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Effects of dry bulk density and particle size fraction on gas transport parameters in variably saturated landfill cover soil

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ABSTRACT

Landfill sites are emerging in climate change scenarios as a significant source of greenhouse gases. The compacted final soil cover at landfill sites plays a vital role for the emission, fate and transport of landfill gases. This study investigated the effects of dry bulk density, ρ_b, and particle size fraction on the main soil–gas transport parameters – soil–gas diffusivity (D_p/D_o, ratio of gas diffusion coefficients in soil and free air) and air permeability (k_a) – under variably-saturated moisture conditions. Soil samples were prepared by three different compaction methods (Standard and Modified Proctor compaction, and hand compaction) with resulting ρ_b values ranging from 1.40 to 2.10 g cm^{-3}. Results showed that D_p and k_a values for the '+gravel' fraction (<35 mm) became larger than for the '−gravel' fraction (<2 mm) under variably-saturated conditions for a given soil–air content (ε), likely due to enhanced gas diffusion and advection through less tortuous, large-pore networks. The effect of dry bulk density on D_p and k_a was most pronounced for the '+gravel' fraction. Normalized ratios were introduced for all soil–gas parameters: (i) for gas diffusivity D_p/D_f, the ratio of measured D_p to D_p in total porosity (f), (ii) for air permeability $k_a/k_{a,\mathrm{pF4.1}}$, the ratio of measured k_a to k_a at 1235 kPa matric potential (=pF 4.1), and (iii) for soil–air content, the ratio of soil–air content (ε) to total porosity (f) (air saturation). Based on the normalized parameters, predictive power-law models for $D_p(\varepsilon/f)$ and k_a (ε/f) models were developed based on a single parameter (water blockage factor M for D_p and P for k_a). The water blockage factors, M and P, were found to be linearly correlated to ρ_b values, and the effects of dry bulk density on D_p and k_a for both '+gravel' and '−gravel' fractions were well accounted for by the new models.

1. Introduction

The enhanced atmospheric concentrations of the major greenhouse gases (GHG) carbon dioxide, methane and nitrous oxide may potentially lead to significant regional and global climate shifts with inherent regional and global environmental problems. Methane in particular is a large potential contributor to climate change as its global warming potential (GWP_{100}) is 25 times that of carbon dioxide (IPCC, 2007). Making up 28% of the total anthropogenic methane emissions, solid waste disposal on land constitutes the second-largest anthropogenic source of methane in Europe, after agriculture (Gebert et al., 2010). In terms of total anthropogenic greenhouse gas emissions, i.e. including carbon dioxide release from fossil fuels, the waste sector globally represents the fourth largest source with an annual release of 0.5 Tg CO_2-equivalents (CO_2e) in 2007 (UNFCCC, 2009). Landfill GHGs are produced mainly under oxygen-limited (anaerobic) conditions and can subsequently emit to the atmosphere through the landfill final cover soil (Hilger et al., 1999; De Gioannis et al., 2009). Therefore, the landfill final cover should be designed to promote oxygen exchange between the atmosphere and waste layer to maintain aerobic conditions and high methane oxidation in the final cover soil layer (Berger et al., 2005; Abichou et al., 2006; Moon et al., 2008), and at the same time secure a good hydraulic performance. The recommended design criteria for a landfill final cover system should also include measures to (i) minimize infiltration of precipitation into the waste, (ii) promote good surface drainage, and (iii) resist erosion (US EPA, 1993).

The soil gas diffusivity (D_p/D_o, ratio of gas diffusion coefficients in soil and free air) is the governing transport parameter for gas

Abbreviations: WLR, water-induced linear reduction; RPL, reference-point power law; M, water blockage factor for WLR model; P, water blockage factor for RPL model.

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diffusion under a concentration gradient, while air permeability, k_a (μm^2), is the governing parameter for advective gas transport under a pressure gradient. Soil physical properties such as dry bulk density (ρ_b) and particle size fraction, and soil pore structure parameters including soil–air content (ε), total porosity (f) and pore connectivity–tortuosity as inferred from gas diffusivity, all strongly affect the gas transport parameters (Moldrup et al., 2001). Recently, Hamamoto et al. (2011) investigated D_p/D_o and k_a in differently-compacted, sandy landfill final cover soils and observed an almost linear increase in measured D_p/D_o values and a non-linear increase in measured k_a values with increasing ε in highly compacted soil. Chamindu et al. (2011) found that soil compaction more than soil type was the major governor of D_p/D_o and to some extent also of k_a. Hamamoto et al. (2009) investigated the effect of particle size distribution on gas transport parameters in sandy soils and observed enhanced D_p/D_o and k_a values for the coarser sands (larger mean diameter d_{50}), suggesting that larger pore diameters become available for gas transport with increasing d_{50}.

Until recently, research on landfill final cover soil design has focused on the hydraulic performance and necessary criteria to minimize water infiltration and soil erosion (Jang et al., 2002; Kamon et al., 2003; Meer and Benson, 2007; Moon et al., 2008). Less research has been devoted to the implications of landfill cover soil gaseous phase performance for greenhouse gas emissions from landfill to atmosphere. The recent soil–gas transport studies cited above (Hamamoto et al., 2009, 2011; Chamindu et al., 2011) all imply that soil compaction and particle size fraction are key parameters to understanding landfill cover soil gaseous phase performance. They suggest that further investigations are needed to understand and predict the combined effects of the basic soil physical characteristics on gas transport parameters in landfill final cover soils that typically are constructed of highly compacted loamy or even clayey soils.

This study therefore focused on the effects of particle size fraction and dry bulk density on D_p/D_o and k_a with the following objectives: (i) to measure the D_p/D_o and k_a as a function of soil–air content (ε) for differently compacted landfill cover soil; (ii) to modify recent models for D_p/D_o and k_a by considering the model parameters as a function of dry bulk density, ρ_b; and (iii) to develop a graph that illustrates the effects of dry bulk density and particle size fraction on both D_p and k_a by model sensitivity analyses using the newly-developed predictive models.

2. Materials and methods

2.1. Soil sampling and properties of soil

The considered waste landfill site is located in the Saitama prefecture in Japan. An approximately 2.5-m thick soil layer is currently used as a final cover above the waste layer. The final cover soil at the sampling site is highly compacted and the *in situ* dry bulk density was around 1.90–1.95 g cm^{-3}. Disturbed soil samples were taken from the final cover and were sieved through a 35-mm mesh in the laboratory to eliminate larger fractions. Subsequently, part of the soils were further sieved through a 2-mm mesh to separate '+gravel' and '−gravel' fractions. The basic soil physical properties are given in Table 1. The particle size distributions for both fractions of soil samples are shown in Fig. 1.

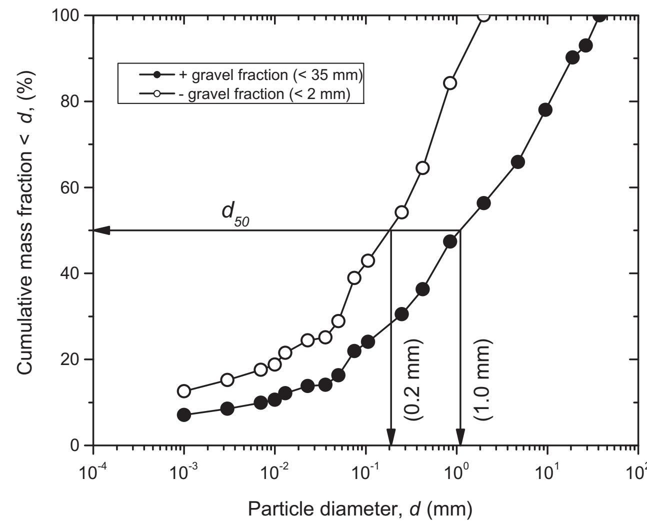

Fig. 1. Particle size distribution for both particle size fractions.

Compaction tests were performed for soil samples at different water contents using Modified (MP, ASTM D 1557-07) and Standard (SP, ASTM D 698-07) Proctor methods. Samples were prepared with six different water contents either by adding distilled water or by air-drying for two fractions of landfill cover soils (see Fig. 2). The different soil samples were then kept for 24 h in closed plastic bags to equilibrate. In the compaction tests, the soil samples were repacked into large soil cores (inner diameter 15 cm, length 12 cm, 2120 cm^3 volume) at two different compaction levels (MP: 2700 kN/m^2 and SP: 600 kN/m^2). The falling height and weight of the rammer for MP and SP compaction levels were 45.7 and 30.5 cm, and 4.5 and 2.5 kg, respectively. Fifty-six blows were applied per layer (MP: five layers, SP: three layers) for both compaction levels. Dry bulk density (ρ_b) ranged from 1.80 to 2.10 g cm^{-3} for the compaction levels. Additionally, hand-compacted (HAC) samples with ρ_b = 1.40, 1.55 and 1.70 g cm^{-3} were prepared for five different water contents in soil cores of 100 and 2120 cm^3, respectively. The soils were packed into the sampling rings in three equal mass portions to make the samples as homogeneous as possible. Each of the portions was compacted using a packer consisting of a steel rod with a disk matching the sampling rings on one end. The number of hits was selected to give the finished small and large core samples volumes of 100 and 2120 cm^3, respectively. When adding subsequent soil portions to the core, the surface of the previous compacted portion was scratched with a thin metal wire to ensure good contact between portions. An overview of sample preparation, treatment, and subsequent measurements is provided in Fig. 2.

Having completed the compaction tests, two 100-cm^3 intact core samples (diameter 5.1 cm, height 4.1 cm) were taken from each of the two molds where the 2-mm particle fraction had been

Table 1
Basic physical and chemical soil properties.

Landfill site	Depth	Particle size fraction (%)[a]				Soil texture[b]	Particle density	Loss of ignition	pH	EC
		Gravel	Sand	Silt	Clay					
	cm	(>4.75 mm)	(4.75–0.075 mm)	(0.075–0.005 mm)	(<0.005 mm)		ρ_s (g cm^{-3})	(%)		(mS m^{-1})
Saitama (Japan)	0–30	36	42	13	9	Silty sand	2.66	2.1	5.6	27

[a] Classification by the ASTM: D422-63(90).
[b] Unified Soil Classification System (USCS).