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

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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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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