Proceedings of the XVII ECSMGE-2019
Geotechnical Engineering foundation of the future
ISBN 978-9935-9436-1-3

doi: 10.32075/17ECSMGE-2019-0226

XVII European Conference
ECSMGE 2019
Reykjavik
on Soil Mechanics
and Geotechnical Engineering

Coupled Thermo-Hydro-Bio-Mechanical Model: A New Modeling Framework for Municipal Solid Waste

Modèle couplé thermo-hydro-biomécanique: un nouveau cadre de modélisation pour les déchets solides municipaux

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ABSTRACT: Landfills remain one of the most dominant waste management options in U.S. and many other countries around the world even today. Recently, the bioreactor landfills are seen as a promising technology for effective management of waste. However, the design, construction and operation of bioreactor landfills is not well established. This is because the understanding on the transient and dynamic coupled interactions between various physico, chemical, biological and thermal processes that influence the behavior of waste and thereby the overall performance of the landfills is not clear. There have been significant efforts over the years towards developing a numerical model that can mathematically simulate the processes that occur within the waste and help predict the overall performance of the bioreactor landfill systems. But, many of these models do not integrate all the major system processes that occur within the waste into their modeling framework and do not holistically assess the influence of the coupled processes on the overall stability and integrity of the landfill and its components. This study presents a numerical framework that accounts for the hydraulic, mechanical, biodegradation and thermal processes within the waste. Each of the individual models integrated into the coupled numerical model is described. A brief overview of the numerical formulation of the coupled thermo-hydro-bio-mechanical model is presented and the application of the model to a typical landfill cell model is discussed. The ongoing research on improvising the predictability of the numerical model is also highlighted.

RÉSUMÉ: Les décharges restent l'une des options de gestion des déchets les plus dominantes aux États-Unis et dans de nombreux autres pays du monde, même aujourd'hui. Récemment, les sites d'enfouissement de bioréacteurs sont considérés comme une technologie prometteuse pour une gestion efficace des déchets. Cependant, la conception, la construction et l'exploitation des sites d'enfouissement de bioréacteurs ne sont pas bien établis. Parce que la compréhension des interactions couplées transitoires et dynamiques entre divers processus physico-chimiques, biologiques et thermiques qui influencent le comportement des déchets ainsi que la performance globale des décharges n'est pas claire. Au fil des ans, des efforts importants ont été déployés pour mettre au point un modèle numérique capable de simuler de manière mathématique les processus qui se produisent dans les déchets et de prédire la performance globale des systèmes de les décharges du bioréacteur. Cependant, nombre de ces modèles n'intègrent pas tous les processus système majeurs qui se produisent dans les déchets dans leur cadre de modélisation et n'évaluent pas de manière globale l'influence des processus couplés sur la stabilité et l'intégrité globales de la décharge et de ses composants. Cette étude présente un cadre numérique prenant en compte les processus hydrauliques, mécaniques, de dégradation et thermiques au sein des déchets. Chacun des modèles individuels intégrés au modèle numérique couplé est décrit. Un bref aperçu de la formulation numérique du modèle thermo-hydro-bio-mécanique couplé est présenté et l'application du modèle à un modèle typique de cellule d'enfouissement est discutée. La recherche en cours sur l'amélioration de la prévisibilité du modèle numérique est également mise en évidence.

Keywords: Municipal solid waste; Bioreactor landfills; Coupled processes; Waste degradation; Heat generation

1 INTRODUCTION

Among various different waste management options (landfilling, incineration, recycling, composting), landfilling remains the major waste management option in the U.S. and many other countries across the globe. There are well-established procedures in practice to design and operate the conventional engineered landfills safely while maintaining the integrity and stability of the landfill and its components. However, the lack of adequate moisture and other favourable conditions in the waste contained in conventional landfills leads to slow waste decomposition rates and thereby prolongs the waste stabilization period. This comes as a long-term liability to the landfill owners with no apparent benefits from the use of such large area of land and other resources.

In this regard, bioreactor landfilling has emerged as a sustainable means of waste management. A bioreactor landfill is similar to a conventional landfill except that it involves recirculation of the collected leachate at the bottom of the landfill or any other permitted liquids using certain leachate recirculation/ injection systems into the waste mass in landfill to enhance moisture levels within the waste across the landfill. Since a major proportion of municipal solid waste (MSW) is comprised of biodegradable organic matter, the addition of moisture accelerates the waste decomposition process and consequently leads to early waste stabilization. Bioreactor landfilling offers several benefits some of the major/primary benefits include, high methane gas generation rates, high settlement rates and low leachate treatment and disposal costs (Sharma and Reddy, 2004). Despite these benefits, the construction and operation of bioreactor landfills is not widespread. This is because the design, construction and operation of a bioreactor landfill is not well understood. The effective performance and operation of a bioreactor landfill is determined by simultaneous interactions between several interdependent complex processes specifically the hydraulic, mechanical, biochemical and thermal processes that occur within the waste mass. Hence, it is of paramount importance to understand these coupled processes to be able to predict the short-term and long-term behavior of the waste and thereby the behavior of the entire bioreactor landfill system itself.

Several researchers have proposed numerical models to predict the behavior of waste for bioreactor landfill conditions. While most of the models focused on simulating either hydraulic, mechanical, biodegradation or thermal processes within the waste, there were only a few that simulated the coupled interactions between these processes, of course with some reasonable simplifications and assumptions. However, none of the models have assessed the influence of the coupled processes within the waste on the holistic performance of the landfill in terms of the landfill stability and integrity of the liner and cover systems. Moreover, there are only a few models that look at the evolution and distribution of temperatures within the landfills. A detailed review of various numerical modeling efforts by other researchers is discussed in Reddy et al. (2017a). This paper presents a new coupled thermo-hydro-bio-mechanical (CTHBM) model that integrates a hydraulic flow model, a mechanical constitutive model, a biodegradation model and a thermal heat conduction model to realistically simulate the coupled behavior of waste in landfills. The formulation of each of the models and their integration is briefly described. The ongoing work on improvising the predictive capabilities of the coupled numerical model is discussed. In addition, a few results showing the application of CTHBM model to a typical landfill model are also presented to demonstrate the predictive capabilities of the numerical model.

2 PRIOR RESEARCH AT UIC

In the past few years a comprehensive research involving field investigations, laboratory tests on synthetic and field waste samples and numerical modeling of MSW behavior based on the characteristics of waste as observed from the experimental studies has been performed at the University of Illinois at Chicago (UIC). Firstly, a thorough field investigation at a landfill in Illinois determining the variation of in-situ moisture and density with leachate injection were monitored across the landfill depth to characterize the field waste. Samples were extracted from different depths for their geotechnical characterization. In addition, geophysical testing was performed to determine other dynamic mechanical properties of waste. Several laboratory investigations were performed involving the testing of waste samples from a leachate recirculation landfill for their geotechnical properties such as the compressibility, shear strength, hydraulic conductivity, specific gravity, and unit weight. These properties were further evaluated at different stages of waste degradation to determine the effect of degradation on waste properties. In addition, biochemical testing was performed on the field MSW samples to determine the biochemical properties (e.g. biochemical methane potential (BMP)) of waste. All the tests performed on field MSW samples were also performed on synthetic waste to have a control on the degradation and thereby evaluate the variation in waste properties with time.

Numerical methods have been extensively used to understand the behavior of MSW and the influence it has on the performance of different components of a landfill. In recent years, a progressive modeling effort has been carried out to realistically and accurately simulate the different processes and their interactions within the waste mass. Most of the initial numerical studies on bioreactor landfills performed at UIC neglected the interdependencies between different processes in landfills and focused primarily on the hydraulic aspects of bioreactor landfills (e.g. moisture and pore pressure distribution). Some of the studies evaluated the effectiveness of different subsurface leachate recirculation systems (horizontal trenches, vertical injection wells, drainage blankets) in uniformly distributing the injected leachate (Reddy et al. 2013a,b; Reddy et al. 2014; Reddy et al. 2015a,b). Thereafter, the numerical investigation was focused on evaluating the stability of landfill slopes under different leachate injection pressures or flow rates (Giri and Reddy 2014a,b,c). Design recommendations were developed based on several parametric analyses performed suggesting the safe injection pressures and setback distance for locating the injection system for different typical landfill slopes.

Recently, there have been efforts to incorporate the coupled interactions between hydraulic, mechanical and biological processes into the numerical model to predict the MSW behavior in landfills (Reddy et al. 2017a). These studies focused on simulating the coupled hydro-bio-mechanical processes to try and understand the complexity associated with the MSW behavior within the landfill and how it affects the holistic performance of a bioreactor landfill. In this regard a mathematical modeling framework that incorporates the coupled hydro-bio-mechanical processes and its impacts on the stability and integrity of the landfill system has been formulated. This mathematical framework integrates a two-phase flow hydraulic model, a 2-D plane strain mechanical model, and a first order decay biodegradation model. The entire mathematical framework is implemented in FLAC, a finite difference code. The published literature on the experimental and numerical investigation on bioreactor landfills performed at UIC is summarized in Reddy et al. (2018).

3 COUPLED THERMO-HYDRO-BIO-MECHANICAL MODEL

The new coupled thermo-hydro-bio-mechanical (CTHBM) model integrates and simultaneously solves a two-dimensional (2D) hydraulic flow model, a mechanical constitutive model, a first order decay biodegradation model and a heat conduction thermal model. The formulation of each of these models is described below.

3.1 Hydraulic model

The hydraulic model is based on the two-phase flow formulation built in FLAC. Since the pore spaces of the MSW disposed in landfills is occupied by landfill gas and leachate, the waste remains mostly unsaturated and the fluid flow through the MSW pore space follows unsaturated flow regime. In the hydraulic model, the fluid flow is governed by Darcy's law given by Equation 1.

$$q_i{}^W = -k_{ij}{}^W \kappa_r{}^W \frac{\partial}{\partial x_j}(P_W - \rho_W g_k x_k) \qquad (1)$$

where, k_{ij} is the saturated mobility coefficient (tensor) defined as ratio of intrinsic permeability to dynamic viscosity; i and j represent the tensor notation for x and y directions respectively; κ_r is the relative permeability for the fluid (a function of saturation, S_w); μ is the dynamic viscosity (m^2/s); P is the pore pressure (Pa); ρ_W is the liquid density (kg/m^3); and g is the acceleration due to gravity (m/s^2). W represents the liquid phase. A similar equation can be written for the gas phase as well to simulate the gas flow in unsaturated porous media.

The relative permeability of the liquid (k_r^W) and gas (k_r^G) phase in the unsaturated MSW are related to S_w through the effective saturation S_e and are expressed by the van Genuchten functions as given by Equation 2 and 3, respectively.

$$\kappa_r^W = S_e^l \left[1 - (1 - S_e^{1/m_{vg}})^{m_{vg}}\right]^2 \qquad (2)$$

$$\kappa_r^G = (1 - S_e)^l \left[1 - S_e^{1/m_{vg}}\right]^{2m_{vg}} \qquad (3)$$

where κ_r^W and κ_r^G are the relative permeability of leachate and gas respectively; S_e is the effective saturation given by $S_e = \frac{S_W - S_r}{1 - S_r}$; S_W is the saturation corresponding to liquid phase; S_r is the residual saturation; m_{vg} is van Genuchten parameter, m_{vg}=1-1/n_{vg}; n_{vg} is the pore-size distribution parameter and is also related to the steepness of the van Genuchten curve; l is the pore connectivity term which is usually taken as 0.5 for soils, but can be different for MSW. A detailed explanation on how the above equations combine with the fundamental balance laws to predict the fluid flow is described in Reddy et al. (2017b).

3.2 Mechanical model

The mechanical model implemented in the CTHBM model is a 2D plane-strain formulation of the Mohr-Coulomb (MC) elastic-perfectly plastic constitutive model where the mechanical computations of the constitutive model are based on effective stresses. The failure envelope is defined by the MC yield function and is given by Equation 4.

$$f^s = \sigma_1 - \sigma_3 N_\phi + 2c\sqrt{N_\phi} \tag{4}$$

where $N_\phi = \frac{1+sin\phi}{1-sin\phi}$, ϕ is the friction angle (degrees), c is the cohesion (Pa), σ_1 and σ_3 are the major and minor principal stresses (Pa). The shear potential function defining the direction of plastic shear strain follows a non-associative flow rule. A detailed explanation on the numerical implementation and stress calculation for the MC model of this form is presented in Reddy et al. (2017b).

3.3 Biodegradation model

The MSW typically consists of organic matter than can undergo anaerobic decomposition to produce predominantly methane (CH_4) and carbon dioxide (CO_2). In the CTHBM model the biodegradation and CH_4 gas generation was formulated based on first order decay kinetics. The biodegradation model used in this study is based on USEPA's LandGEM model. The biodegradation model quantifies the rate of methane (CH_4) gas produced, $q(t)_{CH_4}$, with time based on the mass of the waste in the landfill as given by Equation 5.

$$q(t)_{CH_4} = kL_0 M e^{-k*t} \tag{5}$$

where k is the decay rate constant (yr^{-1}), L_o is the BMP of the waste (m^3/Mg), M is the mass of MSW (Mg), e is the base of natural logarithms, and t is time (years). The rate of waste biodegradation is formulated to account for both moisture and waste temperature as in Equation 6.

$$k(S,T) = \frac{T(mf_w+n)}{C_N\left[1+\exp\left(\frac{T}{4}-18\right)\right]} \tag{6}$$

where $f_w=(S_w-S_r)/(1-S_r)$ is the water content factor similar to effective saturation (S_e), T is the temperature of the waste, m and n are linear constants based on the lower and upper bounds of k which were assumed to be 0.05 and 0.3, respectively, and C_N is a normalization constant. The extent of biodegradation of the waste was represented by the degree of degradation (DOD) which is defined as the ratio of CH_4 gas generated over the BMP of the waste. A detailed explanation on the functionality of the biodegradation model and its influence on waste properties are provided in Reddy et al. (2017b).

3.4 Thermal model

The thermal model incorporated into the CTHBM model is a one-dimensional (1D) heat conduction model developed by Hanson et al. (2013) which accounts for seasonal temperature changes at the ground surface and temperature dependent heat generation induced by biodegradation. The heat transfer in the MSW landfills was described by the classical 1D heat conduction formulation as shown in Equation 7.

$$k_t \frac{\partial^2 T}{\partial z^2} + \dot{q} = C_t \frac{\partial T}{\partial t} \tag{7}$$

where k_t is coefficient of thermal conductivity (W/m-K), $\dot{q}$ is rate of heat generation (heat source term) (W/m^3), C_t is volumetric heat capacity (kJ/m^3-K), T is temperature, z is distance, and t is time. The heat generation from biodegradation was represented by heat generation rate functions that were developed empirically from the field investigations of temperature data at different landfills with waste of different ages (Hanson et al., 2013). The heat generation functions accounted for the normal landfill operations (placement rate, placement moisture and placement waste density) and were based on the net heat gain from the waste decomposition. An exponential growth-decay heat generation rate function was formulated to simulate this heat generation in landfills (Equation 8).

$$H = A\left[\frac{Bt}{B^2+2Bt+t^2}\right] e^{-\sqrt{\frac{t}{D}}} \tag{8}$$

where H is the heat generation rate (W/m^3), A is the peak heat generation factor (W/m^3), B is the shape factor (days), *D* is the decay rate factor (days), and *t* is the time (days). The model also incorporated seasonal temperature variations into the thermal model to realistically predict the spatial and temporal distributions of temperature within the landfills. This model was successfully verified and integrated into the CTHBM model to predict the spatial and temporal distribution of temperatures within the landfill. A detailed explanation on the thermal model is presented in Hanson et al. (2013)

3.5 Integrated framework

A simple schematic showing the conceptual framework of the CTHBM model is shown in Figure 1.

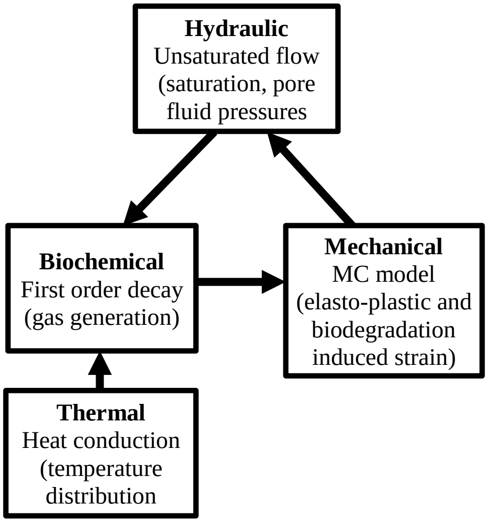

Figure 1. Schematic of the CTHBM conceptual framework.

Once the initial setup of the geometry of the landfill model is completed specific initial and boundary conditions with regard to hydraulic, mechanical, biodegradation and thermal models are assigned. The initial conditions for the hydraulic model include initial saturation and pore water pressures. The initial pore gas pressures are computed based on the capillary pressure law. The boundary conditions for the hydraulic model include fixing the pore water pressures as zero at the bottom of the landfill to simulate leachate collection system (drainage layer). The pore gas pressures could either be calculated based on the calculations of gas generations and using it as the gas pressure source or can be fixed to zero representing instantaneous removal (venting) of the gas generated to prevent pore gas pressures. The former is however the more realistic case in landfills. The transient changes in the saturation and pore pressures under the influence of gravity and under applied fluid sources is computed based on the fluid flow formulation as discussed earlier in the hydraulic model.

The mechanical stresses across the landfill model are calculated based on the mechanical constitutive model. The plastic strains within the waste are calculated using the classical predictor-corrector method based on whether the material has undergone yielding. The change in effective stress causes volumetric strain to occur. Consequently, the volumetric deformation causes changes in pore pressures. This way the numerical formulation allows capturing the coupled fluid-mechanical interactions and incorporates the effects of hydraulic flow on mechanical strains and vice-versa. It should be noted that Bishop effective stress is used in the detection of yield in the formulation of MC model (ICGI 2016).

As it can be seen from Equation 9, the rate of degradation of MSW in landfill is determined by the prevailing moisture (saturation) distribution obtained from the hydraulic model and the waste temperatures from the thermal model. The biodegradation of waste takes place at different rates based on the moisture and temperature of the waste at a specific location. The extent of degradation of waste is then calculated based on the amount of CH4 gas generated which varies spatially across the entire landfill. The phase volumes and ratios, and other geotechnical properties (stiffness, shear strength, saturated hydraulic conductivity) of the waste are altered based on the extent of degradation the waste has undergone. Meanwhile, the temperatures of waste within the landfill are updated based on the conduction of heat from the combined effect of heat generation and seasonal temperature fluctuations as per the thermal model. This incremental solving procedure with time continues until the waste is completely stabilized. In this numerical framework the waste is assumed to be stabilized when the settlement of waste seizes or when the landfill stability is compromised under the dynamically changing waste conditions within the landfill.

4 APPLICATION OF CTHBM MODEL

A numerical simulation demonstrating the applicability of the CTHBM model to predict the influence of coupled processes on the holistic performance of the landfill was carried out. A typical landfill model simulat-ing the placement of waste in layers was used for this numerical exercise. The landfill model comprised of a 75-m subgrade layer of native soil. The waste was assumed to be placed in 3-m thick layers and a total of ten waste layers was assumed to be placed to reach a total waste height of 30-m. A detailed description of the initial properties and boundary conditions pertaining to the landfill model described above is presented in Reddy et al. (2018). A few results obtained from this numerical exercise are discussed below.

Figure 2 shows the variation of waste settlement with time until waste stabilization for two landfill simulations namely CHBM and CTHBM. The landfill simulation CHBM refers to the case where temperature effects on waste degradation are not considered whereas the CTHBM case incorporates the influence of waste temperature on rate of waste degradation as per the biodegradation and thermal model formulation discussed earlier. The influence of waste temperatures on waste degradation and waste settlement is clearly seen in Figure 2. The rate of settlement is much faster in the CHBM case because the waste temperatures in the CHBM case are assumed to be set to optimum temperature resulting in high waste degradation rates. In the CTHBM simulation, the rate of waste settlement was influenced by the waste temperatures predicted by the thermal. In the CTHBM case the rate of settlement was initially subdued but, in the long-term, the waste settlement rates increased.

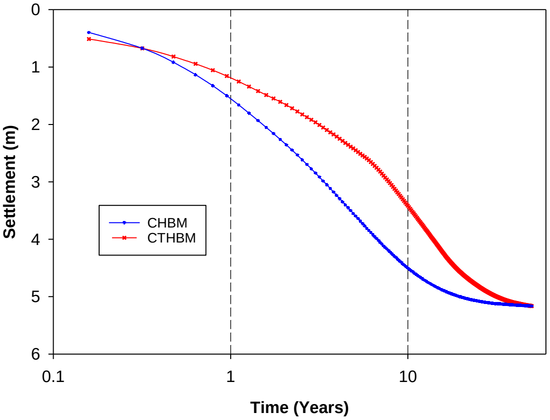

Figure 2. Variation of waste settlement with time for a numerical simulation with and without incorporating temperature effects on biodegradation

Finally, since the biochemical waste characteristics were assumed the same in both the cases, the total waste settlement attained after the waste stabilized was also the same. It is important to note that without incorporating the temperature effects on waste degradation in the numerical model the waste settlement over time can be overestimated as shown in Figure 2. However, the settlement trend observed in Figure 2 must be validated with lab/field data for reliability in the model predictions.

5 ONGOING RESEARCH AT UIC

The ongoing research work at UIC on numerical modeling of coupled processes in MSW is focused on developing the accuracy of the individual system models (hydraulic, mechanical, biodegradation and thermal) to realistically simulate the different processes that occur in the field. Specifically, the biochemical model and the mechanical constitutive model are the areas that need major intervention. Currently, the biodegradation model in the CTHBM modeling framework is based on simple first order decay kinetics. The current biodegradation model may not capture the transport and fate of the biochemical reaction species within the waste. Several biochemical models of varying complexity have been proposed by other researchers, a good brief review of these models is presented in Beaven (2008). However, many of these models are highly parameter intense and hence the practical applicability of these models becomes questionable. In this regard, a two-stage anaerobic digestion model proposed by McDougal (2007) is found to predict the biochemical behavior of waste reasonably well. The leachate chemistry is primarily represented by the concentration of volatile fatty acids and methanogenic biomass, which are the primary variables of the biochemical model proposed by McDougall (2007). Owing to the simplicity and the reasonable accuracy of the biochemical model by McDougall (2007), the current research on biochemical modeling at UIC is focused on utilizing this approach and incorporating the influence of waste temperature on the biodegradation and vice-versa.

One of the other important aspects that is being addressed for improvising the predictive capabilities of the CTHBM model is the mechanical behavior of waste. It is widely known that the majority of the settlement in waste can be attributed to biodegradation of waste and many of the proposed models have also tried to simulate the large settlements that occur with mass loss and how it affects the overall mechanical behavior (strength and deformation) of waste over time. There have been quite a few studies that exclusively looked at the constitutive behavior of waste under drained and undrained conditions and have proposed constitutive models explaining those behaviors. However, the effect of waste degradation on constitutive behavior of waste with time is not clear yet. Some of the studies such as Machado et al. (2008) have investigated the effect of biodegradation on the changes in the mechanical properties of the waste components (e.g. fibrous matter) and were able to demonstrate certain aspects related to degradation and their associated stress-strain paths. However, the authors concluded that such models require large sets of parameters and may require simple yet rigorous testing to arrive at those parameters. An approach similar to the one proposed by Machado et al. (2002, 2008) can be utilized and integrated into the CTHBM modeling framework to simulate the constitutive behavior of waste (considering different waste components) and also the effects of waste degradation on the long-term constitutive response of waste. Research is ongoing to develop and integrate such comprehensive constitutive models into the CTHBM framework and be able to accurately predict the complex coupled behavior of waste realistically and its influence on the holistic performance of the bioreactor landfills.

6 ACKNOWLEDGEMENTS

This material is based upon work supported by the National Science Foundation (NSF) (CMMI #1537514), Itasca Education Program (IEP) and Environmental Research and Education Foundation (EREF). Any opinions, findings and recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the NSF, IEP or EREF.

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