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Research Paper

Numerical modeling of the long term behavior of Municipal Solid Waste in a bioreactor landfill

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ABSTRACT

This paper presents a thermo-hydro-biochemo-mechanical model for simulating the long term behavior of Municipal Solid Waste (MSW) in a bioreactor landfill, in which the multi-physics coupling mechanism plays a dominant role. In the model, a two-stage anaerobic biochemical model based on McDougall's formulation is incorporated into a fully coupled thermo-hydro-mechanical models originally developed for unsaturated porous medium. The mechanical model is a modified Camclay model allowing for biochemical hardening/softening, while the thermal model is described by a classical energy balance equation with a source term accounting for the heat generation from the biodegradation of organic matter. The hydraulic model is an unsaturated flow model using Richard's equation. The derived coupled model is implemented into an in-house built multi-physics finite element code. Finally, numerical simulations were performed to illustrate the capability of the proposed model for estimating long-term settlement of a bioreactor landfill and its aptitude as a landfill management tool for optimizing the landfill operation.

1. Introduction

Recent technological advances in the operation of modern landfills for Municipal Solid Waste (MSW) disposal have led to the emergence of new generation "bioreactor landfill technologies" [52]. The fundamental principle of this new technology is to operate a landfill as a bioreactor to accelerate the decomposition and stabilization of the biodegradable organic waste constituents, which can be done by the recirculation of generated leachate or the addition of water into the landfill [37]. In comparison to the conventional "dry-tomb" landfills, the bioreactor landfills have proven to have many advantages and benefits, which include rapid stabilization of waste, improvement of landfill gas production rate and total yield, significant gain in landfill space and considerable reduction in time and cost of post-closure monitoring and maintenance e.g. [51,6,69]. To optimize the design and operation of the bioreactor landfill, it is essential to be able to accurately assess and predict the landfill gas generation and settlements in both short and long-terms [20]. This study is concerned with those aspects which focus on the long-term settlement behavior of a bioreactor landfill.

Accurate prediction of bioreactor landfill settlement is a great challenge because of the complexity of the landfill system, in which the biochemical reactions of degradable wastes, coupled with thermal, hydraulic and mechanical related processes, play an important role [42,13]. Therefore, the key step to develop any predictive tool for estimating the landfill settlement is to understand the dominant biochemical reactions occurring during the waste decomposition process and thereby create mathematical models to describe those reactions. So far, the former aspect has been widely investigated through both laboratory and field experiments (e.g. [50,1,55,30,21,4,2,36]). Those studies have identified the biodegradation process into two main phases: an aerobic phase followed by an anaerobic phase including four sub-phases: hydrolysis, acidogenesis, acetogenesis and methanogenesis [55]. The former lasts for a short period and can be neglected in most cases, whereas the latter dominates the amount of degraded wastes and gas production. Furthermore, both the aerobic and the anaerobic reactions are affected by a number of environmental factors such as moisture content, pH, temperature, among which the most important is moisture content [37].

With taking into account the two-stage biochemical reactions and associated environmental influencing factors, a great number of mathematical models have been proposed to describe the biodegradation process, such as (i) multi-phases degradation models using Monod kinetics (e.g. [19,27,66]), (ii) two-stage anaerobic digestion models incorporating hydrolysis/acidogenesis and methanogenesis phases, which are correlated by using the primary

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substance of Volatile Fatty Acid (e.g. [42,24,54,11]). In contrast to the formers requiring a great number of parameters, the latters are capable of capturing the dominant biochemical reactions in a simplified manner and thereby have been increasingly adopted in biodegradation modeling.

Both laboratory and field experiments have shown that long-term bioreactor landfill settlement is mainly attributed to mechanically – and biologically – induced compression as well as related creep effects (e.g. [47,7,49,31,26,3,4,59]). With accounting for these mechanisms, a variety of numerical models have been proposed to estimate long-term landfill settlement. These existing models can be divided into two main categories as inspired by Liu et al. [39]; Simões [56]: (i) empirical time-dependent models with or without taking into account decay of waste ([25,58,67,18,8,48]) of which the most common approach is based on Terzaghi's one-dimensional consolidation theory; (ii) integrated analysis models, which incorporate the aforementioned biodegradation models into classical mechanical and/or hydraulic models developed in soil mechanics [28,29,42,26,54,12,65,13,22]. Although the empirical models are useful in practice due to their simplicity, they have very limited capabilities for accurately estimating long-term landfill settlement. In contrast, the integrated analysis models bring an insight into the fundamental multi-physics processes occurring in bioreactor landfills, leading to better prediction of the long-term behavior of the landfills. Up to date, most of existing integrated analysis models are developed for isothermal conditions despite the fact that the considerable variation in waste temperature occurs under field conditions, which can be mainly attributed to the aerobic reaction and leachate recirculation [37]. Although El Fadel et al. [19]; Gholamifard et al. [24] took into account the thermal effects on biological reaction in their hydro-thermo-biological model, the model is incapable to calculate landfill settlement. Additionally, few models [42] employed sophisticated constitutive models within elasto-plastic framework to describe the chemo-mechanical behavior of solid wastes. More importantly, all the existing coupled models were solved in a decoupled manner, which may result in numerical instability as for such highly non-linear system. This study attempts to bring the current integrated analysis a step closer to full thermo-hydro-biochemo-mechanical coupling.

The objective of this study is to incorporate the two-stage anaerobic biodegradation model adopted by McDougall [42] into a fully coupled thermo-hydro-mechanical framework for unsaturated porous media, which has been developed in University of Liege over the last three decades [10,14]. In the derived thermo-hydro-biochemo-mechanical (THBCM) model, the biodegradation model was linked to both the governing mass balance equations for VFA and methanogen biomass and the energy balance equation through source term. The mechanical model adopted is a simplified version of the chemo-hydro-mechanical (CHM) model presented by Liu et al. [40], which has been originally introduced to simulate the behavior of unsaturated clay in presence of chemicals in the pore fluid. The THBCM model was implemented into an in-house built multi-physics FEM code for large deformation simulation (LAGAMINE) [10]. Finally, the simulation was done on a bioreactor landfill with water injection as a boundary value problem to show the performance of the proposed model in terms of predicting the long-term behavior of the landfill. The potential to use this model for optimizing the operation of bioreactor landfills was also explored and discussed.

2. THBCM multi-physics model

The THBCM framework comprises four main ingredient models describing thermal, hydraulic, mechanical and biodegradation behavior. The interdependencies of the different models are schematically shown in Fig. 1. The sub-models will be detailed in the coming sub-sections with emphasis on biochemical model.

2.1. Bio-chemical model

The microbiological activity within the landfills is responsible for the mineralization of the organic content and the production of biogas. This process modifies the hydromechanical properties of the waste and has to be considered if one wishes to perform a rigorous analysis of the MSW behavior.

The biodegradation can be split into two main stages [55], which are quickly described in the following sections.

2.1.1. Aerobic stage

The aerobic phase is the first step of the biodegradation and it begins just after the wastes are landfilled. It lasts at most a few weeks since the deposit of subsequent layers of waste will deprive the previous ones of any oxygen and will cut the aerobic stage short. During this process, the organic content is degraded into macromolecules by bacteria. It is a very exothermal reaction leading to an important temperature raise sometime reaching over 60 °C.

2.1.2. Anaerobic stage

The anaerobic stage begins as soon as the aerobic one ends. It can last 40 to 50 years. This stage consists of the four reactions defined below [55]:

- Hydrolysis: the macromolecules are decomposed by hydrolytic bacteria into smaller molecules (lipid into fatty acid; polysaccharide into monosaccharide; protein into amino acid).
- Acidogenesis: the products of the hydrolysis are transformed into ethanol, organic acid and Volatile Fatty Acid (VFA).
- Acetogenesis: the products of the hydrolysis are consumed and transformed into acetyl acid and hydrogen.
- Methanogenesis: during this last step, the acetyl acid is consumed to produce carbon dioxide and the hydrogen is consumed to produce methane and carbon dioxide.

The two-stage biochemical model described by McDougall [42] was adopted in this study to describe the hydrolysis/acidogenesis and methanogenesis reactions. Fig. 2 presents the structure of this model and different phases of biodegradation as well as associated products: volatile fatty acids (VFA) and methanogenic biomass (MB).

VFAs are intermediate products linking the two stage biochemical reaction and serve as a precursor for methanogen biomass. However, high VFA concentration has inhibitory effects on those reactions [24], which was also taken into account in the model through an inhibitor factor. It is worth noting that the aerobic phase occurring during the early period of biodegradation was neglected due to its short duration [70] and considering the focus of this study on long-term behavior of bioreactor landfills. The formulation of the biochemical model and the governing mass balance equations for organic matter, VFA and MB are presented in the following subsections.

2.1.3. McDougall's formulation for biodegradation

McDougall's formulation neglects the aerobic stage but since the aerobic waste decomposition represents a minor part of the landfill life-time it is, therefore, less significant than anaerobic decomposition [70]. This formulation is used to determine the growth/decay term for the internal variable characterizing the biodegradation. These terms describe the reaction rate and