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Influence of dynamic coupled hydro-bio-mechanical processes on response of municipal solid waste and liner system in bioreactor landfills

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ABSTRACT

A two-dimensional (2-D) mathematical model is presented to predict the response of municipal solid waste (MSW) of conventional as well as bioreactor landfills undergoing coupled hydro-bio-mechanical processes. The newly developed and validated 2-D coupled mathematical modeling framework combines and simultaneously solves a two-phase flow model based on the unsaturated Richard's equation, a plain-strain formulation of Mohr-Coulomb mechanical model and first-order decay kinetics biodegradation model. The performance of both conventional and bioreactor landfill was investigated holistically, by evaluating the mechanical settlement, extent of waste degradation with subsequent changes in geotechnical properties, landfill slope stability, and in-plane shear behavior (shear stress-displacement) of composite liner system and final cover system. It is concluded that for the given specific conditions considered, bioreactor landfill attained an overall stabilization after a continuous leachate injection of 16 years, whereas the stabilization was observed after around 50 years of post-closure in conventional landfills, with a total vertical strain of 36% and 37% for bioreactor and conventional landfills, respectively. The significant changes in landfill settlement, the extent of MSW degradation, MSW geotechnical properties, along with their influence on the in-plane shear response of composite liner and final cover system, between the conventional and bioreactor landfills, observed using the mathematical model proposed in this study, corroborates the importance of considering coupled hydro-bio-mechanical processes while designing and predicting the performance of engineered bioreactor landfills. The study underscores the importance of considering the effect of coupled processes while examining the stability and integrity of the liner and cover systems, which form the integral components of a landfill. Moreover, the spatial and temporal variations in the landfill settlement, the stability of landfill slope under pressurized leachate injection conditions and the rapid changes in the MSW properties with degradation emphasizes the complexity of the bioreactor landfill system and the need for understanding the interrelated processes to design and operate stable and effective bioreactor landfills. A detailed discussion on the results obtained from the numerical simulations along with limitations and key challenges in this study are also presented.

1. Introduction

Landfilling of municipal solid waste (MSW) is one of the most common, cost-effective practices in the United States for proper disposal of MSW. However, the undesirable amounts of landfill gas (LFG) emissions as a result of slow anaerobic decomposition of MSW is one of the major problems in U.S. and other developing countries in the world concerning environment, public health and global climate change (Cai et al., 2014). In the light of rapid urbanization and ever-changing lifestyles there has been an unprecedented increase in waste generated and consequently the number of landfills to dispose it. A recent analysis of data from around 1232 U.S. landfills states that the U.S. MSW stocks at these landfills amounts to about 8.5 billion tons, while demonstrating a great potential to energy recovery and urban landfill mining opportunities (Powell et al., 2016a). In the absence of such attempts at these landfills, they continue to become a long-term liability to the environment with prolonged time for stabilization of MSW and consequently its closure. Over the years, concerted efforts have been made towards achieving sustainability in disposing of MSW. In this regard, the concept of bioreactor landfill technology for MSW has gained favorable response from landfill owners and practitioners in the past decade. The bioreactor landfill as defined by U

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S Environmental Protection Agency (USEPA) is any MSW landfill that operates to enhance microbial processes so as to rapidly degrade the organic waste to achieve early waste stabilization by addition of liquid or air into the landfilled waste. In this study, addition of liquid alone is considered for all the numerical simulations performed. The bioreactor landfills have other advantages such as the potential to expedite waste-to-energy projects due to higher methane gas production, substantially reduce the post-closure monitoring costs and minimize the need for leachate treatment (on-site or off-site), and therefore mitigate some of the serious risks concerning human health and environment (Sharma and Reddy, 2004). The recent statistics imply that MSW landfills that recirculate leachate into the landfills have shown statistically higher gas collection efficiency than the landfills with no leachate recirculation. However, the gas collection efficiency could be significantly higher at leachate recirculating landfills, if adequate gas collection systems are employed (Powell et al., 2016b).

Unlike conventional landfills, the design of bioreactor landfills is uniquely challenging in several aspects. The bioreactor landfills must be designed such that they are physically stable, effective in uniformly distributing adequate levels of moisture through the MSW by leachate injection in a way to achieve high rates of waste degradation for early waste stabilization (Pohland, 1975; Barlaz et al., 1989; Reinhart et al., 2002; Sharma and Reddy, 2004; Townsend et al., 2015). In addition, the bioreactor landfills that involve leachate injection (or recirculation) are invariably subjected to coupled processes including hydraulic, mechanical, biochemical and thermal processes. Consequently, their overall performance evaluation must include successful and accurate prediction of such coupled behavior. Moreover, bioreactor landfills contain several engineered design components (e.g., composite liner system, final cover system typically made of interfaces consisting of geomembrane and geotextiles and leachate recirculation pipes embedded within the MSW) and, it is imperative to evaluate their stability and serviceability over the design period of a landfill. Therefore, the design and performance assessment of bioreactor landfill undergoing coupled processes must consider the overall landfill settlement, slope stability (local and global), evidence of a correlation between geotechnical properties of MSW with extent of waste degradation, changes in hydraulic properties (moisture distribution, pore pressures, saturated hydraulic conductivity, etc.), along with examining the stability and integrity of the composite liner and final cover system.

The MSW settlement comprised of primary compression due to physical mechanism and secondary compression due to biochemical mechanisms (e.g., loss of organics based on anaerobic waste decomposition) has been studied and reported extensively in literature (Sowers, 1973; Jessberger and Kockel, 1993; El-Fadel and Khoury, 2000; Marques et al., 2003; Hossain and Gabr, 2005; Durmusoglu et al., 2005; McDougall, 2007; Yu et al., 2010; Staub et al., 2010, 2013; Sivakumar Babu et al., 2010; Bareither et al., 2010). Most of these mathematical models predicted the overall landfill settlement and the stability of landfill slopes based on individual and/or coupled hydraulic, mechanical and biodegradation process in conjunction with landfill leachate and gas production. Similarly, several studies investigated the influence of leachate injection (without considering biodegradation) as well as the impact of MSW decomposition on the overall stability of composite landfill liner system (Reddy et al., 1996; Jones and Dixon, 2005; Sia and Dixon, 2012). However, only limited experimental, field monitoring and mathematical studies have been performed to assess coupled hydro-bio-mechanical behavior of MSW in landfills.

Several large-scale laboratory experimental studies have been undertaken to study coupled hydro-bio-mechanical behavior of MSW. Although, the investigators used field waste in their experiments, the waste samples were shredded and homogenized to fit within the experimental setup. As a result, their true field heterogeneity was overlooked during those laboratory studies. Some of the other limitations of the previous laboratory experiments include neglecting the spatially changing waste settlement, such as differential waste settlement, while accounting for only the vertical compression as overall MSW settlement. Furthermore, the influence of MSW unsaturated properties, variation in geotechnical properties with degree of degradation of MSW along the landfill depth, extent of moisture distribution, and effects of landfill gas pressures were not considered.

A few mathematical models that focus on coupled hydro-bio-mechanical processes are reported in the literature. For example, a mathematical framework known as the landfill degradation and transport processes (LDAT) was presented by White et al. (2004) to predict the influence of MSW biodegradation (involving enzymatic hydrolysis, acetogenesis and methanogenesis) on the geotechnical properties of MSW and the overall mechanical response of landfills in conjunction with leachate and biogas production. The geotechnical properties of MSW (e.g., unit weight and saturated hydraulic conductivity) were varied with the depth based on empirical relationships. Moreover, the modelers used Monod kinetics to simulate MSW biodegradation and the rate of mass loss in organic solids. McDougall (2007) presented a conceptual framework with one dimensional (1-D) hydro-bio-mechanical (HBM) model for predicting landfill settlements by simulating the biodegradation of waste as a two-stage anaerobic decomposition. The MSW void ratio was correlated with a decomposition-induced void change parameter (Λ) to account for the long-term biodegradation-induced landfill settlement. However, McDougall (2007) overlooked the effects of pore water and pore gas pressures in estimating long-term settlement calculations. Hettiarachchi et al. (2009) combined landfill gas pressure and moisture distribution and developed a one-dimensional (1-D) model for MSW settlement computations. The modelers considered waste degradation based on first-order kinetics. However, the influence of leachate addition in landfills and critical environmental parameters that affect MSW degradation (e.g., moisture and nutrient supply, pH and temperature) were overlooked. Similarly, a numerical modeling study, carried out by Chen et al. (2012), assessed total landfill settlement based on the interaction of solid-liquid-gas phases in MSW landfills. However, the modelers did not account for the waste biodegradation during settlement calculations. A detailed review on the previous efforts on experimental and numerical modeling of individual and coupled processes in MSW landfills is presented by Reddy et al. (2017).

A composite landfill lining system must be stable and able to maintain its integrity over the entire design period of a landfill. In-plane shear characteristics (shear stress and shear displacement) of the composite base and side slope liner consisting of several interfaces, and, critically, an interface of smooth high-density polyethylene (HDPE) geomembrane and nonwoven geotextile, must be carefully evaluated in the long-term as this interface invariably shears more than other known interfaces (e.g., waste-geosynthetic, geosynthetic-subgrade soil interface) in landfill (Reddy et al., 1996; Jones and Dixon, 2005). Over the years, several modelers (Long et al., 1995; Reddy et al., 1996; Jones and Dixon, 2005; Sia and Dixon, 2012) have been able to successfully propose numerous mathematical models to study in-plane shear behavior of composite landfill liner system. For example, Long et al. (1995) studied the shear behavior of composite liner interfaces, using a finite-difference modeling approach. However, in their study, instead of actually modeling the overlying landfilled MSW on liner system, they assumed appropriate boundary conditions and applied an equivalent mechanical load. Reddy et al. (1996) proposed a finite element modeling approach that investigated the shear characteristics of composite side slope and base liner

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