantial amount of secondary compression over an extended period of time. The magnitude of settlement decreases over time and with increasing depth below the surface of the fill.

Hence one can ask the following question. Can the above discussed waste settlement mechanisms explain the way waste settles in a bioreactor landfill? Answer to this question depends on the difference between a traditional dry landfill and a bioreactor landfill. Leachate recirculation is the basic difference between the two types. Recirculation of leachate improves the potential for decomposition of waste by providing a wet environment with a sufficient level of nutrients. At the same time, the downward flow of leachate can transport some waste particles with the flow improving the raveling process. Since leachate recirculation is only a measure of enhancing the biodegradation, the same mechanisms should also be valid for settlement of bioreactor landfills.

Within this context the mechanisms that contribute to the settlement process in a bioreactor landfill can be redefined as re-arrangement and decomposition. Due to the self-weight or the load from the upper layers, and release of load due to biological decomposition, waste tends to rearrange its structure causing reduction in volume and hence causing settlement. Re-arrangement starts soon after placement and continues until there is no more biological activity.

Decomposition is a relatively slow process. This is mostly due to biological degradation of organic matter. Degradable waste decomposes with time producing greenhouse gases and hence increasing void space. Escape of gas from waste mass causes settlement as well as a mass loss. A considerably high percentage of settlement in waste is due to biological decay. The biological processes acting on the organic materials within the refuse commence soon after the placement of waste.

## SETTLEMENT MODELING WITH LEACHATE RECIRCULATION

Only few attempts of modeling time dependent settlement behavior of waste in landfills with leachate recirculation are reported in the literature. Of them some attempts are quite recent while others are adjusted versions of the same models that have been originally proposed for the dry landfills. They are briefly discussed in the following sections.

To predict the settlement in a bioreactor test cell, Wall & Zeiss (1995) applied the secondary compression model, which was originally proposed by Sowers (1973) for long-term waste settlement predictions in sanitary landfills. They assumed that the time dependent settlement was linear with respect to a logarithmic time. Following Sowers (1973), Wall and Zeiss (1995) also suggested using 30 days for the end of the primary compression period.

El-Fadel and Al-Rashed (1998) attributed settlement that occurs after initial settlement to secondary settlements. The two slopes observed in the curve of strain versus logarithm time were defined as intermediate secondary compression and long-term secondary compression. Based on this observation El-Fadel and Al-Rashed (1998) applied two logarithmic functions to represent the time dependent settlement behavior of waste. They used 16 days as the initial settlement period. The time at which, the slope of the strain versus logarithm time changes must be determined graphically from field data. El-Fadel and Al-Rashed (1998) also used the power creep model to analyze the same set of data but they were unable to obtain satisfactory results.

Gabr et al. (2000) identified two stages of decomposition and proposed a two-stage approach to model the settlement behavior of solid waste landfills with leachate recirculation. They suggested that the early stage of the compressibility of the waste does not conform to the traditional consolidation type of model and compressibility of waste is, therefore, governed by changes in the void ratio due to solids loss, and the material physical size and stiffness. Gabr et al. (2000) proposed a new equation to estimate the volume change in the early stage as a function of octagonal normal and shear stresses. This was based on the assumption that the amount of compression due to the increase in void ratio as well as the compressibility of solids is governed by the matrix stiffness changes under its own weight/external loads. As decomposition takes place, the material breakdown may lead to increase in the surface area, and with the leachate recirculation, a secondary compression (consolidation) type of model with primary and secondary settlement was suggested to be applicable. Gabr et al. (2000) also suggested subdividing the fill in to several layers to avoid numerical complication and to address the changes of the waste properties with depth. Settlement in the bottom layer can be calculated considering them to be in the second stage of decomposition, while the settlement in the upper layers is found using the equation proposed. This approach was not validated with field or laboratory data.

In an attempt to estimate long-term settlement of waste, Hettiarachchi et al. (2003) used first order reaction kinetics to relate the rate of waste decay to the rate of biological compression as the reduction in waste mass should be reflected by increased settlement. They proposed the following model to predict the settlement behavior in a bioreactor landfills.

$$\in = \in_o + \lambda C_i \left(1 - \exp(-Kt)\right) \quad (1)$$

Where $t$ = time since placement $(days)$, $\in$ = strain $(\%)$ at time $t$, $\in_o$ = initial strain $(\%)$, $\lambda$ = correlation coefficient of compression due to biodegradation $(kg^{-1})$, $C_i$ = initial mass of the biodegradable waste $(kg)$, and $K$ = the first order kinetic constant $(day^{-1})$. Performance of this model was compared with those proposed by Wall and Zeiss (1995) and El-Fadel and Al-Rashed (1998). Data from four different test bioreactor landfills were analyzed using all three models to predict the time dependent settlements. It was found that model proposed by Hettiarachchi et al. (2003) was able to provide a better prediction than both Wall and Zeiss (1995) and El-Fadel and Al-Rashed (1998) models.

However, since the above efforts were simple curve fitting techniques, a joint project between New Jersey Institute of Technology and University of Calgary was initiated in early 2002 to develop a model based on fundamental mechanisms to predict the settlements in bioreactor landfills. The following section elaborates this effort.

## GOVERNING EQUATION FOR SETTLEMENT OF WASTE

In this analysis, the waste mass is assumed to be consisting of infinitely extended horizontally parallel layers of waste. Weight of an elementary waste layer of $dz$ thickness (see Fig. 1) at time $t$ can be found by two ways; one considering the change in strain and another considering the change in the mass.

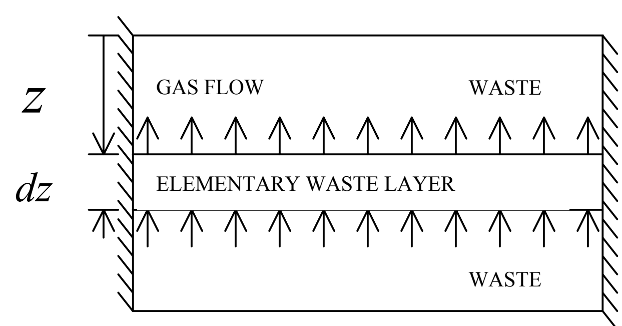


*Fig. 1. Elementary waste layer considered in the analysis.*

Thickness of the waste layer $dz$ at time $t$ is,

$$dz = (1 - \in) dz_o \quad (2)$$

where $\in$ is strain at time $t$ and $dz_o$ is the initial thickness of the waste layer. Weight of the waste layer per unit area $[M_w(t)]$ can now be written as,

$$M_w(t) = \rho(dz)(1) \tag{3}$$

where $\rho$ is the density of the waste in the layer considered at time $t$. Considering the first order kinetics, an equation can be written for the mass of the waste layer per unit area at time $t$ as,

$$M_w(t) = \rho_o dz_o \left[ f_1 + f_2 \exp(-Kt) \right] \tag{4}$$

where $\rho_o$ is the initial density of waste. Non-degradable fraction of the initial waste mass is taken as $f_1$. Since the degradability of waste is not homogeneous, it would be best if the degradable fraction of the initial waste mass was divided into few classes depending on the degree of the degradability. But for the simplicity the whole degradable mass is taken as one fraction $(f_2)$. The constant of the first order reaction kinetics of the degradable fraction of the waste is taken as $K$. Now equations (2), (3) and (4) produce the following relationship.

$$\rho(1-\in) = \rho_o \left[ f_1 + f_2 \exp(-Kt) \right] \tag{5}$$

Greenhouse gases are produced by waste as a result of decay. But only decomposition itself is not the reason for the increased strain in the waste. The movement of gases to the surface should occur after waste decomposition. The above should be included in order to fully account the vertical settlement and subsequent re-arrangement of waste. Therefore, the gas permeability will be incorporated into the model to estimate delayed settlement due to dissipation of gas pressure. Also raveling by transporting waste particle with the leachate flow can be accounted by both the reduction in gas permeability and the increase in waste density.

An equation for the rate of strain can be generated by differentiating equation (5) with respect to time.

$$(1-\in)\frac{\partial \rho}{\partial t} - \rho \frac{\partial \in}{\partial t} = -\rho_o f_2 k \exp(-Kt) \tag{6}$$

Equations (5) and/or (6) explain the variation of waste density and strain with time and hence can be considered as the relationship which is the governing equation of waste settlement. Right hand side of the equation demonstrates how mass is converted into a gas as a result of biodegradation while left-hand side of the equation explains how density and strain vary accordingly.

The equation (5) and/or (6) should also represent the waste settlement behavior of a selected layer of waste, which is located at a certain depth from the top surface of the waste mass. But the effect of depth on the settlement process looks missing from the final form of the equation. When the waste is decayed a void space is created in the waste, which occupies greenhouse gases under pressure. These gases flow through voids to the surface of the landfill, causing an increase in the effective stresses at that depth. This should act immediately to break the waste structure to let the waste particles gets rearranged more densely. Therefore stress level also play an important role in the settlement process, but is also absent from the governing equation. But since the stress at a certain depth in waste is a function of both density and depth, although not apparent the effect of both these missing terms are already included in the model.

The density of waste that appears in the governing equation could be expanded to accommodate other important variables such as stress level and depth. Use of density as a variable instead of a constant, makes this approach superior to other existing waste settlement models. This is well demonstrated by the fact that the model proposed by Hettiarachchi et al. (2003) which is given in equation (1) can be easily deduced from equation (6) by making the waste density a constant.

Although the governing equation is capable of linking biodegradation with strain, its capacity to capture any contribution of raveling in the settlement process cannot be evaluated directly. When waste layers become denser, as a result of rearrangement after decomposition, it may reduce the chances for raveling. Therefore, gas permeability and density of waste should be able to give an indirect measurement of the degree of raveling due to leachate recirculation. In addition the inclusion of parameters to account for moisture content and the level of nutrients available are considered as future improvements to the model.

The nature of the problem will allow consideration as a one-dimensional model. However, if there are complications, it can be easily extended to a full 3-D model. A numerical technique will be used for model calculations. Since the current governing equation is 1-D, a finite difference method (FDM) is used for the analysis. It is being planned to compare the model predictions with the data that will be collected from a field test bioreactor that will be constructed in Calgary, Canada. Model will be validated with this data before it is recommended for the general use as a design tool. It is believed that the proposed approach will make a revolutionary change in design as well as construction of bioreactor landfills.

SUMMARY

A summary of literature review was provided to identify the mechanisms of waste settlement and the attempts of modeling settlement behavior in a bioreactor landfill. Literature review showed the absence of models that can simulate the field conditions. New set of governing equations was derived to explain the waste settlement behavior of a bioreactor landfill. New approach treats density of waste as one of the variables. Use of density as a variable allows, the depth and the stress level available in the waste to be incorporated into the model.

Leachate recirculation helps raveling by transporting waste particle with the leachate flow. Decomposition followed by dense packing may reduce the chances for raveling. It also can disturb the escape of the gas flow causing a time lag in the settlement process. Therefore gas permeability will be incorporated into the model to quantify the contribution of raveling due to leachate recirculation and also to find the time lag in the settlement process due to generation and subsequent dissipation of greenhouse gases.

This comprehensive model with several new variables and parameters makes the proposed model more accurate and it gives insights for the future improvements. Inclusion of moisture content and the level of nutrients available are considered as further improvements. An improved version of this model is expected make a revolutionary change in designing as well as construction of bioreactor landfills.

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