Waste Management xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

Optimization of first order decay gas generation model parameters for landfills located in cold semi-arid climates

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A R T I C L E I N F O

Article history:
Received 26 February 2017
Revised 14 July 2017
Accepted 14 August 2017
Available online xxxx

Keywords:
LandGEM
Afvalzorg simple
IPCC
FOD model
Methane generation
Landfill gas modeling

A B S T R A C T

Canada has one of the highest waste generation rates in the world. Because of high land availability, land disposal rates in the province of Saskatchewan are high compared to the rest of the country. In this study, landfill gas data was collected at semi-arid landfills in Regina and Saskatoon, Saskatchewan, and curve fitting was carried out to find optimal k and L_o or DOC values using LandGEM, Afvalzorg Simple, and IPCC first order decay models. Model parameters at each landfill were estimated and compared using default k and L_o or DOC values. Methane generation rates were substantially overestimated using default values (with percentage errors from 55 to 135%). The mean percentage errors for the optimized k and L_o or DOC values ranged from 11.60% to 19.93% at the Regina landfill, and 1.65% to 10.83% at the Saskatoon landfill. Finally, the effect of different iterative methods on the curve fitting process was examined. The residual sum of squares for each model and iterative approaches were similar, with the exception of iterative method 1 for the IPCC model. The default values in these models fail to represent landfills located in cold semi-arid climates. The use of site specific data, provided enough information is available regarding waste mass and composition, can greatly help to improve the accuracy of these first order decay models.

1. Introduction

Canada has one of the highest per capita waste generation rates in the world (Bruce et al., 2016; Wang et al., 2016, Richter et al., 2017). Statistics Canada reported the 2010 national per capita waste generation rate at about 965 kg/year (2010). Canada has adopted numerous programs in past decades to promote waste minimization, and to assist in the development of more sustainable solid waste management methods. Despite many efforts, waste recycling and composting are less common, and landfilling remains the predominant municipal non-hazardous solid waste treatment method in Canada. According to Statistics Canada (2010), permanent waste disposal such as landfilling accounted for over 75% of all solid waste managed. The reliance on landfilling as the primary treatment method is more pronounced in Saskatchewan, a Canadian Prairie province with a cold semi-arid climate. Saskatchewan has a higher than national land disposal rate of about 86.8% (Statistics Canada, 2010), probably due to the availability of affordable land. One of the major concerns of landfill use is the generation of Greenhouse Gases (GHGs) such as methane (CH_4) and carbon dioxide (CO_2) from the anaerobic decomposition of buried organics. In Canada, GHG emissions from landfills were 19 megatonnes (or 550 kg per capita), making up more than 90% of total Canadian GHG emissions within waste management sector (Environment Canada, 2015).

Landfill gas generation and emissions are of great importance to landfill operators and regulatory agencies, not only because of the contributions of GHGs, but also because of the explosive risk of methane gas. First order decay (FOD) gas generation models were developed and continue to be used by researchers around the world to quantify gas generation during the landfill lifespan due to their user-friendliness and comprehensive sets of default values. Among these FOD models, LandGEM, Afvalzorg, IPCC, Scholl Canyon and EPER are widely studied and reported (Scharff and Jacobs, 2006; Faour et al., 2007; Machado et al., 2009; Bella et al., 2011; Amini et al., 2012; Govindan and Agamuthu, 2014; Mou et al., 2015a). However, questions regarding the reliability and applicability of default values and suggested model parameters have been raised over the past decades (Faour et al., 2007; Govindan and Agamuthu, 2014; Mou et al., 2015a, 2015b), specifically for landfills subjected to unconventional climatic conditions (Ishii and Furuichi, 2013).

Bella et al. (2011) conducted a field study with direct measurements using a flux chamber at a municipal landfill in Italy, and found that LandGEM slightly overestimated methane generation.

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http://dx.doi.org/10.1016/j.wasman.2017.08.028

Govindan and Agamuthu (2014) noted that the IPCC model with default k and degradable organic carbon (DOC) values overestimated methane generation in a Malaysian sanitary landfill. However, Govindan and Agamuthu (2014) found that modeling errors were significantly reduced (by 69 and 81% from 2 different approaches) with the use of site specific parameters. Similarly, Mou et al. (2015a) found that the default parameters used by LandGEM, Afvalzorg and IPCC models failed to represent low-organic waste materials and overestimated methane generation at four landfills in Denmark.

Inconsistencies in the literature on the use of FOD model default parameters are not uncommon. Faour et al. (2007) stated that LandGEM model results fitted reasonably well to actual gas data at three wet landfills in the US with a 1.5 year lag phase. On the contrary, Amini et al. (2012,2013) and Wang et al. (2013) reported that LandGEM generally underestimated methane generation in a number of US landfills. Similar observations were made by Thompson et al. (2009) with Canadian landfills. Mou et al. (2015a) conducted a comprehensive review on 9 gas modeling studies using over 50 landfills in Europe, North America and Asia, and concluded that the ratios between modeled CH_4 generation estimations and field generation and emission measurement results varied from 0.7 to 3.3.

Care should be taken when interpreting and comparing these landfill gas modeling studies, as different model inputs, quantification methods, and assumptions were adopted in different studies. However, all of the above studies have stressed the importance of the use of site specific parameters in gas modeling. Table 1 summarizes results from different studies on FOD landfill gas model parameters. The decay rate (k) for cold, semi-arid landfills derived from empirical models are typically lower, ranging from 0.006 to 0.023 $year^{-1}$, whereas the k value for warmer climates ranges from 0.04 to 0.21 $year^{-1}$. The decay rate is sensitive to the climatic conditions where the landfill is located (Machado et al., 2009, Thompson et al., 2009, Ishii and Furuichi, 2013), and k values are lower for landfills located in dry, cold climates (Thompson et al., 2009). Sufficient moisture is essential for the growth of the microbial community, while a lack of moisture delays the waste decomposition process (Barlaz et al., 1992; Fourie and Morris, 2004). Unlike the decay rate (k), the methane generation potential (L_o), or the degradable organic carbon (DOC), only depends on the type and composition of disposed waste (Thompson et al., 2009). L_o values reported from the literature using field studies and experimental measurements varied from 8 to 214.4 m^3/Mg (Table 1).

Generally, the default set of k values for each landfill gas model are chosen based on the climatic condition (such as precipitation and temperature conditions), while the L_o values or DOC values are selected based only on the waste sources or waste characteristics. For example, IPCC adopted four distinct climate groups (dry temperate, wet temperate, dry tropical, and wet tropical) with different sets of k values. In many reported studies, different approaches have been proposed to determine site-specific k and L_o or DOC values, such as the use of multi-variable precipitation-based empirical equations, direct field measurements using tracer dispersion and a flux chamber, theoretical estimates based on waste chemical composition, and curve fitting to the field data (Machado et al., 2009; Amini et al., 2012; Govindan and Agamuthu, 2014).

The decay rates reported in warmer and wetter climates appeared higher in the literature (Table 1), suggesting a possible correlation between climatic conditions and waste decay rates in FOD models. However, the literature on landfill gas modeling in cold, semi-arid climates is very limited, and most studies focused on methane oxidation of cover soils (Bogner et al. 1997; Zeiss, 2006). This paper reports k, L_o, and DOC parameters by curve fitting using three different FOD models (LandGEM, Afvalzorg Simple and IPCC) with actual gas data in two cold semi-arid landfills in Saskatchewan, Canada. Most landfill gas studies in the literature measured gas generation and emission rates using discrete sampling intervals, and reported gas data as an average value for a given period of time. The present work, however, utilizes continuous daily and monthly recovery gas rates for curve fitting.

The objectives of this paper are (i) to estimate and compare methane generation rates in Regina and Saskatoon landfills with the selected FOD models at default k and L_0 or DOC values; (ii) to determine optimal sets of FOD model parameters by minimizing the residual sum of squares (RSS) values between the predicted and the actual gas rates; (iii) and to examine the effects of different iterative methods on the curve fitting process using mean percentage error.

2. Materials and methods

2.1. The landfills and the waste records

Regina and Saskatoon are both located in the province of Saskatchewan, Canada. Regina is located approximately 160 km from the US border (bordering Montana), while Saskatoon is located more centrally in the province, approximately 250 km northwest of Regina. The citys' landfills are about 270 km apart and both are located in a cold semi-arid climate area. The climate in Regina and Saskatoon is classified as "Dfb" using the Koppen-Geiger classification system, implying a cold climate, with no dry season, and a warm summer (Peel et al., 2007). The average temperatures in Regina and Saskatoon are 3.1 °C and 3.3 °C, respectively (Canada Climate Normals, 2016). The annual precipitation in Regina and Saskatoon in the period from 1981 to 2010 are 389.7 mm and 353.7 mm, respectively (Canada Climate Normals, 2016).

The Regina landfill began operating in 1961, and served as a non-hazardous municipal waste landfill for Regina and surrounding areas. The landfill was capped with a 1 m compacted clay liner and 0.15 m of topsoil (Conestoga-Rovers & Associates, 2006). The total buried waste in the study area is approximately 3.1 million tonnes. The input waste mass was estimated using national statistics and local waste records from three separate periods due to changes in disposal practices and regulations. For example, construction and demolition waste was separated from the main disposal area in 1992 (Conestoga-Rovers & Associates, 2006; City of Regina, 1995–2011; Barlishen, 1996), thereby reducing inert materials and altering average methane generation potential of the buried waste. The 16 ha well field is located in the North part of the old disposal area. The Regina gas collection and management system consists of 27 vertical gas wells at a 15 m depth, a condensation sump and a flare system. Real-time gas data was collected from July 2008 to December 2014. LFG from Regina and Saskatoon landfills was measured automatically via SCADA (Supervisory Control and Data Acquisition system) on a daily basis by a gas analyzer system. In Regina, about 44% of the collected landfill gas was CH_4, 37% was CO_2 and 19% was residual gas during the study period, and the average methane generation rate was about 4.17 m^3/min. Gas residuals were ignored in the gas modeling, and CH_4 and CO_2 fractions were adjusted accordingly. A CH_4 fraction of 54% was used as input for the Regina landfill.

The Saskatoon landfill has been serving the City of Saskatoon and nearby towns since 1955. The non-hazardous municipal landfill site was lined with a 0.45 m clay liner. From 1955 to 1981, waste disposed in the landfill was estimated based on population records and an average waste generation rate of 1.75 kg/capita, and from 1982 to 1997, waste disposed in the landfill was calculated based on a generation rate of 1.7 kg/capita. From 1998 to 2010, the mass of disposed waste was taken from landfill waste

Please cite this article in press as: Vu, H.L., et al. Optimization of first order decay gas generation model parameters for landfills located in cold semi-arid climates. Waste Management (2017), http://dx.doi.org/10.1016/j.wasman.2017.08.028