Journal of Hazardous Materials B139 (2007) 514–522

Journal of Hazardous Materials

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Numerical model to predict settlements coupled with landfill gas pressure in bioreactor landfills

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Available online 2 May 2006

Abstract

Landfills settle due to its weight 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. Traditionally, the compressibility index based on settlement of clays is used to explain the settlement of waste. Literature review showed that there are limited research attempts of landfill settlement predictions by coupling with landfill gas generation and transport. This research describes a model which couples settlement in a bioreactor landfill with the generation and subsequent upward movement of landfill gases. The mass balance of the landfill gas was used to link settlement and gas pressures. In the absence of a closed-formed analytical solution, a computer program was developed to numerically predict the settlements and gas pressures in a bioreactor landfill using landfill geometry and waste properties. Explicitly computed settlement values were then used to predict the pressure profile implicitly. To test the mathematical formulations, a numerical exercise was performed using a single-cell hypothetical bioreactor landfill. The numerical simulation produced satisfactory trends of the settlement and the landfill gas pressure profiles.

Keywords: Settlement; Bioreactor landfill; Biodegradation; Mechanical compression; Modeling

1. Background

Enhanced microbiological activity occurs in a bioreactor landfill to transform and stabilize the decomposable organic waste. Fast degradation rate in bioreactor landfills is an attractive feature of this innovative technology. 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 landfill waste settlement is difficult since the density is dependent upon the waste type, moisture content, depth, and time of placement. A number of factors contribute to changes in waste density with landfill depth, which includes the increased strain in the waste layers due to the weight of the overlying layers [1]. Bottom layers in a deep landfill settle immediately due to the weight of new layers. In addition, as waste decomposition occurs there is settlement over time. These results in a much higher waste density values at the bottom layers compared to that of top layers.

Concepts borrowed from soil-mechanics were used to model the settlement of waste in landfills. Sowers [2] was the first to report the similarity between settlement of waste and peat, where large initial settlements followed by substantial secondary compressions were observed in both materials. Edil et al. [3] also showed that compressibility of solid waste was similar to that of organic soils. However, landfill waste is inherently heterogeneous and anisotropic, therefore, it is more difficult to characterize than soils.

In bioreactor landfills, the collected leachate is pumped back into the waste matrix causing accelerated waste decomposition and gas production. Hence the waste settlement in a bioreactor landfill is different from that of a traditional ‘dry’ landfill. With time waste begins to show high compressibility and fast degradation rate. This manifests significant changes in waste properties and hence stability and settlement of bioreactor landfills. An accurate prediction of volume change is needed for effective operation of leachate recirculation and gas collection pipes, to estimate biogas volume, and to design both intermediate and final covers.

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doi:10.1016/j.jhazmat.2006.02.067

Nomenclature

C_g	concentration of landfill gas (kg m^{-3})
C_c^*	compression ratio (slope of the graph strain versus log of loading stress)
C_s^*	swelling ratio (slope of the graph strain versus log of loading stress)
D	diffusion coefficient (m^3 day^{-1})
g	acceleration due to gravity (m s^{-2})
G	rate of generation of gas per unit volume of waste (kg m^{-3} day^{-1})
G_s	specific gravity of the solids
k_g	landfill unsaturated gas conductivity (m day^{-1})
m	molar mass of the landfill gas (kg mol^{-1})
M	mass (kg)
p	pressure beyond the atmospheric pressure (relative pressure) (N m^{-2})
P_{atm}	atmospheric pressure (N m^{-2})
R	universal gas constant (J mol^{-1} K^{-1})
t	time (day)
T	temperature (K)
v_g	gas velocity (m day^{-1})
Z	height of the waste element (volume = height × unit area) (m^3)

Greek letters

ε	strain (m m^{-1})
λ	first-order kinetic constant (day^{-1})
θ_w	volumetric water content (m^3 m^{-3})
ρ	density (kg m^{-3})
σ'	effective stress (kN m^{-2})

Subscripts

g	gas
i	initial
j	number of the solids group
s	solids
w	water (or leachate)

For dry landfills, one objective of settlement computation was to establish the space that can be recovered at the end of the degradation process. Therefore, landfill designers frequently used the 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 was treated as a single waste mass or the landfill was assumed to be filled in a short time frame. Hence no attention was paid to the settlement during initial construction period. The impact of high settlement during construction of a bioreactor landfill on leachate recirculation and the gas collection pipe networks is a key design factor due to the rapid degradation of waste. Rapid settlement of waste mass can impose a significant load on pipe networks causing distortion and/or damage. Therefore, proper planning is crucial from the beginning and it is essential to know how the waste mass behaves and settles during the period of bioreactor landfill construction and its subsequent operation.

Typically there is immediate settlement of waste upon placement followed by a time dependent component. The settlement that takes place immediately is believed to be due to re-arrangement of the waste skeleton caused by the self-weight. With time, decomposition of waste is a major contributor of landfill settlement.

Current practice in modeling landfill settlement is mostly empirical. These empirical methods heavily rely on laboratory and field data without rigorous theories. El-Fadel and Khoury [4] classified existing settlement models into four broad categories: soil-mechanics based models; rheological models; empirical models; and models that account decay of waste. Only a few time dependent settlement models of bioreactor landfills are cited in the literature. Almost all of them are either direct or adjusted versions of soil-mechanics based models for dry landfills.

Heterogeneity of waste prevents use of simple equations to adequately describe the rate of biodegradation and gas generation. Qualitative models such as those found in Farquhar and Rovers [5] have been proposed to describe 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 model for microbial growth. Such a model relates variation of microbial population to substrate concentration [4].

Most landfill gas transport models are based on the assumption that the landfill can be treated as a porous medium [6,7]. The resulting gas velocity is given by Darcy's law [6,7]. Gas extraction models rely on change in gas pressure between landfill and atmospheric pressures during static or dynamic gas extractions. Young [8] developed a complete model to describe transport of gas within a rectangular cross-section of a landfill. Arigala et al. [9] improved Young's model by incorporating a realistic description of waste biodegradation. In this model Arigala et al. [9] represented the waste by three classes having different degrees of biodegradability similar to that suggested by Findikakis and Leckie [7].

2. Proposed model

The change in volume of waste is mainly due to the load (or stress) acting on it and the mass loss due to decay. Hence mechanisms of waste settlement can be divided into two broad categories, mechanical compression, and biodegradation-induced settlements. Biodegradation creates voids in the waste mass. However, settlement occurs as a result of stress acting on it. Thus, the total settlement has to be modeled as a combination of mechanical compression and biodegradation-induced settlements. This combination is accomplished with the help of a phase diagram consisting of solid, liquid, and gas phases (see Fig. 1). The proposed model keeps track of the changes in the volume in each phase (Eq. (1)). In this manuscript it is assumed that the waste mass is comprised of horizontal waste layers that are parallel to each other and infinite in length. Therefore, volume per unit area can be replaced by corresponding heights. The

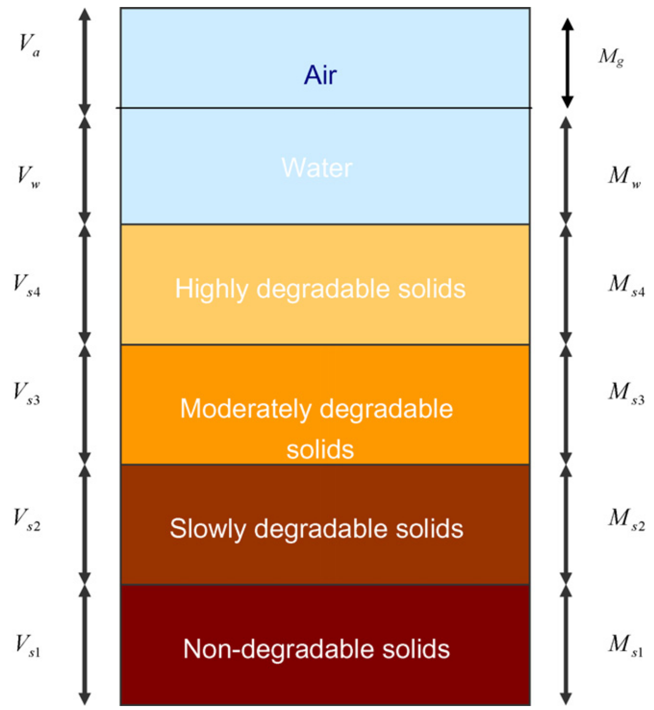

Fig. 1. Phase diagram for waste.

mass of solids, water and volumes of air, water and solids are defined below.

Z_g, volume available for gas in the element at time t.
Z_w, volume of water in the element at time t.
$Z_{sj,i}$, initial volume of the jth group of waste solids, where $j = 1, 2, 3, 4$.
Z_{sj}, volume of the jth group of waste solids at time t, where $j = 1, 2, 3, 4$.
$Z_{si} = \sum_{j=1}^{4} V_{sj,0}$, initial total volume of the solids in the waste element.
$Z_s = \sum_{j=1}^{4} V_{sj}$, volume of the solids in the waste element t.
M_w, mass of water in the waste element at time t.
$M_{sj,i}$, initial mass of jth group of waste solids, where $j = 1, 2, 3, 4$.
M_{sj}, mass of jth group of waste time, where $j = 1, 2, 3, 4$.
$M_{si} = \sum_{j=1}^{4} M_{sj,0}$, initial total mass of solids in the waste element.
$M_s = \sum_{j=1}^{4} M_{sj}$, mass of the total solids in the waste element at time t.

Total height of waste, which will be used to calculate settlement can be written as:

$$Z = Z_s + Z_w + Z_g \tag{1}$$

Movement of gas and moisture is assumed to occur in the vertical direction. Due to the recirculation of leachate the waste is assumed to be always at its field capacity. Gas is expected to reach the top surface where it is mixed with atmospheric air at zero excess pressure.

The waste settlement is caused by compression of voids and solids due to the weight of the overlying waste. Since the strain is a function of stress, mechanical compression at a given depth is a function of stress. While addition of new waste layers increases settlement, loss of mass due to biodegradation causes swelling or rebound. This makes the stress at a given depth a function of time (see Fig. 2). It shows that stress is instantaneously increased due to the construction of a new layer followed by gradual decrease in stress due to biodegradation.

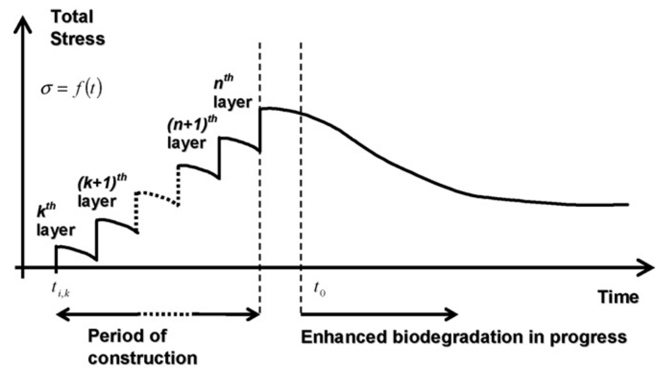

Fig. 2. Stress at kth layer as a function of time.

If the compressibility of the waste is known, then the strains corresponding to a given level of stress can be calculated. In this research, a relationship between mechanical compression and stress was established using laboratory compression tests. Fig. 3 shows the stress–strain relationship of fresh waste. It was obtained from a series of laboratory compression tests [10]. Both curves in Fig. 3 are straight lines in semi-logarithmic plots. Unloading causes a shallower stress–strain curve than that for loading. Fig. 3 shows that the loading produces both elastic and plastic deformations in the waste structure and the unloading produces elastic deformation. Therefore, change in strain corresponding to a given change in stress can be expressed as shown below by Eq. (2).

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

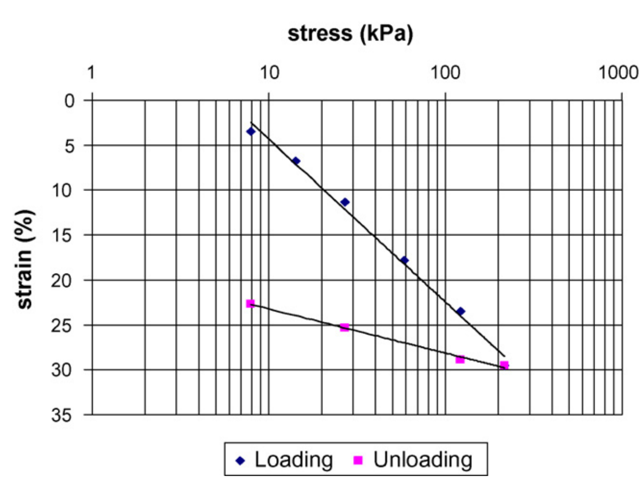

Fig. 3. Stress–strain behavior of fresh waste under loading and unloading.

The change in strain given by Eq. (2) can be converted to the corresponding change in the height (δZ) as shown in Eq. (3), where Z_i is the initial height.

$$\delta Z = Z_i C^* \log\left(\frac{\sigma' + \delta\sigma'}{\sigma'}\right) \tag{3}$$

Similar to soils, waste also comprises three phases: solids, water, and air. But decay of waste solid mass is different from that of soils, where there is no volume change in solids mass of soil. Since waste solids are highly heterogeneous, use of average waste properties could produce incorrect and misleading estimations. In this research, solid phase of the waste was divided into four categories depending on its degradability. Those four categories were non-degradable, slowly degradable, moderately degradable, and rapidly degradable waste.

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 jth group of waste solids and its solution, are presented by Eqs. (4) and (5), respectively, where λ_j the first-order kinetic constant for the jth group ($\lambda_1 = 0$).

$$\frac{dM_{sj}}{dt} = -\lambda_j M_{sj} \tag{4}$$

$$M_{sj} = M_{sj,i} \exp(-\lambda_j t) \tag{5}$$

If the initial solids fraction for each waste group is $f_{sj} = (M_{sj,i}/M_{si})$, then the total solid waste mass can be expressed as:

$$M_s = M_{si} \sum_{j=1}^{4} f_{sj} \exp(-\lambda_j t) \tag{6}$$

The volume of the decayed waste (Z_s) can be computed as shown in Eq. (7) where G_{sj} is the specific gravity of the jth group of the waste solids.

$$Z_s = \frac{M_{si}}{\rho_w} \sum_{j=1}^{4} \frac{f_{sj}}{G_{sj}} [1 - \exp(-\lambda_j t)] \tag{7}$$

The total volume (or height) at a given time can be found by subtracting the change in heights due to mechanical compression and biodegradation from the initial volume (Eq. (8)).

$$Z(t) = Z_i - \delta Z_s - Z_i C^* \log\left(\frac{\sigma' + \delta\sigma'}{\sigma'}\right) \tag{8}$$

The volumetric water content is used to determine the change in the liquid phase. Since the volume of the solids and liquids can be found independently, if the total volume is known, volume occupied by gas can be found by subtracting solids and water volumes from total volume.

Considering the amount of gas present in a unit volume of landfill the overall mass balance is established as:

$$(\text{Rateofchangeofgasmassinthewasteelement}) = (\text{gassfluxthroughtheelement}) + (\text{rateofgasgeneration})$$

$$\left(\frac{1}{Z}\frac{\partial M_g}{\partial t}\right) = -\frac{\partial}{\partial z}\left(\rho_g v - D\frac{\partial C}{\partial z}\right) + G(t) \tag{9}$$

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

$$G(t) = -\frac{1}{Z}\frac{\partial M_s}{\partial t} \tag{10}$$

Velocity of landfill gas is calculated using Darcy's equation as shown in Eq. (11).

$$v_g = -k_g \frac{\partial}{\partial z}\left(\frac{1}{\rho_{atm} g}(P_{atm} + p) + z\right) \tag{11}$$

Mass of the gas present in the waste element, its density, and concentration are estimated using ideal gas law (Eqs. (12) and (13))

$$M_g = \frac{m}{RT}(P_{atm} + p) Z_g \tag{12}$$

$$\rho_g = C_g = \frac{m}{RT}(P_{atm} + p) \tag{13}$$

A general governing equation (Eq. (14)), which links landfill gas pressure to settlement, is obtained by combining Eq. (11) to (13).

$$\frac{\partial p}{\partial t} + (P_{atm} + p)\frac{\partial}{\partial t}(\ln Z_g) = \left(\frac{Z}{Z_g}\right)\left(k_g \frac{\partial p}{\partial z} + D\frac{\partial^2 p}{\partial z^2} + \frac{RT}{m}G\right) \tag{14}$$

3. Numerical solution

The idealized landfill cross-section as shown in Fig. 4 was used for the numerical computations. It is assumed that each waste layer had a constant initial height and density at the placement. A flow chart for the proposed method to obtain numerical solution for settlement and gas release is given in Fig. 5. First, strain is computed using waste properties and the geometry of the landfill. Please note that leachate recirculation is not expected to commence until the filling is complete at a future time t_0. Hence, up to that time, t_0, biodegradation-induced strain can be computed using a lower first-order decay constant for each waste group to account for reduced rate of biological activity due to low moisture content. For each time step, once the strain was computed, Eq. (14) was solved for gas pressure. Then, the stress was updated for possible mass loss due to biodegradation as well as for increase in stress due the addition of new waste layers. Once the leachate recirculation has started ($t > t_0$) appropriate first-order decay constants corresponding to field moisture contents were used. This procedure is repeated for each waste layer. The time dependent strain from each layer is summed to obtain the vertical variation of waste settlement with time.

The equations and approximations used in the numerical solution are briefly discussed in the following sections.

Total mass of kth waste layer and the effective stress at the kth node for the $(l+1)$th time step are calculated as shown in Eqs. (15) and (16), where (g/1000) is used to convert the units

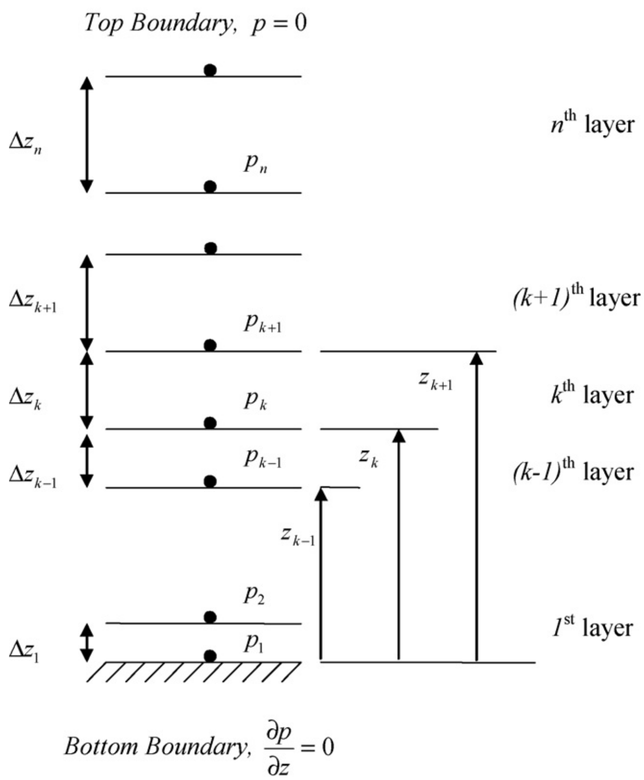

Fig. 4. Idealized landfill cross-section considered in the numerical solution.

from Pa to kPa.

$$M_k^{l+1} = (\rho_c \, \Delta z_i) \sum_{j=1}^{4} f_{sj} \, \exp(-\lambda_j (l \, \Delta t)) + \rho_w \theta_w (\Delta z)_k^l \quad (15)$$

$$(\sigma')_k^{l+1} = \left(\frac{g}{1000}\right) \left(\sum_{j=k}^{n} M_k^{l+1} + \rho_s \, \Delta z_s\right) - p_k^{l+1} \quad (16)$$

Thickness of the kth waste layer for the $(l+1)$th time step and the selection of the compressibility parameters is presented as shown in Eq. (17).

$$(\Delta z)_k^{l+1} = (\Delta z)_k^l - ((\Delta z_s)_k^l - (\Delta z_s)_k^{l+1}) - \Delta z_i C^* \log\left(\frac{(\sigma')_k^{l+1}}{(\sigma')_k^l}\right) \quad (17)$$

Heights of each phase in the kth waste layer for the $(l+1)$th time step can be calculated as shown in Eqs. (18)–(20), where ρ_w (kg m^{-3}) is the density of liquids in the landfill and it is assumed to be equal to density of water.

$$(\Delta z_s)_k^{l+1} = \left(\frac{\rho_c \, \Delta z_i}{\rho_w}\right) \sum_{j=1}^{4} \left(\frac{f_{sj}}{G_{sj}}\right) \exp(-\lambda_j (l \, \Delta t)) \quad (18)$$

$$(\Delta z_w)_k^{l+1} = \theta_w (\Delta z)_k^{l+1} \quad (19)$$

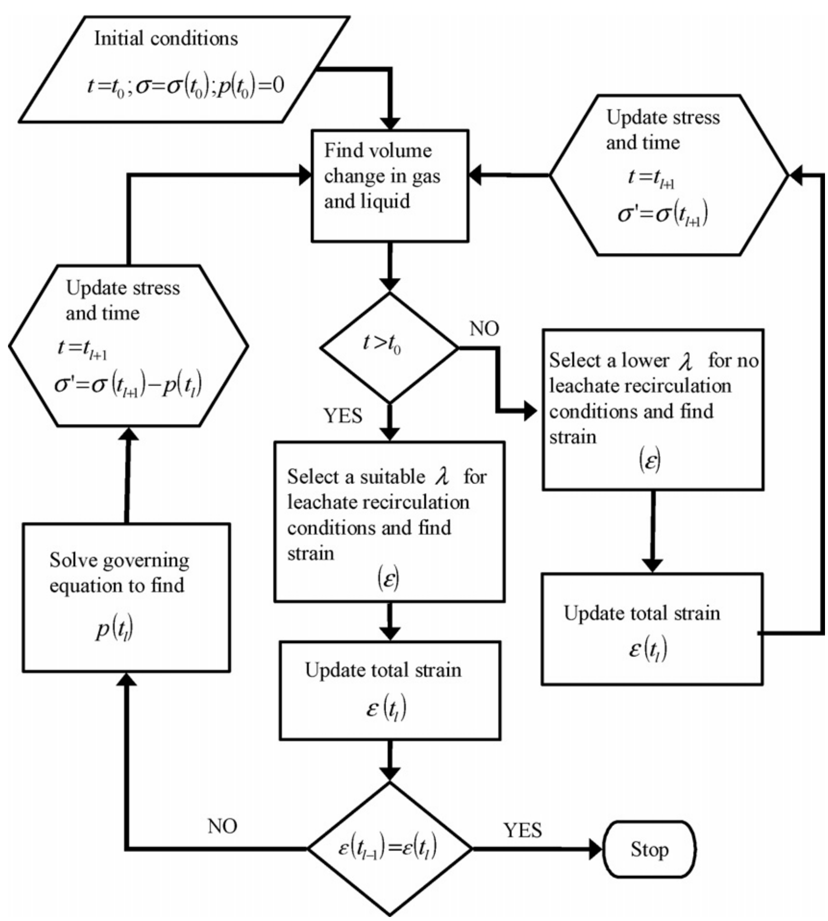

Fig. 5. Flowchart of numerical strain computations for a given waste layer.

$$(\Delta z_g)_k^{l+1} = (\Delta z)_k^l - (\Delta z_s)_k^{l+1} - (\Delta z_w)_k^{l+1} \quad (20)$$

Eq. (14) 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. Eq. (14) was solved implicitly using finite difference approximations (see Appendix A) and finite grid with variable non-uniform grid spacing as shown in Fig. 4. The central difference scheme was used to determine the space derivatives and hence a second order accuracy was expected with respect to space. Following pressure equation (Eq. (21)) was generated by substituting the finite difference approximations (see Appendix A) in Eq. (14).

$$(a_k^{l+1})p_{k-1}^{l+1} + (b_k^{l+1})p_k^{l+1} + (c_k^{l+1})p_{k+1}^{l+1} = d_k^{l+1} \quad (21)$$

The coefficients of Eq. (21) are defined as follows:

$$a_k^{l+1} = \Delta t\left(\frac{\Delta z}{\Delta z_g}\right)_k^l \times \left(\frac{(k_g)_k^l}{\Delta z_{k-1}^l + \Delta z_k^l} - \frac{2D}{(\Delta z_{k-1}^l)(\Delta z_{k-1}^l + \Delta z_k^l)}\right) \quad (22)$$

$$b_k^{l+1} = 1 + \ln\frac{(\Delta z_g)_k^l}{(\Delta z_g)_k^{l-1}} + \Delta t\left(\frac{\Delta z}{\Delta z_g}\right)_k^l \frac{2D}{(\Delta z_{k-1}^l)(\Delta z_k^l)} \quad (23)$$

$$c_k^{l+1} = -\Delta t\left(\frac{\Delta z}{\Delta z_g}\right)_k^l \times \left(\frac{(k_g)_k^l}{\Delta z_{k-1}^l + \Delta z_k^l} + \frac{2D}{(\Delta z_{k-1}^l + \Delta z_k^l)(\Delta z_k^l)}\right) \quad (24)$$

$$d_k^{l+1} = p_k^l + \Delta t\left(\frac{\Delta z}{\Delta z_g}\right)_k^l RTG_k^l - P_a \ln\frac{(\Delta z_g)_k^l}{(\Delta z_g)_k^{l-1}} \quad (25)$$

It is assumed that the initial gas pressure was atmospheric throughout the landfill. It is also assumed that the upper boundary always remain at the atmospheric pressure irrespective of the downward movement of top surface due to settlement. Therefore, the relative pressure at the top boundary is always zero. In general, bottom of the landfill is assumed to be comprised of an impermeable boundary. Therefore, a general no gas flow condition can be imposed at the bottom node.

4. Analysis of a hypothetical landfill

The above numerical equations were computer coded and applied to a simple hypothetical bioreactor landfill to compute the settlements and gas pressures. It should be noted that the objective of this numerical exercise was to demonstrate the efficiency and the capacity of the proposed model. A single-cell bioreactor landfill was taken into consideration. It was assumed that this cell was constructed in 10 waste layers with each layer 0.5 m high at the time of placement. To keep this demonstration simple it was assumed that there was no time delay between the construction of two lifts. The waste properties, initial conditions, and other constants used in the computations are listed in Tables 1–3. Even though the goal of this numerical exercise was to test the accuracy of the solution significant effort was made to choose representative values for model parameters.

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 first, fifth, and ninth waste lifts are given in Fig. 6. Variation of relative pressure (pressure beyond atmospheric pressure) at the top of the first, fifth, and ninth waste lifts and the pressure profiles at the end of 1 month 1 year, 10 years, and 25 years are given in Fig. 7.

Proposed model was able to produce the typical shape of a waste settlement curves (Fig. 6). When additional waste layers are added the existing landfill, old layers are compressed due to the weight of new lifts. This compression is different from layer to layer depending on its location. It is evident from Fig. 6 that the proposed model is capable of capturing this increase in strain due to mechanical compression. Slightly different slopes of the curves suggest that they are settling at different rates. According to Fig. 6a the total settlement reached 26% after 25 years. In order to maintain numerical stability, time step had to be increased

Table 2
Initial conditions and landfill geometry

Atmospheric pressure (kPa)	101
Dry density of waste at the placement (kg m^{-3})	600
Layer thickness at the placement (m)	0.5
Number of layers	10

Table 3
Constants used in the analysis

Landfill temperature (T, K)	315
Diffusion coefficient (D, m^2 day^{-1})	0.6
Universal gas constant (R, J mol^{-1} K^{-1})	8.3
Molar mass of methane (m, g mol^{-1})	44
Volumetric moisture content (θ_w)	0.3
Gas conductivity (k_g, m day^{-1})	3.0
Compressibility ratio (C_c)	7.8
Swelling ratio (C_s)	2.8

Table 1
Group properties of waste solids

Group	Non-degradable waste (1)	Slow degradable waste (2)	Moderately degradable waste (3)	Highly degradable waste (4)
Initial fraction (f_s)	0.35	0.25	0.25	0.15
Specific gravity (G_s)	3.0	2.0	1.2	1.0
Decay constant (λ, day^{-1})	0.0	0.000005	0.00005	0.0005

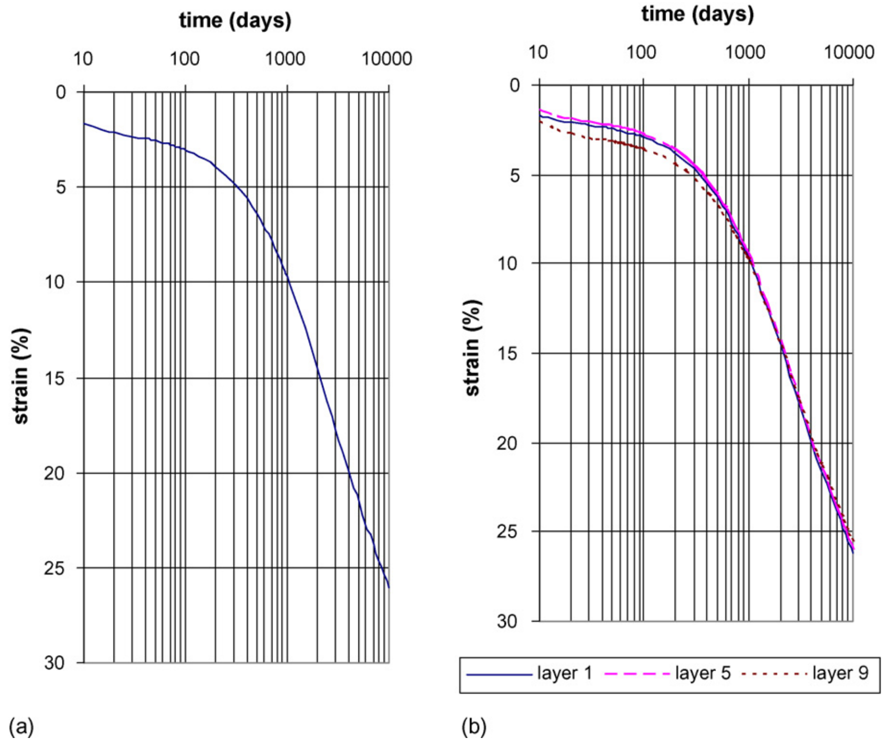

Fig. 6. Variation of total average strain (a) and variation of average strains in the first, fifth, and ninth waste lifts (b).

to 1 day. This resulted in oscillations at the beginning of the simulation (Fig. 7a). However, overall trend of the gas pressure, a gradual dissipation of pressure with time was captured in the simulation (Fig. 7a).

The magnitude of relative landfill gas pressure was in the range of 0–16 kPa throughout the simulation period. High gas pressures in the bottom affect settlement by reducing effective stress. High-pressure values are usually not observed in

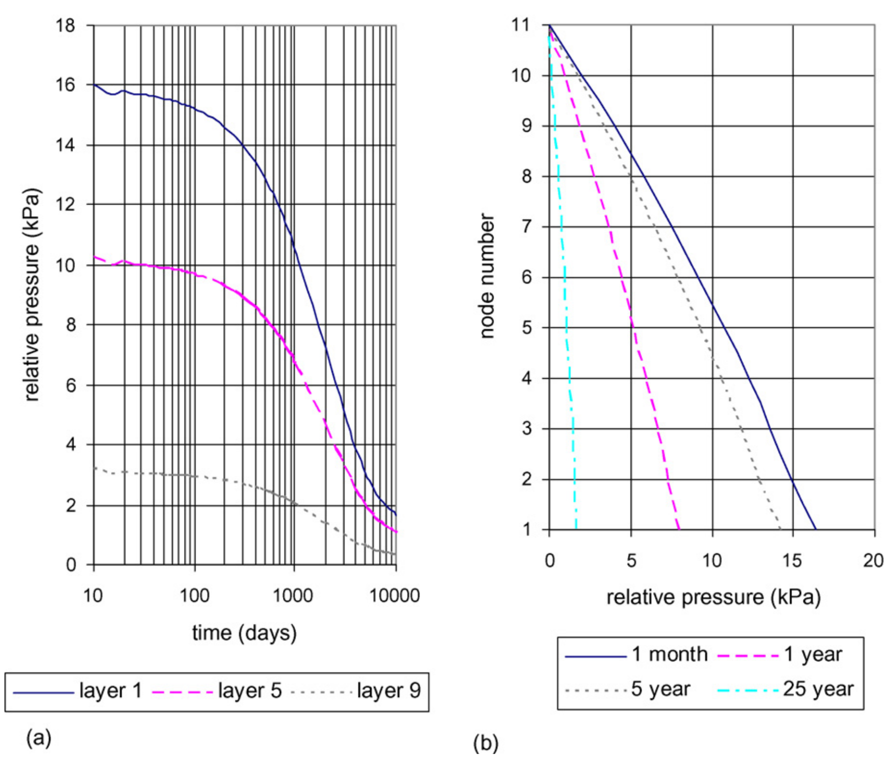

Fig. 7. Variation of average relative pressure in the first, fifth, and ninth waste lifts (a) and pressure profiles at the end of 1 month 1 year, 10 years, and 25 years (b). *Note*: nodes 1 and 11 represent the bottom ant the top surface of the landfill, respectively.

traditional landfills. According to Young [8], maximum pressure is unlikely to be grater than 0.5 kPa (approximately 0.5% of atmospheric pressure). But in biocell landfills, high-pressure build-up is a possibility, due to the accelerated biodegradation if a proper gas extraction system was not installed.

Settlements in the middle and the bottom layers (see layers 1 and 5 in Fig. 6b) are lower than that of top layers of waste (see layer 9 in Fig. 6b). This could be due to the build-up of gas pressure in the landfill. Gas generated at deeper depths takes more time to move to top surface to escape from the landfill than those generated in the upper layers. The pressure profile given in Fig. 7b was resulted from this time lag.

The magnitudes of pressure and settlement are highly dependent on the waste and other properties, listed in Tables 1–3, selected for this simulation. Because of the rather indiscriminate selection of values for input variables in this numerical exercise, magnitudes of settlements, and gas pressures are not discussed in details.

5. General discussion

The methodology presented in this manuscript 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 data. In the absence of a proper theoretical explanation, laboratory experiments are perhaps the best possible alternative to study the mechanical compression of waste. To model the settlements due to biodegradation, it is assumed that waste degradation obeys the first-order kinetic equation (Eq. (3)). Even though there is no direct evidence to prove its validity, many have recognized the accuracy of the first-order equation [11–14]. When predicting 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 resulting from mass lost due to biodegradation.

A diagram was constructed to relate masses and volumes of all phases. Biological degradation of the solid phase was considered. In order to have a better representation and also to reduce simulation errors, solids phase was further subdivided into four groups based on its degradability. Number of subdivisions of the solid phase can be increased or decreased depending on the nature of the waste to be analyzed.

For the simulation, each layer is considered separately starting from its placement in the landfill until end of its biodegradation. Strains in each layer was summed to calculate the total landfill strain and hence the settlement. By considering the initial time of placement, the proposed model has the ability to predict settlement during the construction phase. Since time dependent settlement is a concern in a bioreactor landfill (especially during construction phase) an improved version of the current model could be helpful during design and construction stages. The total strain predicted from this model should be lower than actual due to minor mechanisms that are active during rearrangement of waste after biodegradation, such as arching actions, raveling, and change in particle sizes. Although the contribution from each of those minor mechanisms may not be significant, the total may be high. Identification of each of these minor mechanisms is difficult and hence modeling them is almost impossible. Therefore, the current attempt is limited to modeling the two major mechanisms responsible for the settlements.

The work presented here is only focused on solids and gas phases of waste. Any contribution or influence from the water (or leachate) phase on the total strain, was not taken into consideration. Moisture profile in a bioreactor landfill is highly site specific due to the amount and frequency of leachate recirculation. Authors understand the importance of the moisture phase as an integral part of the settlement analysis and hence are developing an advance model where settlement is coupled with gas generation and moisture movement.

6. Summary

A new methodology was proposed to predict bioreactor landfill settlement. The major mechanisms of waste settlement were identified as due to mechanical compression and biodegradation-induced strains. Then a procedure was proposed to compute settlements due to mechanical compression 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 major mechanisms in settlement computations, the proposed model can capture the major contributors of the waste settlement. A phase diagram was introduced to relate masses and volumes of all phases. In order to better represent the waste characteristics the solids phase was further subdivided into four groups based on degradability. Hence the model can select appropriate values for waste properties depending on the degradation rate.

A numerical exercise was performed to check the suitability of the proposed model and to predict settlements in bioreactor landfills. For this a simple single-cell hypothetical bioreactor landfill was analyzed. Settlement and the landfill gas pressure profiles were generated with the help of a computer program and satisfactory trends were observed.

Acknowledgements

The work described in this manuscript was partially supported by grants from the US National Science Foundation (Grant # OISE-0405900) and the Natural Science and Engineering Research Council of Canada. The authors would also wish to acknowledge the constructive suggestions from two anonymous reviewers, which significantly improved the presentation.

Appendix A

The time derivative of pressure (p) and $\ln Z_g$ are approximated using forward time scheme as shown in Eqs. (A.1) and (A.2).

$$\left(\frac{\partial p}{\partial t}\right)_k^{l+1} = \frac{p_k^{l+1} - p_k^l}{\Delta t} \tag{A.1}$$

$$\left(\frac{\partial}{\partial t}\ln Z_{\mathrm{g}}\right)_k^{l+1}=\frac{1}{\Delta t}\ln\frac{(\Delta z_{\mathrm{g}})_k^l}{(\Delta z_{\mathrm{g}})_k^{l-1}} \tag{A.2}$$

The space derivatives were approximated using center space scheme as shown in Eqs. (A.3) and (A.4). Since the space in not uniform and layer thicknesses vary with time, explicitly computed 'Δz' are used in the denominator.

$$\left(\frac{\partial p}{\partial z}\right)_k^{l+1}=\frac{p_{k+1}^{l+1}-p_{k-1}^{l+1}}{\Delta z_{k-1}^l+\Delta z_k^l} \tag{A.3}$$

$$\left(\frac{\partial^2 p}{\partial z^2}\right)_k^{l+1}=\frac{(p_{k+1}^{l+1}-p_k^{l+1}/\Delta z_k^l)-(p_k^{l+1}-p_{k-1}^{l+1}/\Delta z_{k-1}^l)}{0.5(\Delta z_{k-1}^l+\Delta z_k^l)} \tag{A.4}$$

References

[1] D.E. Bleiker, G. Farquhar, E. McBean, Landfill, Settlement and the impact on site capacity and refuse hydraulic conductivity, Waste Manage. Res. 13 (1995) 533–554.

[2] G.F. Sowers, Settlement of waste disposal fills, in: Proceedings of the Eighth International Conference on Soil Mechanics and Foundation Engineering, Moscow, USSR, vol. 2, Pt.2, 1973, pp. 207–210.

[3] T.B. Edil, V.J. Ranguette, W.W. Wuellner, Settlement of Municipal Refuse, Geotechniques of Waste Fills—Theory and Practice: ASTM STP 1070, Philadelphia, 1990, pp. 225–239.

[4] M. El-Fadel, R. Khoury, Modeling settlement in MSW landfills: a critical review, Crit. Rev. Environ. Sci. Technol. 30-3 (2000) 327–361.

[5] G.J. Farquhar, F.A. Rovers, Gas production during refuse decomposition, Waste Air Soil Pollut. (1973) 483–495.

[6] M. El-Fadel, A. Findikakis, J. Leckie, A numerical model for methane production in managed sanitary landfills, Waste Manage. Res. (1989) 31–42.

[7] A.N. Findikakis, J.O. Leckie, Numerical simulation of gas flow in sanitary landfills, J. Environ. Eng. Div., ASCE 105-EE5 (1979) 927–945.

[8] A. Young, Mathematical modeling of landfill gas extraction, J. Environ. Eng., ASCE 115-6 (1989) 1073–1087.

[9] S.G. Arigala, T.T. Tsotsis, I.A. Webster, Y.C. Yortsos, J.J. Kattapuram, Gas generation transport and extraction in landfills, J. Environ. Eng. 121-01 (1995) 33–44.

[10] C.H. Hettiarachchi, J.N. Meegoda, J.P.A. Hettiaratchi, Settlement of Bioreactor Landfills, Laboratory Investigation of Waste Compressibility: Interim Report, Department of Civil Engineering, University of Calgary, Alberta, Canada, 2004.

[11] L. Edgers, J.J. Noble, E. Williams, A biological model for long term settlement in landfills, in: Useman, Acer (Eds.), Environmental Geotechnology, Balkema, Rotterdam, 1992, pp. 177–184.

[12] S.T. Kang, H.S. Shin, C.Y. Lee, N.H. Lee, Relationship between biological decomposition and landfill settlement at various leachate recirculation rates, in: Proceedings of the Seventh KAIST-NTU-KU tri-Lateral Seminar/Workshop on Environmental Engineering, Kyoto, Japan, 1997, pp. 29–31.

[13] I.S. Oweis, R.P. Khera, Geotechnology of Waste Management, PWS, Boston, 1998.

[14] C.H. Hettiarachchi, J.N. Meegoda, J.P.A. Hettiaratchi, Settlement of Bioreactor Landfills, Modelling of Settlement Behavior of Bioreactor Landfills: Interim Report, Department of Civil Engineering, University of Calgary, Alberta, Canada, 2003.