Gas and Heat Transport in Variably-Compacted Landfill Cover at Variably-Saturated Condition

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Abstract: Understandings of gas and heat transport in the landfill covers are essential for enhancing the landfill site stabilization and reducing the greenhouse and toxic gas emissions. Gas diffusion and thermal conduction are main mechanisms for gas and heat transport in soils. Gas diffusion coefficient and thermal conductivity govern gas diffusion and thermal conduction, respectively. In this study, we developed a unified predictive model for gas diffusion coefficient and thermal conductivity considering soil compaction level. Numerical simulations of gas (methane, carbon dioxide, and oxygen) and heat transport in a landfill cover were performed using the developed predictive model. Increase of compaction level enhanced not only heat transport in the landfill cover but also methane gas emissions due to reduced methane gas oxidation nearby soil surface.

Keywords: Landfill cover soil, gas diffusivity, thermal conductivity, numerical simulation.

1. INTRODUCTION

Landfill sites are a significant source of methane (CH\textsubscript{4}) which has a high global warming potential, estimated to be more than 20 times that of carbon dioxide. The estimated CH\textsubscript{4} emissions from landfills are 550-635 Mt CO\textsubscript{2}-eq. year\textsuperscript{-1} corresponding to about 9\% of global anthropogenic methane emissions (Rogner et al., 2007; Bogner et al., 2008). In addition, the emissions of toxic gases such as a hydrogen sulfide and volatile organic chemicals from landfill sites affect surrounding local environments. The exothermal reactions also occur due to the microbiological processes in the waste layer. These gases and heat produced in the waste layer move through landfill covers and emit to the atmosphere. Therefore, the understandings of gas and heat transport in the landfill covers are essential for enhancing the landfill site stabilization and reducing the greenhouse and toxic gas emissions. Gas diffusion and thermal conduction are main mechanisms for gas and heat transport in soils. Gas diffusion coefficient (D\textsubscript{g}) and thermal conductivity (\lambda) govern gas diffusion and thermal conduction, respectively. Gas diffusion coefficient is controlled by air-filled networks, while thermal conductivity is affected by both solid phase configuration and water-filled pore networks. Since the bulk soil-pore structure is composed of the three phase (air, water, and solid) geometries, gas and heat transport characteristics at different moisture conditions are expected to be interrelated. Such a relation enables to develop a unified predictive model for gas and transport parameters which are promising for simulating simultaneous gas and heat transport in the landfill covers.

In this study, we developed a unified predictive model for gas diffusion coefficient and thermal conductivity considering soil compaction level (i.e., dry bulk density). Numerical simulations of gas (methane, carbon dioxide, and oxygen) and heat transport in a landfill cover were performed using the developed predictive model. The effects of soil compaction level and thickness of the landfill cover on gas and heat transport were investigated.
2. MATERIAL AND METHODS

2.1. Soil Samples and Gas Diffusivity Measurements

A waste landfill site in Saitama Prefecture, Japan, was selected as a sampling location. The final cover soil (size fraction less than 2-mm) was used in this study. The soil texture was a sandy loam. Compaction tests were performed for soil samples at different water content. In the compaction tests, the soil samples were repacked into large soil cores (i.d. 15-cm, length 12-cm) at two different compaction levels (high: 2700 kJ m$^{-3}$ and low: 600 kJ m$^{-3}$). After compaction tests, 100-cm$^3$ core samples were taken inside each repacked large core. The core samples were classified into two different $\rho_b$ ranges (1.80-1.90 g cm$^{-3}$, labelled as extreme compaction (EC), and 1.70-1.80 g cm$^{-3}$, labelled as high compaction (HC)). After the core samples were water-saturated, they were drained at different matric suction and the gas diffusion coefficient ($D_p$) was measured. For comparison, disturbed soil samples at different water contents were repacked into 100-cm$^3$ cores at dry density of 1.55 g cm$^{-3}$, representing normal compacted soils (labelled as normal compaction, NC), and the $D_p$ was measured on the repacked soil samples at different soil-air contents. The $D_p$ was measured on the repacked 100-cm$^3$ soil cores with a diffusion chamber method (Rolston and Moldrup, 2002). Oxygen was used as tracer gas and measured as a function of time in the diffusion chamber. The $D_p$ was calculated according to Osozawa (1998). In this study, the gas diffusion coefficient of oxygen in free air ($D_0$) at 20 °C was taken as $0.20 \times 10^{-24}$ (m$^2$ s$^{-1}$).

3. DEVELOPMENT OF UNIFIED PREDICTIVE MODEL FOR GAS DIFFUSIVITY AND THERMAL CONDUCTIVITY CONSIDERING COMPACTION LEVEL

3.1. Gas Diffusivity ($D_p$) Measurements and Development of Compaction-Dependent Predictive $D_p$ Model

Figure 1a shows the measured gas diffusivity. At the same soil-air content ($\varepsilon$, m$^3$ m$^{-3}$), higher $D_p$ for soils at higher $\rho_b$ were observed. It is because the soil samples at higher $\rho_b$ have lower volumetric water content as compared to those at lower $\rho_b$. This effect is more significant for soils under wet conditions (i.e., lower $\varepsilon$). The following power-law function was fitted against the measured data.

$$\frac{D_p}{D_0} = \alpha_p \varepsilon^{X_p}$$

where $\alpha_p$, $X_p$ are fitting parameters to represent air-filled pore connectivity. Figure 1b shows the fitted $\alpha_p$ and $X_p$ values as a function of $\rho_b$. Both $\alpha_p$ and $X_p$ linearly decreased with increasing $\rho_b$, suggesting that larger pore-networks for loosely-compacted soils more dramatically

Figure 1 (a) Gas diffusivity as a function of soil-air content, (b) fitted $\alpha_p$, $X_p$ as a function of dry bulk density.
Redrawn from Hamamoto et al. (2011).
3.2. Unified Predictive Model for Gas Diffusivity and Thermal Conductivity

In addition to the measured $D_p$ data for landfill cover soils, $D_p$ and thermal conductivity data ($\lambda$, $W \cdot m^{-1} \cdot K^{-1}$) were collected from literature (e.g., Lu et al., 2007). Figure 2 shows transport parameter ($P$: $D_p$ or $\lambda$) normalized by $P$ at fluid saturation ($D_p$: air saturation, $\lambda$: water saturation), $P_{sat}$, as a function of fluid saturation ($\phi/\phi_{sat}$). $\phi$ is the fluid content ($m^3 \cdot m^{-2}$) and $\phi_{sat}$ is the total porosity ($m^3 \cdot m^{-2}$). The $\phi$ for $D_p$ and $\lambda$ represents soil-air content ($\varepsilon$) and volumetric water content ($\theta$), respectively. As shown in Fig. 2, the $D_p$ rapidly increased at higher fluid saturation since at dry condition (higher $\phi/\phi_{sat}$), gas diffusion is enhanced due to well-connected larger pore-networks. On the other hand, more marked increase in the $\lambda$ was observed under lower fluid saturation. Since thermal conduction process is mainly governed by thermal conduction through solid phase, at dry condition, water bridges begin to form between soil particles, and the $\lambda$ starts to increase rapidly because of the improved thermal contact between particles.

![Figure 2 Normalized transport parameter as a function of fluid saturation. Redrawn from Hamamoto et al. (2010).](image)

As shown in solid and dotted lines in Fig. 2, the normalized $D_p$ and $\lambda$ values could be well expressed by $(\phi/\phi_{sat})^{2.5}$ and $(\phi/\phi_{sat})^{1/2.5}$, respectively. Thus, the clear mirror image was obtained for $D_p$ and $\lambda$ behaviours as a function of fluid content. By combining the obtained relation between $D_p$ and $\lambda$, and predictive $D_p$ model as a function of $\rho_b$ (Fig. 2), the following unified predictive model for $D_p$ and $\lambda$ considering compaction level ($\rho_b$) can be derived.

$$\frac{P}{P_{sat}} = \left( \frac{\phi}{\phi_{sat}} \right)^{X_p}$$  \hspace{1cm} (2)

where the $X_p$ in Eq. (2) can be expressed as a function of $\rho_b$ shown in Fig. 1b, and for $\lambda$, inverse of $X_p$ ($1/X_p$) instead of $X_p$. In this study, $P_{sat}$ values for $D_p$ and $\lambda$ were estimated by Eq. (1) and predictive model from literature (Lu et al., 2007), respectively.

4. NUMERICAL SIMULATIONS ON GAS AND HEAT TRANSPORT IN LANDFILL COVER

4.1. Governing Equations for Gas and Heat Transport

In this study, CH$_4$, CO$_2$, and O$_2$ movements in the landfill cover were simulated. By assuming Fickian diffusion process and methane oxidation as main gas transport mechanisms, the governing equation for gas transport for each gas species can be expressed as,

$$\varepsilon \frac{\partial C_i}{\partial t} = D_p \frac{\partial^2 C_i}{\partial z^2} - \chi R_{CH4}$$  \hspace{1cm} (3)
where $C_i$ is the gas concentration (mol m$^{-3}$) of species $i$ (i.e., $i = \text{CH}_4, \text{CO}_2$, or $\text{O}_2$), $R_{\text{CH}_4}$ is the methane oxidation rate (mol m$^{-3}$ s$^{-1}$), and $x_i$ is the stoichiometric factors ($x_{\text{CH}_4} = 1.0$, $x_{\text{O}_2} = 1.5$, $x_{\text{CO}_2} = -0.5$), $t$ is the time (s), $z$ is the length (m). Following Michaelis-Menten equation, the $R_{\text{CH}_4}$ can be expressed as,

$$R_{\text{CH}_4} = \rho_b V_{\text{max}}/\left(\left[1 + \frac{K_{m,\text{CH}_4}}{C_{\text{CH}_4}}\right]^{\frac{x_{\text{CH}_4}}{C_{\text{CH}_4}}} + \frac{K_{m,O_2}}{C_{O_2}}\right)$$

where $V_{\text{max}}$ is the maximum methane oxidation rate (mol g$^{-1}$ s$^{-1}$), $K_{m,\text{CH}_4}$ and $K_{m,O_2}$ are the half-saturation constants of $\text{CH}_4$ and $\text{O}_2$ (mol m$^{-3}$), respectively. In this study, $V_{\text{max}} = 750 \times 10^{-12}$, $K_{m,\text{CH}_4} = 0.29$, $K_{m,O_2} = 0.49$ were used based on de Visscher and van Cleeppan (2003).

When thermal conduction process is considered as a heat transport mechanism, the governing equation for heat transport can be expressed as,

$$C_v \frac{\partial T}{\partial t} = \lambda \frac{\partial^2 T}{\partial z^2}$$

where $C_v$ is the volumetric heat capacity (J m$^{-3}$ K$^{-1}$) and $T$ is the soil temperature (K). The $C_v$ value can be estimated from specific heat and volumetric ratio of each solid, liquid, and air phase. The temperature dependency on $D_p$ is considered as $D_{0,T(K)}/D_{0,293(K)} = (T/293)^{1.67}$ ($D_{0,T(K)}$, m$^2$ s$^{-1}$: gas diffusion coefficient in free air at $T$ (K), $D_{0,293(K)}$, m$^2$ s$^{-1}$: gas diffusion coefficient in free air at 293 (K)).

4.2. Model Domain and Parameters for Numerical Simulations

Figure 3 shows the model domain for the numerical simulations. The thickness of the landfill final cover was set as 1 m. For $\text{CH}_4$ movement, a constant flux boundary of $1.2 \times 10^{-5}$ (mol m$^{-2}$ s$^{-1}$) was applied at the bottom boundary based on the field measurements of methane emission flux at the landfill site where the soil samples were taken in this study. In addition, to express the exothermal reactions in the waste layer, the heat rate, $P(t)$ (W m$^{-2}$), was applied as $P(t) = 200 \exp(-t/10^5)$ based on Klein et al. (2003).

Numerical simulations were performed against two model cases: landfill cover soils at extreme compaction ($\rho_b = 1.85$) and loose compaction ($\rho_b = 1.44$) levels. The moisture condition for each model case was assumed as a field moisture condition represented by $\theta$ at soil-water matric potential of -100 cm H$_2$O. The total porosity, soil-air content, volumetric water content at field moisture condition for each model case were obtained by separate measurements using repacked soil cores in a laboratory. In addition, based on the obtained soil physical properties, volumetric heat capacity ($C_v$) and $D_p$ and $\lambda$ were estimated by Eqs. (1) and (2), respectively. Table 1 shows the parameter values used in the numerical simulations. The COMSOL Multiphysics Ver. 3.5a was used for solving gas and heat transport in the landfill cover soils.
Table 1 Parameter values used in the numerical simulations.

<table>
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<tr>
<th>Bulk density</th>
<th>Total porosity</th>
<th>Soil-air content</th>
<th>Soil-water content</th>
<th>Soil heat capacity</th>
<th>Gas diffusivity</th>
<th>Thermal conductivity</th>
</tr>
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<td>( \rho_b )</td>
<td>( \phi_{tot} )</td>
<td>( \varepsilon )</td>
<td>( \theta )</td>
<td>( C_v )</td>
<td>( D_{g}/D_{o} )</td>
<td>( \lambda )</td>
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<tr>
<td>g/cm(^3)</td>
<td>m(^3)/m(^3)</td>
<td>m(^3)/m(^3)</td>
<td>m(^3)/m(^3)</td>
<td>J/m(^3)/K</td>
<td>W/m(^3)/K(^{-1})</td>
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<tr>
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<td>0.26</td>
<td>3.51E+06</td>
<td>5.91E-04</td>
<td>3.24</td>
</tr>
</tbody>
</table>

4.3. Numerical Simulation Results

Figure 4a shows changes of soil temperature with time in the landfill cover soils at \( \rho_b = 1.85 \) and 1.44. For the extremely-compacted cover soil, soil temperature increased up to 60 °C after 5 days at bottom boundary (at the interface between waste layer and cover soil), while for loosely-compacted cover soil, increased up to 90 °C. Furthermore, soil temperature reach equilibrium with atmospheric temperature after 60 days for the extremely-compacted cover soil but longer time period was needed for the loosely-compacted cover soil. The finding suggests that the extremely-compacted cover soil has higher heat exchange ability since the extreme soil compaction increases contact number of soil particles, giving higher \( \lambda \) value (Table 1). Figure 4b shows changes of methane concentration profile with time in the landfill cover soils at \( \rho_b = 1.85 \) and 1.44. After 120 days, extremely-compacted cover soil exhibited around 90% of CH\(_4\) at the bottom boundary, while CH\(_4\) concentration rapidly decreased nearby soil surface due to a methane oxidation effect. The CH\(_4\) concentration for the loosely-compacted cover soil increased up to only 30% and more marked effect of methane oxidation was observed. Since at field moisture condition, the extremely-compacted cover soil has higher water retention, soil-air content is lower as compared to loosely-compacted cover soil, giving lower \( D_o \) (Table 1). Hence, lower gas diffusion characteristics for extremely-compacted soil caused higher CH\(_4\) concentration and lower methane oxidation effect as compared to the loosely-compacted soil.

![Figure 4](image)

Figure 4 (a) Soil temperature profile and (b) methane concentration in the landfill cover soils at two different compaction levels.

CH\(_4\) and CO\(_2\) emission fluxes to the atmosphere were calculated for cover soils with different thickness and compaction levels shown in Fig. 5. The CO\(_2\) emission flux was higher as compared to the CH\(_4\) emission flux due to methane oxidation near soil surface. In addition, with increasing thickness of the cover soil, CO\(_2\) and CH\(_4\) emission fluxes increased and decreased, respectively. Higher methane oxidation ability for the loosely-compacted soil (Fig. 4b) caused higher CO\(_2\) and lower CH\(_4\) emission fluxes as compared to those for extremely-compacted cover soil. The numerical simulation results suggest that landfill cover soils with extreme compaction may contribute to global warming due to its high CH\(_4\) emission ability since CH\(_4\) has 20 times higher global warming potential than CO\(_2\). In addition, when the thickness of the landfill cover is less than 50 cm, the CH\(_4\) emission flux rapidly increased, indicating methane oxidation is not effective for cover soils with very thin thickness, enhancing the CH\(_4\) emission.
5. CONCLUSIONS

Using a developed unified predictive model for gas diffusivity and thermal conductivity, gas and heat transport in landfill cover soils at different compaction levels were simulated. Higher compaction enhances heat exchange through landfill cover soil, possibly contributing rapid site stabilization in the landfill site. On the other hand, lower gas diffusion characteristic in the highly-compacted cover soils decreased gas diffusivity, hereunder causing enhancement of CH$_4$ emission flux to the atmosphere due to ineffective methane oxidation ability. The methane oxidation ability is also highly affected by the thickness of the landfill cover. In perspective, more accurate simulations to represent more complex gas and heat transport such as heat-induced density-driven gas flow and further model developments for biological kinetic parameters to evaluate methane oxidation rate are needed to reduce and control greenhouse and toxic gas emissions from the landfill site and more rapid site stabilization.

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7. REFERENCES


