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One-dimensional coupled model for landfill gas and water transport in layered unsaturated soil cover systems*

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Abstract: Cover systems are used to prevent water infiltration into a waste body. They also play an important role in controlling landfill gas transport from the waste body to the atmosphere. It is important to assess the flux of landfill gas at the surface of a cover system by considering the coupled effects of rainwater infiltration and gas transport in the cover soils. We have developed a 1D mathematical model for coupled transient gas and water transport in unsaturated cover soils. The coupled model was solved by the finite element method. Results obtained by the proposed model agreed well with experimental data. Based on the proposed solution, the influences of gas pressure, gas permeability, and the thickness of the cover soils on soil gas concentration profiles were investigated. The difference in soil gas concentration reached up to 31% as the thickness of cover increased from 1 to 2 m. Gas concentration at a depth of 0.2 m decreased by 6% as the amplitude of atmospheric gas pressure fluctuation increased from 20 to 100 Pa. The gas concentration increased by only 3% when gas permeability increased by a factor of 2 for a relatively long period of gas migration (e.g., 60 h) under the given conditions. Results suggest that both diffusion and advection should be considered when estimating gas transport in unsaturated cover soils. The numerical model can be used in the design of cover systems in relation to gas breakthrough time, breakthrough concentration, and flux.

Key words: Landfill gas, Cover systems, Unsaturated soils, Gas-water transport, Coupled model
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1 Introduction

Landfills are a major source of methane emissions and contribute about one-third of human-related methane in the USA. Landfill gas (LFG) is generated through decomposition of biodegradable landfilled material under anaerobic conditions and consists mainly of methane and carbon dioxide, with smaller (<0.5%) amounts of non-methane organic compounds (Scheutz *et al.*, 2009; Menard *et al.*, 2012; Amini *et al.*, 2013; Li *et al.*, 2013). Landfill cover systems are constructed to prevent water infiltration and reduce the amount of leachate (Kwon and Cho, 2011; Feng *et al.*, 2013), and they play an important role in controlling LFG migration from the waste body.

Previous studies have focused on gas pressure distribution in landfills and gas transport in municipal solid waste (MSW) layers. Mathematical models have been developed for predicting gas pressure distributions and LFG flow patterns in landfills (Chen *et*

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al., 2000; 2003; Jung *et al.*, 2009). Nastev *et al.* (2001) used TOUGH 2 to simulate gas production and migration in landfills. Li *et al.* (2013) presented a 1D analytical model for pressure distributions in MSW layers. Woodman *et al.* (2013) investigated the effect of settlement and gas on solute flow and transport through treated MSW. Moreover, increasing attention has been paid to gas transport in landfill cover systems. Moon *et al.* (2008) investigated the effect of three different compaction methods on gas permeability of compacted soil liners and found that the hydraulic requirement for the compacted soil liner was not enough to control gas emissions from a landfill. Wickramarachchi *et al.* (2011) studied the effects of dry bulk density and particle size fraction on the soil gas diffusivity in soil and free air and air permeability under variably-saturated moisture conditions. Reichenauer *et al.* (2011) compared the effect of four different plant covers and bare soil on the corresponding concentrations of methane, carbon dioxide, and oxygen in landfill lysimeters filled with compost.

Mathematical models have also been developed to investigate gas transport in unsaturated soils. Mbomimpa *et al.* (2003) developed analytical solutions to calculate the oxygen flux through covers with capillary barrier effects. Kim and Benson (2004) evaluated the relative contributions of four mechanisms of oxygen transport in multilayer composite caps placed over oxygen-consuming mine waste using numerical and analytical methods. They found that diffusion was the dominant process for oxygen transport in the covers. Binning *et al.* (2007) studied a 1D multicomponent unsaturated zone to determine the balance between advective and diffusive transport. They concluded that advection contributed about 23% of the total oxygen flux. However, the coupled transient transport of water and LFGs in layered cover systems has not previously been reported.

Landfill cover systems are always unsaturated since they are located above the groundwater table (Rowe *et al.*, 2004). Migration of LFG in unsaturated soils is mainly determined by the soils' physical properties such as water content and gas permeability, especially in the deeper soils (Poulsen *et al.*, 2001). However, the water content of cover soils is greatly affected by the hydrogeological and weather conditions at landfill sites. Therefore, it is important to investigate the effect of transient water variation in cover soils on gas transport through layered cover systems.

The objective of this work was to develop a coupled gas and water transport model of landfill cover systems to assess the amount of emissions of methane and other landfill gases from landfill cover soils. The model was validated after comparison with experimental data. The effects of cover soil thickness, atmospheric pressure, and gas permeability of the soils on gas concentration breakthrough curves were then investigated. The relative importance of molecular diffusion and convection in relation to coupled water and gas transport in unsaturated soils was also determined.

2 Mathematical model

The proposed mathematical model for gas-water transport in an unsaturated layered cover system is shown in Fig. 1. Above the cover system is the atmospheric environment, and below the system is the waste body. The cover soils consist of *n* different unsaturated layers of thickness l_i and porosity ε_i (i stands for the serial number of each layer). The total thickness of the system is l. The origin of the z coordinate is set to be at the surface of the system.

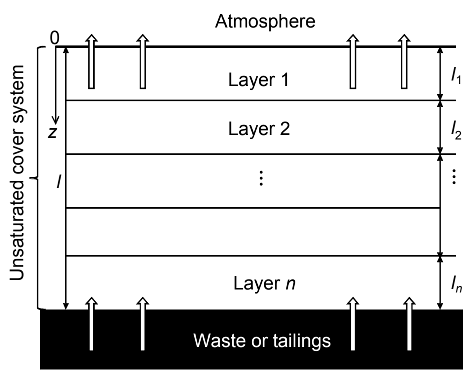

Fig. 1 Schematic of gas-water transport in an unsaturated layered cover system

2.1 Basic assumptions

The mathematical model was developed based on the following assumptions:

(1) Landfill gas transport in the cover soils is a 1D problem; (2) Gas diffusion in the soils can be described by Fick's second law; (3) The effects of gas adsorption and degradation in the cover materials are not considered in this model; (4) The effects of gas dissolution volatilization are ignored; (5) Gas flow is assumed to be isothermal (Feng *et al.*, 2015), incompressible and driven by barometric pressure fluctuations; and (6) Each layer of the cover system is homogeneous.

2.2 Equations governing water content

The equation of water content migration in a layered cover system can be described as (Fityus *et al.*, 1999)

$$\frac{\partial\theta_i}{\partial t}=D_{\mathrm{m},i}(\theta)\frac{\partial^2\theta_i}{\partial z^2}-\alpha_i D_{\mathrm{m},i}(\theta)\frac{\partial\theta_i}{\partial z},\tag{1}$$

where θ_i is the volumetric water content of layer *i*, *z* is the vertical depth, *t* is the time, and α_i is the empirical parameter of layer *i* indicating the relative importance of the capillary force and gravity. $D_{\mathrm{m},i}(\theta)$ is the water diffusion coefficient of layer *i* and can be determined by

$$D_{\mathrm{m},i}(\theta)=D_{\mathrm{m0},i}\mathrm{e}^{\gamma_i\theta},\tag{2}$$

where $D_{\mathrm{m0},i}$ is the water diffusion coefficient when the water content of the soils is approaching zero, and γ_i is the empirical parameter of layer *i*.

The corresponding surface and bottom boundary conditions for the cover soil system can be described as follows:

$$\theta_1=\theta_\mathrm{t},\quad z=0,\tag{3}$$

$$\theta_\mathrm{n}=\theta_\mathrm{b},\quad z=l,\tag{4}$$

where θ_b and θ_t are the given water contents of the bottom layer and the top layer, respectively ($\theta_\mathrm{b}>\theta_\mathrm{t}$).

According to Fityus *et al.* (1999), the initial distribution of the water content of the entire cover is assumed to fit a linear equation:

$$\theta=\frac{\theta_\mathrm{b}-\theta_\mathrm{t}}{l}\times z+\theta_\mathrm{t},\quad t=0.\tag{5}$$

2.3 Equations governing gas diffusion and convection

The convection-diffusion transport of gas in an unsaturated cover system can be expressed as (Townsend *et al.*, 2005)

$$\theta_{\mathrm{g},i}\frac{\partial C_i}{\partial t}=D_{\mathrm{e},i}\frac{\partial^2 C_i}{\partial z^2}-\frac{\partial(v_{\mathrm{g},i}C_i)}{\partial z}+M_i,\tag{6}$$

where C_i is the gas concentration in the pores of layer *i*, $\theta_{\mathrm{g},i}$ is the gas volume content of layer *i*, and M_i is the rate of gas generation of layer *i*. When the gas dissolved in water is not considered, the volume gas content $\theta_{\mathrm{g},i}$ in layer *i* can be expressed as

$$\theta_{\mathrm{g},i}=\varepsilon_i-\theta_i.\tag{7}$$

$D_{\mathrm{e},i}$ is the gas diffusion coefficient of layer *i* and can be determined as a linear function of $\theta_{\mathrm{g},i}$ (Kim, 2000; Bartelt-Hunt and Smith, 2002)

$$D_{\mathrm{e},i}=0.66D_0\theta_{\mathrm{g},i},\tag{8}$$

where D_0 is the gas diffusion coefficient in free air.

Darcy's law can be used to calculate the convective velocity of a gas when gas gravity is ignored (Townsend *et al.*, 2005):

$$v_{\mathrm{g},i}=-\frac{k_{\mathrm{g},i}}{\mu_{\mathrm{g},i}}\frac{\partial p_i}{\partial z},\tag{9}$$

where $k_{\mathrm{g},i}$ is the gas permeability of layer *i*, $\mu_{\mathrm{g},i}$ is the gas viscosity of layer *i*, and p_i is the gas pressure of layer *i*.

As shown by Li *et al.* (2012), the gas flux $g(z, t)$ can be expressed as

$$-\rho\frac{K}{\mu}\times\frac{\partial P(z,t)}{\partial z}=g(z,t),\tag{10}$$

where $P(z, t)$ is the gas pressure for the depth *z* and time *t*. *K* , μ, and ρ are the permeability, the dynamic viscosity, and the density of the gas, respectively.

Specified outward gas flux is assumed at the bottom for scenarios having horizontal landfill gas collection systems or leachate collection systems serving dually as landfill gas collection systems. In this case, it is assumed that a constant pressure was applied at the bottom boundary:

$$P(z,t)|_{z=l}=h(P,t). \tag{11}$$

A constant pressure of 40 kPa was assumed at the bottom of the cover system in case studies as shown in Section 4 ($h(P, t)$ equals 40 kPa in Eq. (11)). Poulsen *et al.* (2001) showed that gas permeability could be expressed as a function of the gas content of soils at a sanitary landfill site in the east of Zealand Island in Denmark. An approximately linear relationship can be obtained between gas permeability and the degree of gas saturation (Bustos and Toledo, 2003; Kim *et al.*, 2013):

$$k_{\rm g}=35.8S_{\rm g}, \tag{12}$$

where $S_{\rm g}$ is the degree of gas saturation in cover soils and can be determined according to the air-water two-phase complementary equation:

$$S_{\rm w}+S_{\rm g}=1, \tag{13}$$

$$S_{\rm w}=\frac{\theta}{\varepsilon}, \tag{14}$$

The relationship between gas permeability and water content can be obtained by combining Eqs. (12)–(14):

$$k_{\rm g}=35.8\left(1-\frac{\theta}{\varepsilon}\right). \tag{15}$$

The top surface boundary of the model is assumed to have a constant gas concentration:

$$C_1(0,t)=0. \tag{16}$$

For the bottom boundary condition, the concentration of gas is assumed to be a function of time, $f(t)$:

$$C_n(l,t)=f(t). \tag{17}$$

The initial distribution of the gas concentration in layer i can be assumed to a function $g(z)$:

$$C_i(z,0)=g(z). \tag{18}$$

The interface of the layered soil system was assumed to obey the following equations (Kim and Benson, 2004):

$$C_i(z_i,t)=C_{i+1}(z_i,t), \tag{19}$$

$$\varepsilon_i D_i\frac{\partial C_i(z_i,t)}{\partial z}=\varepsilon_{i+1}D_{i+1}\frac{\partial C_{i+1}(z_i,t)}{\partial z}. \tag{20}$$

The coupled model for gas and water transport in the cover soils developed in this section can be solved using the modelling software package COMSOL 3.5a (COMSOL, 2013). In the model, the spatial domains were discretized into unstructured Lagrange-linear elements with a maximum global element size of 1×10^{-3} m, and a maximum local element size at the end boundaries of 1×10^{-4} m. The sub-time steps were set to 0.1 h. The corresponding solutions have been confirmed to be independent of the size of time-steps and meshes.

3 Comparisons with experimental data

Yanful (1993) carried out model tests on oxygen migration through a three-layer cover system consisting of a 0.15 m-thick fine sand layer, 0.3 m-thick clay layer, and 0.15 m-thick coarse sand layer from the top to the bottom. The experiments involved four Plexiglas square columns, each of which had an area of 28 cm^2 and a length of 105 cm. Each column was instrumented to measure gaseous oxygen concentration in the pores and volumetric water content. The gas diffusive coefficients of the three layers were obtained by diffusion tests. The effective diffusion coefficients for fine sand, clay, and coarse sand were 2.9×10^{-6} m^2/s, 3.9×10^{-9} m^2/s, and 1.6×10^{-6} m^2/s, respectively. The experimental duration of gas migration in the soils was 65 d. The detailed values of the parameters used in this section are listed in Table 1.

A constant source concentration of oxygen at the top of the column (open to the atmosphere) and a zero flux boundary at the base of the column were applied in the tests. In our study, the initial gas concentration was set to zero as in the study of Yanful (1993). The gas concentration results obtained by the proposed model when the water content reached a steady state were compared with those of Yanful (1993). The results obtained by the model agreed well with the experimental data (Fig. 2), which verified our proposed mathematical model.

Table 1 Experimental parameters used for comparison with our proposed model

Layer	Thickness (m)	D_e (m^2/s)	θ_a	θ_t	θ_w
Fine sand	0.15	2.9×10^{-6}	0.360	0.380	0.020
Clay	0.30	3.9×10^{-9}	0.018	0.455	0.437
Corse sand	0.15	1.6×10^{-6}	0.265	0.320	0.055

Note: values of parameters were cited from Yanful (1993). D_e is the effective diffusion coefficient; θ_a, θ_t, and θ_w are the air-filled, total porosity, and volumetric water contents, respectively

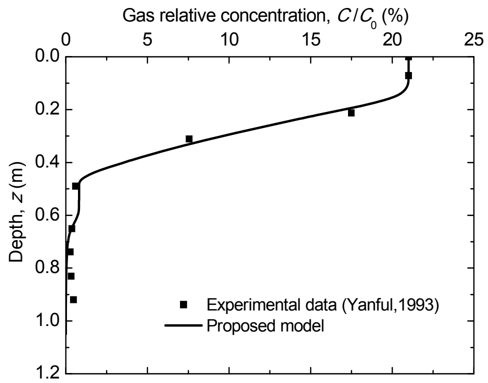

Fig. 2 Comparison of proposed model results with experimental results (Yanful, 1993)

4 Results and discussion

4.1 Input parameters

After verification, the model is applied to investigate a new case. The values of the parameters for water and gas transport in the model are listed in Table 2. The values of empirical constants were referenced as from the experimental study at a landfill site (Fityus *et al.*, 1999; Poulsen *et al.*, 2001). The gas permeability value was obtained from You and Zhan (2012).

When the initial distribution of water content was assumed to be linear, the water content distribution in a 1 m-thick cover layer at different times was as shown in Fig. 3. When the linear distribution of the initial water content and effects of atmospheric pressure on gas and water migration were considered, the curve of water content versus time gradually deviated from the initial linear distribution (Fig. 3). The pressure at the surface was assumed to be constant (equal to atmospheric pressure). The water content at a depth of 0.5 m was increased by only 4% when the time increased from 2 h to 100 h. When the time increased from 2 h to 40 d, the water content at the same depth was increased by 17%.

Table 2 Values for gas-water transport parameters adopted in the model

Parameter	Value
Gas density, ρ_g (kg/m^3)	1.17
Gas viscosity, μ_g (kg/(m·s))	1.83×10^{-5}
Gas permeability coefficient, k_g (m^2)	1×10^{-13}
Porosity, ε	0.4
Empirical constant, γ	11.05
Empirical constant, α (m^{-1})	0.3
Cover thickness, l (m)	1
Initial water content, θ_0	0.1
Gas concentration constant, C_0 (mg/L)	1
Gas free diffusion coefficient, D_0 (m^2/s)	2.0×10^{-5}
Water diffusion coefficient in dry porous media, D_{mo} (m^2/s)	1.5×10^{-9}
Atmospheric pressure, P_0 (Pa)	1.0×10^5

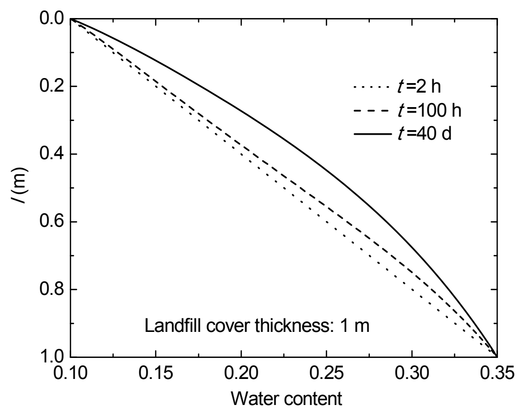

Fig. 3 Changes in water content with time under a linear initial water content distribution

4.2 Influence of cover thickness on landfill gas migration

The effect of cover thickness on the distribution of gas concentration was investigated. The thicknesses considered in this case were 1 m, 1.5 m, and

2 m. From Fig. 4a, it could be seen that the cover thickness greatly influenced gas migration. When the thickness of the cover soil increased from 1 m to 1.5 m, the gas concentration at 0.4 m below the top of the cover soil decreased from 0.93 to 0.80. The difference in soil gas concentration reached up to 31% when the thickness of the landfill cover increased from 1 m to 2 m.

On the other hand, the gradient of the gas concentration at the top of the cover system declined as the cover thickness increased (Fig. 4b). The gradient of gas concentration became stable and reached a relatively large value of 0.079×10^{-3} mg/(L·m) in a short time (about 0.8 h) for the case with *l*=1 m. As the thickness of the cover increased to 2 m, the concentration gradient reached a steady state in 6 h and maintained a relatively low value of 0.039×10^{-3} mg/(L·m) at the top of the cover layer. Thus, the gradient of gas concentration was reduced by a factor of 2 at the top of the cover system when the thickness of the cover layer increased from 1 m to 2 m.

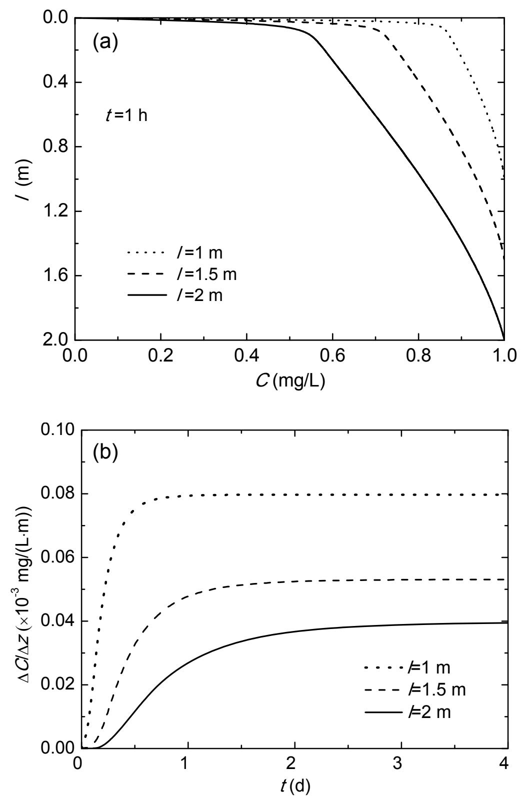

Fig. 4 Effect of cover thickness on gas concentration (a) and gas concentration gradient (b)

4.3 Effect of amplitude of pressure fluctuations on landfill gas migration

Fluctuations in atmospheric pressure by daily alternating heat and cold are usually expressed by a sine equation (You and Zhan, 2012):

$$P_{\text{atm}} = P_{\text{avg}} + A\sin(\omega t), \tag{21}$$

where A is the amplitude of the atmospheric pressure fluctuation (Pa), ω is the fluctuation frequency of daily atmospheric pressure (s^{-1}), and P_{avg} is the average atmospheric pressure (Pa). The measured data of surface gas pressure were obtained from the US National Oceanic and Atmospheric Administration's National Data Center. These data were fitted using Eq. (21) (Fig. 5) (Choi *et al.*, 2002). Here x_c, w, and A are the constants to be determined according to the equation of sine function in Fig. 5. Therefore, curve fitting means an exact relationship between two variables of pressure fluctuations (y) and time (x). Correlation coefficients obtained by fitting a sine function reached about 0.94, indicating that the sine function was reasonable and good for studying variation in atmospheric pressure. These fitted results were adopted as an input for the numerical analysis in this section.

The sine function in this case is:

$$P = P_0 + A\times369\sin\left[\frac{\pi\times(669+t)}{175027}\right], \tag{22}$$

where P_0 is the initial atmospheric pressure.

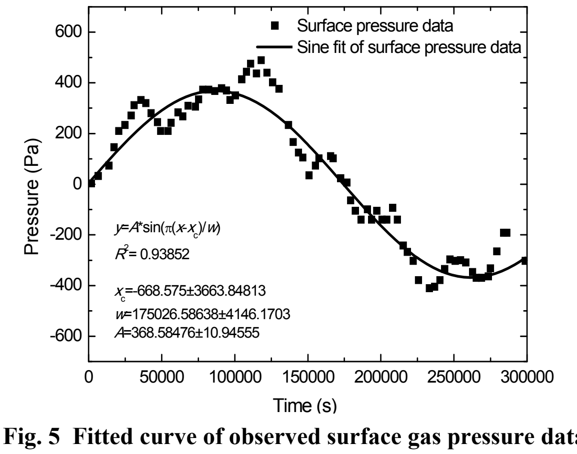

Fig. 5 Fitted curve of observed surface gas pressure data
Data of x_c, w, and A are presented as mean±standard deviation

The effect of the variation in the amplitude A on landfill gas transport through the cover system was investigated (Fig. 6). When the amplitude A increased from 1 Pa to 20 Pa, the concentration profile of the landfill gas showed negligible change during 60 h of gas migration. This indicates that the effect of atmospheric pressure fluctuations can be ignored when the amplitude A is less than 20 Pa. When the amplitude A increased from 20 Pa to 100 Pa, the relative gas concentration at a depth of 0.2 m decreased from 0.99 to 0.93. When the amplitude A increased from 20 Pa to 100 Pa, the relative gas concentration at z=0.2 m reduced by 6%. When the amplitude A was assumed to be rather large (such as of the order of 10^3), the concentration curve was significantly affected by the pressure fluctuations, and changed to a sinusoidal wave. This result indicates that an increase in the amplitude A of this order of magnitude will have a relatively large influence on gas transport through a landfill cover system. The landfill gas migration caused by atmospheric pressure fluctuations cannot be ignored in these cases.

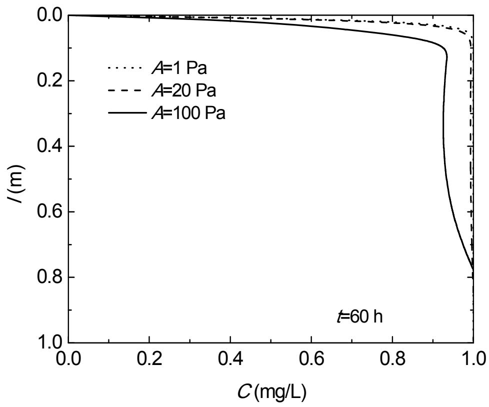

Fig. 6 Influence of atmospheric pressure on gas concentration profiles under different amplitudes

The relative sensitivity of landfill gas migration to diffusion and convection was investigated for the case with A=100 Pa (Fig. 7). The difference in gas concentration between the pure-diffusion case and the convection-diffusion case reached up to 88%. With t =60 h, the gas concentrations at a depth of 0.01 m were 0.93 mg/L and 0.05 mg/L for the cases considering convection-diffusion and pure-diffusion, respectively. The above results indicate that the effect of gas convection caused by atmospheric pressure fluctuations should be considered for landfill sites with large atmospheric pressure fluctuations (e.g., A> 100 Pa).

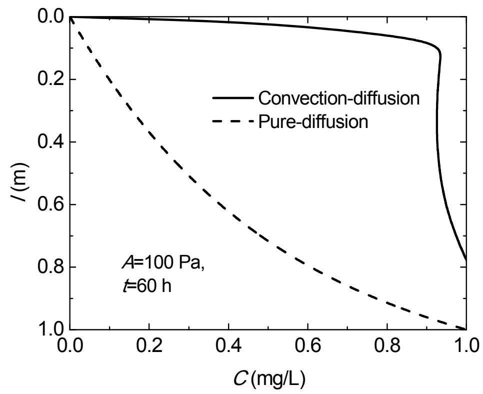

Fig. 7 Comparisons between the effect of convection and diffusion (A=100 Pa)

4.4 Effect of gas permeability

The influence of gas permeability on soil gas concentration distribution varied for couple influences of different thicknesses of unsaturated cover layers and different times. This effect was analyzed by the proposed model using Eq. (15) as input (Figs. 8a and 8b). Two time periods of 10 h and 60 h and a depth of 0.2 m were selected for the discussion in this section. The concentration of LFG at a depth of 0.2 m was 0.92 mg/L with k_g=1×10^{-11} m^2 after 10 h of gas migration. At the same depth, the gas concentration increased to 1 mg/L when the time increased to 60 h (Fig. 8a). With k_g=1×10^{-13} m^2, the 10-h LFG concentration was 1 mg/L, which was slightly higher than that at t=60 h (0.97 mg/L). The gas concentration increased by only 3% when gas permeability increased by a factor of 2 for a relatively long duration of gas migration (e.g., 60 h) under the given conditions. It could be seen that the influence of gas permeability coefficients on gas migration is more significant in the initial stages (e.g., <10 h) of landfill gas migration. This may be because the gas concentration distribution takes a relatively long time to reach the steady-state (e.g., >60 h).

Fig. 8b shows the influence of gas permeability on gas migration through unsaturated landfill covers considering atmospheric pressure fluctuations (A= 100 Pa). The gas concentration at a depth of 0.2 m was 0.86 mg/L for the case with A=100 Pa, and k_g= 1×10^{-11} m^2 at t=10 h. The gas concentration decreased by 7% compared with the case with A=10 Pa.

This indicates that the effect of gas permeability on gas migration in cover soils becomes more significant in cases with relatively large amplitudes.

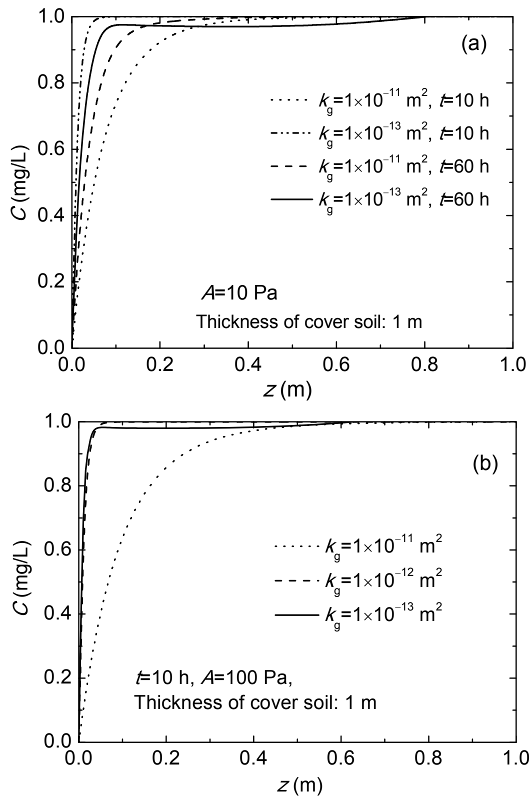

Fig. 8 Effect of gas permeability on gas concentration profiles: (a) A=10 Pa; (b) A=100 Pa

5 Conclusions

A 1D gas-water two-phase mathematical model is proposed for landfill gas transport in layered cover systems. Both gas convection and diffusion transport in the cover systems are considered in the model. The mathematical model was solved using the commercial finite element software COMSOL Multiphysics. The results obtained by the proposed model show good agreement with published experimental data. On the basis of the proposed solution, the influences of gas pressure, gas permeability, and thickness of the cover soils on soil gas concentration profiles were investigated. The main conclusions are as follows:

1. The difference in soil gas concentration can reach up to 31% when the thickness of the landfill cover increases from 1 m to 2 m. This indicates that the performance of the landfill cover systems can be improved greatly by increasing the thickness of the cover system.

2. When the amplitude A increases from 20 Pa to 100 Pa, the relative gas concentration can be reduced by 6%. When the amplitude A is relatively large (e.g., 1×10^3 Pa), the concentration curve is significantly affected by pressure fluctuations. Effect of atmospheric pressure on the performance assessment of landfill cover systems should be considered when pressure fluctuations are large.

3. The gas concentration increases by only 3% when gas permeability doubles for a relatively long period of gas migration under the given conditions. The influence of gas permeability coefficients on gas migration is more significant in the initial stages of landfill gas migration (e.g., <10 h) for the same gas permeability coefficient as in Section 4.4.

The proposed numerical model provides a useful tool for assessing the amount of gas released from a practical landfill cover system, evaluating the performance and designing landfill cover systems under the coupled effects of gas convection, diffusion, and moisture transport in the cover soils.

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中文概要

题　目：填埋场非饱和成层覆盖层一维气水耦合运移模型

目　的：为更好地评价填埋场覆盖层系统的闭气性能，建立水气耦合条件下的覆盖层中气体运移模型。在此基础上分析大气压强波动、渗透系数变化和对流扩散等因素耦合作用下填埋气在覆盖层中的运移规律。

创新点：建立水气耦合条件下填埋气在覆盖层中的运移模型，分析多种因素耦合作用下填埋气的运移过程，并比较对流运移和扩散运移的相对重要性。

方　法：1. 通过理论分析，建立考虑压强、对流、扩散和非饱和情况的填埋气耦合运移模型；2. 通过试验拟合，得到大气压强波动的拟合经验公式（公式（22）），构建考虑压强波动下填埋气多场耦合运移模型；3. 通过仿真模拟，验证所建模型的可行性和正确性（图 2），并分析包含大气压强波动和渗透率等影响因素作用下填埋气的运移规律（图 6~8）。

结　论：1. 覆盖层厚度从 1 米变化到 2 米，覆盖层中填埋气的浓度变化可达 31%；2. 对于受大气压强波动影响较大的覆盖层系统（如 1×10^3 Pa），不能忽略压强波动对填埋气运移的影响；3. 气体渗透系数在初期对气体运移有较大影响，随运移时间增加直至气体运移达到稳定状态，渗透率的影响可以忽略（仅 3%）。

关键词：填埋气；覆盖层系统；非饱和土；气水运移；耦合模型