RESEARCH ARTICLE

Field investigation and numerical modelling of gas extraction in a heterogeneous landfill with high leachate level

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Abstract
A field gas extraction experiment is carried out at a high-kitchen food large-scale landfill site with high leachate level. The leachate level was decreased to improve the pumping efficiency. Considering the heterogeneity of the municipal solid waste (MSW), the pores in the unsaturated MSW are divided into matrix pores and fractures. A transient dual-porosity model was then developed to analyze the pumping test results. The first and second boundary conditions considering the effect of cover layers of landfills was involved. The results show that the gas flow rate can be increased by 14–37% due to the drawdown of the leachate level. Compared with the single pore model, the dual-porosity model can better predict the field results, indicating that the preferential flow in the landfill caused by the heterogeneity of MSWs is very important. As the pumping pressure increases by a factor of 5, the ratio of fractures to pores $w_f$ can be decreased by a factor of 4.4. This may be due to the fact that the fractures will be compressed when the effective stress was increased as the negative pumping pressure was applied. The pumping pressure and the anisotropy value of the MSWs have the greater influence on the well radius of influence. The proposed model can be used for effective design of the field gas pumping experiments. The obtained gas generation rate, gas permeability of the dual porosity MSWs can be useful for gas transport analysis and gas pumping well design for the high-kitchen food content landfills.

Keywords Landfill · Gas extraction experiment · Field investigation · Numerical model · Dual-porosity · Heterogeneous porous media

Notations

- $\beta_i$: The mass exchange coefficient of the $i$-th layer.
- $K_{mi}$: The air permeability of the fracture and matrix exchange of the $i$-th layer.
- $K_{fr1}$: The horizontal air permeability of the fracture flow of the $i$-th layer.
- $K_{fz1}$: The vertical air permeability of the fractures flow of the $i$-th layer.
- $K_{mr1}$: The horizontal air permeability of the matrix pores flow of the $i$-th layer.
- $K_{mz1}$: The vertical air permeability of the matrix pores flow of the $i$-th layer.
- $K_{ri}$: The horizontal air permeability of the MSW of the $i$-th layer.
- $K_{zi}$: The vertical air permeability of the MSW of the $i$-th layer.
- $T$: Temperature.
- $R$: The gas constant.
- $\mu$: The viscosity coefficient.
- $\omega$: The molar mass of the gas.
- $a_i$: The gas production rate of the $i$-th layer.
Introduction

With the rapid development of China’s economy, the generation of municipal solid waste (MSW) has increased rapidly. Landfilling has been one of the main methods for disposal of municipal solid waste in China (Ma et al. 2019; Li et al. 2019). Landfilling has been one of the main methods for disposal of municipal solid waste (MSW) has increased rapidly. With the rapid development of China’s economy, the generation of MSW has increased rapidly. Landfilling has been one of the main methods for disposal of MSW. Landfills can not only solve the hazards of landfill gas, alleviate a series of environmental problems such as air pollution and greenhouse effects, but also generate better economic benefits through recycling (Park and Shin 2001). In addition, through the pumping experiment, the mechanisms of landfill gas migration in the heterogeneous waste body can be investigated. Moreover, the parameters related to gas production and migration model can be determined, which can be used for effective design of the landfill gas extraction system.

Due to the difficulty and high cost of field tests, there are very few field pumping experiments reported. Jain et al. (2005) injected air into three different wells of a landfill in Florida. Based on the experimental data, the air permeability is estimated to be between $1.6 \times 10^{-13} \text{ m}^2$ and $3.2 \times 10^{-11} \text{ m}^2$. Martin et al. (2001) conducted a gas extraction experiment at the La Zoreda landfill in Asturias, Spain. The depths of the landfill and the pumping well are 24 m and 6 m, respectively. They found that there is an approximately linear relationship between gas flow rate and the pumping pressure. Xie and Chen (2014) conducted a gas extraction test at the Xiangshan Landfill in Ma’anshan, China. The methane concentration was monitored in the test area with the pumping flow rates $= 60$ and $90 \text{ m}^3/\text{d}$. Liu et al. (2016a, b) conducted pumping tests at different pumping pressures $(-100$ to $-800 \text{ Pa})$ at the Yiling landfill and found its horizontal air permeability is $6.8 \times 10^{-11} \text{ m}^2$. Compared with the “dry tomb” type landfills in Europe and the United States, the leachate levels in landfills in China are generally higher (e.g., $> 10 \text{ m}$) (Chen et al. 2021). The pumping efficiency will be greatly decreased due to entering of the leachate into the wells (Chen et al. 2021). However, the above-mentioned pumping experiments did not consider the effect of high leachate level in the landfill. The air permeability of the MSWs will be greatly decreased under the saturated condition (Zhan et al. 2015). Therefore, it is very necessary to carry out pumping experiments under drawdown conditions to improve the pumping efficiency (Hu et al. 2021).

Numerical models have been developed to analyze the pumping experiments. Young (1990) proposed a mathematical model for single-species gas flow inside a non-isotropic porous medium, within which gas is continuously generated. Martin et al. (2001) developed a two-dimensional steady-state flow model in porous media with infinite landfill gas sources by using the finite-difference method. Yu et al. (2009) proposed an analytical model to predict the two-dimensional radial transient gas flow to a vertical gas extraction well in deformable MSW landfills. Feng et al. (2017) proposed a two-dimensional axisymmetric analytical model for a layered landfill with vertical wells. The waste non-homogeneity with depth in gas production, permeability and temperature was considered. Based on Darcy’s law (Young 1990; Wise and Townsend 2011) and ignoring diffusion (Massmann and Farrier 1992), a two-dimensional axisymmetric and normalized analytical model for landfill gas (LFG) migration around a vertical well was developed by Zheng et al. (2019). Zeng (2020) developed a gas–solid coupling model to simulate

\begin{align*}
\text{n}_{gi} & \quad \text{The pore gas content of the } i \text{-th layer of landfill.} \\
\rho_{ji} & \quad \text{The absolute pressure of the fractures flow in the } i \text{-th layer.} \\
\rho_{mi} & \quad \text{The absolute pressure of the matrix pores flow in the } i \text{-th layer.} \\
p_i & \quad \text{The absolute pressure of the } i \text{-th layer.} \\
w_f & \quad \text{The volume of fractures divided by the total pores.} \\
d_a & \quad \text{The anisotropy value.} \\
\rho_l & \quad \text{The density of the landfill.} \\
\rho_g & \quad \text{The density of landfill gas.} \\
Q_i & \quad \text{Gas production rate of garbage in the } i \text{-th year.} \\
M_i & \quad \text{The mass of the landfilled waste.} \\
L_0 & \quad \text{The potential LFG generation capacity.} \\
k & \quad \text{The average gas production rate constant of the landfill waste.} \\
\text{DOC}_i & \quad \text{The content of degradable organic carbon of the } i \text{-th component.} \\
W_i & \quad \text{The wet weight content of the } i \text{-th component.} \\
d_i & \quad \text{The moisture content of the } i \text{-th component.} \\
p_t & \quad \text{The pumping pressure.} \\
p_0 & \quad \text{The atmospheric pressure.} \\
L_c & \quad \text{The cover layer coefficient.} \\
k_i & \quad \text{The vertical air permeability of the cover layer.} \\
d_l & \quad \text{The thickness of the cover layer.} \\
D & \quad \text{The diameter of the well.} \\
H & \quad \text{The thickness of the unsaturation waste.} \\
H_0 & \quad \text{The thickness of the initial unsaturated landfill} \\
s & \quad \text{The drawdown}
\end{align*}
the influence of extraction pressure, anisotropy, coverage thickness and coverage air permeability on gas migration. In field, the landfilled wastes have a strong heterogeneity, and the void size of the waste and the permeability at different locations vary significantly (Woodman et al. 2014, 2015; Li et al. 2020a, b). Therefore, it is very necessary to develop a dual-porosity landfill gas migration model to better analyze the results of the gas pumping experiment and reveal the influence of the dual media characteristics of waste on landfill gas migration. Liu et al. (2016a, b) developed a steady-state dual-permeability (DPM) model to predict landfill gas distribution at extraction well operations. Compared to the single-permeability model, the dual-permeability model can better simulate the field monitoring results. However, the steady state gas migration was assumed and the generation rate of landfill gas was not considered.

The aim of this article is to investigate the gas production and migration under different drawdown conditions in the large-scale landfill with high water level. An integrated full-scale pumping experiment was carried out in Jiangcungou Landfill in Xi’an, Shanxi Province, China. The transient gas migration and pressure distribution models in the landfill are proposed. The different boundary conditions were considered to account for the different landfill cover conditions. The heterogeneity of the MSWs is considered by assuming that the pores of the MSWs can be divided into matrix pores and fractures. The numerical model was validated by the field test results. The influence of the cover coefficient, anisotropy value, fracture and matrix ratio, and mass exchange coefficient on the pressure distribution in the landfill was analyzed. The research findings in this article can provide guidance for in-situ deployment of pumping wells.

Materials and methods

Landfill description

The Jiangcungou Landfill is located in Xi'an, Shanxi Province, China. It is about 16 km from the city of Xi’an. The location of the landfill site is shown in Fig. 1. This landfill is the only valley-type landfill in the local area and one of the largest sanitary landfills in the country. This landfill has been in operation since 1994 and covers an area of 730,000 m². The capacity of the landfill is 49 million m³ (Shen et al. 2018; Wang et al. 2020; Dang et al. 2020). A layer of loess with 30 cm is used for the temporary landfill cover. The fresh solid waste was mainly composed of food waste, plastics, and inert materials, among which there are 51.4% food waste, 2% wood, 4.1% textile, 12.3% plastic, and 12% paper.

Fig. 1 Location of Xi’an Jiangcungou landfill
and 12.3% ash (Shen et al. 2018). It is a typical landfill with high food waste content. The leachate level in the landfill was quite high. The thicknesses of the saturated and unsaturated zones are 62–72 m and 8 m, respectively. The gas collection rate is about 4000 m$^3$/h, and the collection rate is 28.3% in the effective collection zones (Shen et al. 2018).

**Gas pumping test**

The gas pumping test was carried out in the landfill from June to September in 2014. The test area has a radius of 25 m around the pumping well. The waste ages within the depths of 0–10 m, 10–20 m, and 20–34 m in the test area are 2–3 months, 1 year, and 2 years, respectively. The field test profile is shown in Fig. 2a. Prior to the test, a water level survey was conducted in the test area where the test well was located. The survey results showed that the leachate level in this area was 8 m below the top surface, which was very high and also stable. The pumping well was installed in the temporary coverage area of the landfill. The well with a diameter (D) of 800 mm was equipped with HDPE pipes with a diameter of 200 mm. The well length was 31 m. The top of the well was sealed with about 0.5–1.0 m thickness of bentonite. In total, 16 gas monitoring wells and 16 water monitoring wells were installed within the area. The monitoring wells were installed in four directions around the pumping wells. There were four gas monitoring wells and four water monitoring wells in each direction, with an even spacing of 5 m. The spatial distribution of wells is shown in Fig. 3.

The surface of the pumping test area was covered with a geomembrane to increase the efficiency of pumping test. However, due to poor construction quality, many holes were induced on the surface of the geomembrane. Therefore, the cover layer of the test area is poorly sealed. The pumping test was carried out under different drawdowns including 8 m, 15 m, 20 m, and 23 m. Different pumping pressures, that is, 0 kPa (static test), -1 kPa, -3 kPa, and -5 kPa, were considered. The pumping tests stopped after the pumping volume and monitoring well pressure became stable. The air pressure in the gas monitoring well under each stage of pumping test was monitored. The air pressure variation can be obtained by subtracting the air pressure measured by the air pressure monitoring well in the static test and that at the pumping state.

**Mathematical model**

**Assumptions**

In order to better analyze the in-situ pumping experiments, the air pressure model based on the dual-porosity medium seepage theory was developed (see Fig. 2b). The main assumptions of the model are as follows:

1. The flow direction of the gas is parallel to the horizontal axis (x axis) and the vertical axis (y axis);
2. The landfill gas entering the gas well are from the matrix pores and the fractures. Gas exchange occurs between the two domains (Gerke and van Genuchten 1993), and the anisotropy values of the air permeability are the same in the two domains (Hu et al. 2021). Due to the heterogeneity of waste, the sizes of pores in the landfills vary greatly and the preferential flow in MSWs was reported (Woodman et al. 2014, 2015; Liu et al. 2016a, b; Zhang and Lin 2019; Li et al. 2020a, b; Hu et al. 2020; Ke et al. 2022). When the heterogeneous nature of waste was considered, the landfilled waste was usually considered to be a two-domain media with diverse characteristics, i.e., a fracture domain with rapid flow and a surrounding matrix domain with slow movement (Liu et al. 2016a, b; Zhang and Lin 2019; Li et al. 2020a, b).
3. The landfill gas is assumed to be an ideal gas, and it satisfies the Ideal Gas Law. The landfill gas tends to be at normal temperatures and pressures. In addition, the interactions of the landfill gas components were not considered (e.g., Young 1990; Liu et al. 2016a, b; Zheng et al. 2019; Hu et al. 2020).
4. The flow of landfill gas obeys Darcy’s law (Young 1990; Wise and Townsend 2011). Jain et al. (2005) and Hu et al. (2020) reported that the gas well extraction test data can be well fitted by the gas simulation model based on the Darcy’s law.

**Governing equations**

Considering the non-homogeneity of the MSWs, pores in MSWs are divided into fractures and matrix. The gas flow in the fractures and matrix pores are both considered to be anisotropic. Firstly, the pressure in the pumping well would decrease. Then, the gas in the fractures and matrix pores would flow to the well under the pressure gradient. Gas mass exchange between fractures and matrix pores would occur during this process.

Considering the non-homogeneity of waste in the vertical direction, the waste was assumed to be composed of n layers. The gas production rate was assumed to be a constant. Combining with Liu and Zheng’s model (Liu et al. 2016a, b; Zheng et al. 2019), a dual-porosity model for gas transport in the waste and the pumping well was developed:
Fig. 2 Profiles for landfill gas extraction: (a) Field test profile at Xi’an Jiangcungou landfill; and (b) Mathematical model for gas transport in layered landfill and single extraction well.
\[ K_{fi}\left(\frac{\partial^2 p_{fi}}{\partial r^2_i} + \frac{1}{r_i} \frac{\partial p_{fi}}{\partial r_i}\right) + K_{ri} \frac{\partial^2 p_{ri}}{\partial r^2_i} \]
\[ + \beta_i K_{mri} (p_{mi}^2 - p_{ri}^2) - 2\mu \frac{\partial n_{f}\rho_{fi}}{\partial t} + \frac{2RT\mu}{\alpha} n_i = 0 \]

\[ K_{mi}\left(\frac{\partial^2 p_{mi}}{\partial r^2_i} + \frac{1}{r_i} \frac{\partial p_{mi}}{\partial r_i}\right) + K_{mri} \frac{\partial^2 p_{mri}}{\partial r^2_i} - \beta_i K_{mri} (p_{mri}^2 - p_{mi}^2) - 2\mu \frac{\partial n_{m}\rho_{mi}}{\partial t} + \frac{2RT\mu}{\alpha} n_i = 0 \]

\[ p_i = w_f p_{fi} + (1 - w_f) p_{mi} \]

\[ K_{ri} = w_f K_{fri} + (1 - w_f) K_{mri} \]  \hspace{1cm} (4)

\[ K_{zi} = w_f K_{fzi} + (1 - w_f) K_{mzi} \]  \hspace{1cm} (5)

where \( \beta_i \) is the mass exchange coefficient of the \( i \)-th layer; 
\( K_{m} \) is the air permeability of the fracture and matrix exchange of the \( i \)-th layer; 
\( K_{f} \) is the horizontal air permeability of the fractures flow of the \( i \)-th layer; 
\( K_{fz} \) is the vertical air permeability of the fractures flow of the \( i \)-th layer; 
\( K_{mi} \) is the horizontal air permeability of the matrix pores flow of the \( i \)-th layer; 
\( K_{mz} \) is the vertical air permeability of the matrix pores flow of the \( i \)-th layer; 
\( T \) is Temperature; 

\[ 1 \circ \] Extraction well
\[ 2 \circ \] Water Monitoring Well
\[ 3 \circ \] Gas Monitoring Well
\[ 4 \circ \] Gas Monitoring Well

Fig. 3 Distribution of the gas extraction well and monitoring wells in Xi’an Jiangcungou landfill

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\[ R \text{ is the gas constant; } \mu \text{ is the viscosity coefficient; } \omega \text{ is the molar mass of the gas; } a_i \text{ is the gas production rate of the } i \text{-th layer; } n_{v_i} \text{ is the void gas content of the } i \text{-th layer of landfill; } p_{b_i} \text{ is the absolute pressure of the fractures flow in the } i \text{-th layer; } p_{m_i} \text{ is the absolute pressure of the matrix pores flow in layer } i; \ p_i \text{ is the absolute pressure of the } i \text{-th layer; } w_i \text{ is the volume of fractures divided by the total pores (0 < } w_i < 1); \ K_{ri} \text{ is the horizontal air permeability of the MSW of the } i \text{-th layer; and } K_{zi} \text{ is the vertical air permeability of the MSW of the } i \text{-th layer.}

\text{The landfill gas production rate can be calculated by (Christensen and McCarty 1975; Thompson et al. 2009):}

\[ a_i = \frac{1}{3.15 \times 10^{10}} \frac{Q_i}{M_i} \times \rho_i \times \rho_f \tag{6} \]

where \( \rho_i \) is the density of the landfill; \( \rho_f \) is the density of landfill gas; \( M_i \) is the mass of the landfilled waste; \( Q_i \) is gas production rate of waste in the \( i \text{-th year and can be determined by}

\[ Q_i = M_i \times L_0 \times k \times e^{-kt} \tag{7} \]

where \( k \) is the average gas production rate constant of the landfill waste; and \( L_0 \) is the potential LFG generation capacity:

\[ L_0 = 1867 \times \sum_{i=1}^{d} \left[ W_i \times (1 - d_i) \times DOC_i \right] \tag{8} \]

where \( DOC_i \) is the content of degradable organic carbon of the \( i \) component; \( W_i \) is the wet weight content of the \( i \) component; and \( d_i \) is the moisture content of the \( i \) component.

According to the degradable components in the fresh solid waste of the landfill from 2009 to 2011, as well as the wet weight content and moisture content of each component, \( L_0 \) can be calculated through the Christensen biodegradable model (Christensen and McCarty 1975).

**Initial and boundary conditions**

The upper boundary of the proposed model is the cover layer. The radial gas flow at this boundary can be ignored. The gas flow is mainly vertical flow (Yu et al. 2009). The upper boundary conditions can then be

\[ \frac{\partial p_f}{\partial z} = \frac{Lc}{H} \left( p_f - p_0 \right) \left( 0 \leq r \leq R_b, z = H \right) \tag{9} \]

\[ \frac{\partial p_m}{\partial z} = \frac{Lc}{H} \left( p_m - p_0 \right) \left( 0 \leq r \leq R_b, z = H \right) \tag{10} \]

where \( Lc \) is the cover layer coefficient. Equations (9) and (10) belong to the second type boundary condition. The cover layer coefficient was defined as (Yu et al. 2009):

\[ Lc = \frac{k_i H}{d_i K_{zi}} \tag{11} \]

where, \( k_i \) is the vertical air permeability of the cover layer; \( d_i \) is the thickness of the cover layer; The cover layer coefficient \( Lc \) ranges from 0.001 to 10 (Yu et al. 2009).

where \( H \) is the thickness of the unsaturated landfill:

\[ H = H_0 + s \tag{12} \]

where \( H_0 \) is the thickness of the initial unsaturated landfill; and \( s \) is the drawdown.

When the cover layer is composed of materials with relatively high air permeability, such as loess, the landfill gas can exchange with the atmosphere freely. In this case, the landfill gas pressure and atmospheric pressure tend to be the same (Liu et al. 2016a, b; Townsend et al. 2005; Chen et al. 2003). Then the corresponding upper boundary conditions are

\[ p_f = p_0 \left( r_w \leq r \leq R_b, z = H \right) \tag{13} \]

\[ p_m = p_0 \left( r_w \leq r \leq R_b, z = H \right) \tag{14} \]

where \( p_0 \) is the atmospheric pressure. The Eqs. (12) and (13) belong to the first type boundary condition.

The boundary at \( r = R_b \) is (Liu et al. 2016a, b; Vigneault et al. 2004; Chen et al. 2003; Yu et al. 2009)

\[ \frac{\partial p_f}{\partial r} = 0 \left( r = R_b, \ 0 \leq z \leq H \right) \tag{15} \]

\[ \frac{\partial p_m}{\partial r} = 0 \left( r = R_b, \ 0 \leq z \leq H \right) \tag{16} \]

The lower boundary condition is also assumed to be zero flux (Young 1990; Chen et al. 2003; Vigneault et al. 2004; Yu et al. 2009; Liu et al. 2016a, b):

\[ \frac{\partial p_f}{\partial z} = 0 \left( r_w \leq r \leq R_b, z = 0 \right) \tag{17} \]

\[ \frac{\partial p_m}{\partial z} = 0 \left( r_w \leq r \leq R_b, z = 0 \right) \tag{18} \]

When the pumping pressure is constant, the pressure at the well wall is the pumping pressure (Yu et al. 2009; Liu et al. 2016a, b). The boundary condition near the pumping well is

\[ p_f = p_0 + p_1 \left( r = r_w, 0 \leq z \leq H \right) \tag{19} \]

\[ p_m = p_0 + p_1 \left( r = r_w, 0 \leq z \leq H \right) \tag{20} \]

where \( p_1 \text{(kPa)} \) is the pumping pressure of the extraction well.
At the interfaces between the i-th layer and the i + 1-th layer, the pressure and the gas flow rate are assumed to be continuous:

\[
\frac{\partial p_i}{\partial z} = \frac{\partial p_{i+1}}{\partial z} (r_w ≤ r ≤ R_b, z = z_i)
\]

(21)

\[
\frac{\partial p_{mi}}{\partial z} = \frac{\partial p_{m,i+1}}{\partial z} (r_w ≤ r ≤ R_b, z = z_i)
\]

(22)

\[
p_f = p_{f,i+1} (r_w ≤ r ≤ R_b, z = z_i)
\]

(23)

\[
p_m = p_{m,i+1} (r_w ≤ r ≤ R_b, z = z_i)
\]

(24)

The initial conditions of this model are assumed as follows:

\[
p_f = p_0 (t = 0)
\]

(25)

\[
p_m = p_0 (t = 0)
\]

(26)

**Parameterization**

According to the radius of influence of the in-situ pumping well, the radius of the landfill is set to be 25 m. The diameter of the pumping well is 800 mm. The values of temperature, ideal gas constant, viscosity, and the molar mass of landfill gas are set as 303 K, 8.31 kg·m²·s⁻²·mole⁻¹·K⁻¹, 1.76×10⁻⁵ kg·m⁻¹·s⁻¹, and 0.03 kg/mole, respectively (Zhan et al. 2015). The constant air permeability in the middle of the landfill layer was used.

The specific wet weight content, moisture content and the content of degradable organic carbon of each component of the MSW are shown in the Table 1. The \( L_0 \) of food waste is 5.8 times larger than that of wood. According to Eqs. (6)–(8), \( L_0 \) and \( k \) were determined to be 163.2 m³/t, and 0.347 a⁻¹, respectively. The ages of the three layers of waste were 2.5 months, 1 year and 2 years, respectively. The corresponding gas production rates are 1.75×10⁻⁵, 1.33×10⁻⁵, and 9.43×10⁻⁶ kg/(m³·s), respectively. The value of \( L_0 \) is 1.3 times larger than that of the Tianziling landfill, which is mainly because the food waste content of the two landfills is similar (Feng et al. 2017). The gas production rates of these high-kitchen food content wastes were quite high just after several months after the wastes were landfilled (Chen et al. 2010; Shen et al. 2018). The value of \( L_0 \) is 1.63–3 times larger than that of a landfill in the European countries such as Greece and Denmark. This is mainly due to the fact that the proportion of kitchen waste at this landfill is much greater than those at the landfills in the Europe (Chalvatzaki and Lazaridis 2010; Cho et al. 2012).

The values of all parameters are summarized in Table 2. The partial differential Eqs. (1) and (2) and the above parameters are used. The model was solved by COMSOL Multiphysics 5.5 (COMSOL 2014). The complete mesh contains 548 domain elements and 81 boundary elements, and each cell ranges from 0.007 m to 1.3 m.

**Results and discussion**

**Gas pumping test results**

Figure 4 shows the results of the landfill gas flow rate obtained by pumping wells under different pumping pressures and drawdown conditions in a single well pumping test. The pumping flow rate increased with the increase of absolute value of pumping pressure. When there is no drawdown, the pumping flow rate with \( p_1 = -5 \) kPa is 2 and 1.3 times larger than that with \( p_1 = -1 \) kPa and \( p_1 = -3 \) kPa, respectively. In general, under the same pumping pressure, the pumping flow rate under drawdown is higher than that without drawdown. However, the relationship between

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**Table 1** Components and properties of the MSWs

| Properties                  | Food waste | Paper | Textile | Wood |
|-----------------------------|------------|-------|---------|------|
| The wet weight content \( W_i \), (%) | 55.3       | 12.3  | 2.7     | 1.5  |
| The moisture content \( d_m \), (%)     | 85.0       | 20.0  | 15.0    | 25.0 |
| The content of degradable organic carbon \( \text{DOC} \), (%) | 38.0       | 44.0  | 30.0    | 50.0 |
| The potential LFG generation capacity \( L_0 \), (m³/t) | 58.8       | 81.1  | 13.1    | 10.2 |
drawdown and the pumping flow rate is not obvious. For example, under $p_1 = -1$ kPa, the pumping flow rate under drawdown is 1.37 times greater than that without drawdown, but the pumping flow rate under drawdown is almost the same at different drawdowns.

The pumping flow rate was related to the area of the landfill. The gas flow rate in this test can reach 110 m$^3$/kPa, which is 10–30 times larger than that in the test at the Maanshan landfill reported by Xie and Chen (2014). This is because the Maanshan landfill is relatively small with an area of 90,000 m$^2$ and average thickness of only 10 m. The area and the thickness of this landfill are 7.6 times and 8.0 times smaller than those of Jiangcungou landfill, respectively. The gas flow rate with $p_1 = -3$ kPa in this test is similar to that in the test at the La Zoreda landfill reported by Martín et al. (2001). But the gas flow rate with $p_1 = 0$ kPa in this test is 17 m$^3$/h less than that reported by Martín et al. (2001). This is because at the La Zoreda landfill, the surface area within 7 m away from the pumping well was relatively impermeable, and the airtightness was ensured. However, the airtightness of the test area in this experiment was relatively poor. The air pressure in the landfill under static conditions was only about 0.2 kPa due to the poor pumping effect under static conditions.

Figure 5 shows the monitoring results of the gas extraction wells under the different drawdowns and pumping conditions. In general, under the same drawdown, the lower pumping pressure resulted in the lower air pressure. For instance, at the same drawdown and at the location of 5 m away from the pumping well, the air pressure with $p_1 = -1$ kPa is 1.3–2.0 times higher than that with $p_1 = -3$ kPa. Under the same conditions of pumping pressure and drawdown, the air pressure decreased with the increase of the distance to the pumping well. For instance, when the pumping pressure $p_1$ is -1 kPa, the air pressure at $r = 5$ m is 1.3–1.7 times higher than that at $r = 10$ m. Under the same drawdown, the pumping pressure mainly affects the pressure distribution within 15 m of the pumping well, which is believed to be the influence of the gas well. The results show that the air pressure did not change much under different pumping pressures, with a narrow range from 0 to 0.6 kPa. This may be due to the fact that the landfill was at the peak of gas production and it was generated quickly (Chen et al. 2010).

### Comparison of mathematical model and field experiment results

Figures 6, 7, 8, and 9 show the comparisons between field measurements and the simulation results from the single-porosity model (SPM) and the proposed model when the drawdown reaches 0, 7, 12, and 15 m, respectively. It indicates that the results of the proposed model agree well with the observed data. It was also indicated that the field monitoring data were better fitted by the proposed model than the single-porosity model, especially when the drawdown is relatively small (i.e., < 12 m). For example, the calculated $p$ with $p_1 = -5$ kPa and without drawdown using the proposed model and the single-porosity model was 1.16 and 9.3 times larger than measured value at $r = 15$ m, respectively. This may be due to the effect of water on gas transport in the landfill was reduced when the drawdown is relatively large.

The air permeability of the landfill decreased significantly with the increase of the depth of the landfill. The air permeability of the layers at a depth of 5 m was obtained to be 2.10 and 12.5 times greater than that under 12.5 m, 15 m, and 21.5 m, respectively. This is consistent with the experimental result in Qizishan landfill in China (Wei et al. 2007). Wei et al. (2007) suggested that the air permeability of the landfill at 5 m, 15 m, and 25 m are $10^{-11}$ m$^2$, $10^{-12}$ m$^2$ and $7 \times 10^{-13}$ m$^2$, respectively. The horizontal air permeability of the fractures was obtained to be between $8 \times 10^{-13}$ m$^2$ and $1 \times 10^{-11}$ m$^2$. These values were in the range of that in the test at the Florida landfill reported by Jain et al. (2005). However, they were 6.8–85 times lower than those at the Yiling landfill reported by Liu et al. (2016a, b). This is because the waste age in the region was younger, i.e., about 22 months. Furthermore, the average depth of the involved wastes was only 6 m.

According to the field test results and model fitting, the anisotropy value and the fracture matrix ratio was determined to be 1.25 and 10, respectively (Ke et al. 2022). The anisotropy value in this test is 1.6–4 times lower than that at the Yiling landfill (Liu et al. 2016a, b) and the La Zoreda landfill (Yu et al. 2009). This may be due to the fact that the compositions and water content of the MSWs...
from the different landfills are quite different. The other reason may be the age of the MSWs herein are relatively old and the organic content of the MSWs were degraded. The large pores would be filled by the degraded small particles. The anisotropy value can then be reduced.

It was found that the $w_f$ decreases with the increase of the pumping pressure. As the pumping pressure increases by a factor of 5, $w_f$ decreases by a factor of 1.1–4.4. This may be due to the fact that fracture will be compressed when the effective stress was increased as the negative pumping pressure was applied. In addition, $w_f$ increased with the increase of the thickness of the unsaturated waste. As the thickness of the unsaturated waste increases from 8 to 20 m, $w_f$ increases by a factor of 2.1–8.4. This may be due to the fact that more fractures for gas transport will appear with the reduction of water content of the wastes. However, when the drawdown reached 15 m, $w_f$ was less than the cases when the drawdown reached 7 m and 12 m. When the drawdown reached 15 m, the age of the waste was over 2 years and the porosity is relatively small. Furthermore, the effective stress in this layer is relatively large (Zhang and Lin 2019). Therefore, the waste in this layer are more homogenous than the upper layers (Xu et al. 2019; Hu et al. 2021).

Effects of fracture matrix ratios on gas pressure distribution

Figure 10 shows the gas pressure distribution in the landfill under different boundary conditions with different fracture matrix ratios. The relative pressure at the same point decreases as $K_f/K_{mr}$ increases. With $r = 20$ m, the relative pressure with $K_f/K_{mr} = 1$ is 2.8–3 times larger than that with $K_f/K_{mr} = 10$. When $K_f/K_{mr}$ increases, the heterogeneity of waste increases, and more amount of gas was pumped away through the fracture. The relative pressure was then reduced. In addition, under the first type boundary condition, when $K_f/K_{mr}$ increases from 10 to 100, the relative pressure at the same location does not change. This may be because when $K_f/K_{mr}$ increases to a certain extent (i.e., $\geq 10$), the dimension of the fracture is much higher than that of the matrix pores. The fracture is the main pathway for gas transport in this case. However, under the second type boundary condition, the pressure values under different fracture matrix
Fig. 6 Numerical simulation results under different pumping pressures and without drawdown in Xi’an Jiangcungou landfill: (a) $p_1 = -1$ kPa; (b) $p_1 = -3$ kPa; and (c) $p_1 = -5$ kPa (initial depth of unsaturated landfill is 8 m)

Fig. 7 Numerical simulation results under different pumping pressures and 7 m drawdown in Xi’an Jiangcungou landfill: (a) $p_1 = -1$ kPa; (b) $p_1 = -3$ kPa; and (c) $p_1 = -5$ kPa (initial depth of unsaturated landfill is 8 m)
Fig. 8 Numerical simulation results under different pumping pressures and 12 m drawdown in Xi'an Jiangcungou landfill: (a) \( p_1 = -1 \) kPa; (b) \( p_1 = -3 \) kPa; and (c) \( p_1 = -5 \) kPa (initial depth of unsaturated landfill is 8 m)

Fig. 9 Numerical simulation results under different pumping pressures and 15 m drawdown in Xi'an Jiangcungou landfill: (a) \( p_1 = -1 \) kPa; (b) \( p_1 = -3 \) kPa; and (c) \( p_1 = -5 \) kPa (initial depth of unsaturated landfill is 8 m)
ratios are generally higher than those under the first type boundary condition. This may be due to the fact that the gas in the landfill is not easy to circulate with the atmosphere under the second type boundary condition. When increasing $K_{fr}/K_{mr}$, the air pressure can still be reduced and the pumping effect can be enhanced.

Liu et al. (2016a, b) found that when $r=1m$, there is almost no difference in the pressure distribution when $K_{fr}/K_{mr}=20$ and $K_{fr}/K_{mr}=200$. It was indicated that when $r=5m$, the pressure with $K_{fr}/K_{mr}=10$ was 0.4–2 kpa lower than that with $K_{fr}/K_{mr}=100$ herein. This is because the pumping pressure in Liu et al. (2016a, b) is only -250pa, which is 12 times smaller than that in this paper. Liu et al. (2016a) studied the influence of $K_{fr}/K_{mr}$ on the pumping flow rate and found that at the depth of 15 m, $K_{fr}/K_{mr}$ increased by a factor of 4 and pumping flow rate increased by a factor of 2. As this is consistent with the conclusion of this article.

Monte Carlo analysis

The Monte Carlo method (Xie et al. 2018) was adopted to carry out the statistical analysis for the reference scenarios. The ranges of the mass exchange coefficient $\beta$, the anisotropy value $a_n$, the fracture matrix ratio, the cover layer coefficient, and the pumping pressure were assumed to be 8.4–11.6, 2.4–5.7, 8.4–11.8, 2.3–5.7, -1.3–-4.6 kPa, respectively, for the reference scenario. One thousand data were randomly generated by normal distribution for each parameter.

Six cases are chosen to analyze the influence of different parameters on the radius of influence of the landfill under the first and second type surface boundary conditions. Among them, case 1 is the reference case. For cases 2–5, the mass exchange coefficient $\beta$, the anisotropy value, the fracture matrix ratio, the cover layer coefficient, and the pumping pressure in case 1 are increased by a factor of 5, respectively. The specific parameters used in the Monte Carlo analysis are shown in Table 3. Assuming that each parameter follows a normal distribution, and the mean value is the same as that of case 1. By taking an appropriate confidence interval in the model, the confidence interval of the radius of influence can be calculated. The results are presented by the red line in the Figs. 11 and 12.

| Case  | 1    | 2    | 3    | 4    | 5    | 6    |
|-------|------|------|------|------|------|------|
| $\beta$ | 5    | 25   | 5    | 5    | 5    | 5    |
| $a_n$  | 4    | 4    | 20   | 4    | 4    | 4    |
| $K_{fr}/K_{mr}$ | 10   | 10   | 10   | 50   | 10   | 10   |
| $Lc$   | 8    | 8    | 8    | 8    | 40   | 8    |
| $p_1$ (kPa) | -3   | -3   | -3   | -3   | -3   | -15  |
Figure 11 shows the distribution of the radius of influence of the pumping well under different boundary conditions. It can be seen from Fig. 11a that the most influential factor on the radius of influence is the pumping pressure. If the pumping pressure is increased by a factor of 5, the radius of influence will be increased by a factor of 2–2.5. The secondary important factor is the anisotropy. When the anisotropy value is increased by a factor of 5, the radius of influence is increased by a factor of 1.6–2.5. The deeper depth of the landfill causes the larger radius of influence under the same anisotropy value. This may be because at the deeper depth, it is more difficult for landfill gas to exchange with the atmosphere. The higher air pressure in the MSW can lead to the better pumping effects and hence the larger radius of influence. When the fracture matrix ratio is increased by a factor of 5, the radius of influence is increased by a factor of 1.07. When cover layer coefficient is increased by a factor of 5, the radius of influence is reduced by a factor of 2. Therefore, the cover layer coefficient also has a great influence on the radius of influence of the landfill. The mass exchange coefficient has almost no influence on the radius of influence of the landfill. Although increasing the mass exchange coefficient can enhance the gas exchange between matrix pores and fractures, these gas exchanges are negligible. Therefore,
the mass exchange coefficient has almost no effect on the radius of influence of the pumping well.

It can be seen from Fig. 11b that at 8 m, the radius of influence of case 6 is 2.2 times greater than that of case 1. The radius of influence of case 3 is 1.6 times greater than that of case 1. The anisotropy value also has a certain influence on the radius of influence of the landfill. The larger anisotropy value results in the larger radius of influence of the landfill. The radii of influence of case 4, case 2 and case 1 are almost the same. The pumping pressure has the greatest influence on the radius of influence. If the pumping pressure is increased by a factor of 5, the radius of influence will be increased by a factor of 2–2.7. The secondary influential factor is the anisotropy value. If the anisotropy value is expanded by a factor of 5, the radius of influence is increased by a factor of 2. Besides, the mass exchange coefficient and the fracture matrix ratio have almost no influence on the radius of influence of the landfill under the second type boundary condition. Under the same cases, the radius of influence is lower at the shallower depths. It can also be seen from Fig. 11 that under the same cases, the radius of influence of the landfill under the second type boundary condition is 30–50% lower than that of the first type boundary condition. This may be due to the fact that the landfill gas can interact with the atmosphere easily under the second type boundary condition.

Figure 12 shows the variation of the gas flow rate in the landfill with time for the six cases under different boundary conditions. The results show that the flow rate at \( t = 0 \) is the rate under the steady state when the pumping pressure \( p_1 \) is 0 kPa. It is demonstrated from Fig. 12 that within 0–2 h, the variations of gas flow rate with time are obvious. At 2 h, the majority of the cases have reached a stable state. In addition, when \( t = 2 \) h, the gas flow rate of case 6 is 3.7–5 times greater than that of case 1. The gas flow rate of case 3 is 4.4 times greater than that of case 1. The larger anisotropy results in the greater gas flow rate. The gas flow rate of case 4 is 1.3–4.1 times greater than that of case 1. Therefore, the larger fracture matrix ratio can lead to the larger gas flow rate. The gas flow rates of case 2 and 5 are similar to that of case 1. As a result, the mass exchange coefficient has no obvious influence on the flow in the first 2 h. Therefore, the pumping pressure and the anisotropy of the waste have the greater impact on the pumping flow. When the pumping pressure is increased by a factor of 5, the gas flow rate can be increased by a factor of 3.7–5. When the anisotropy is increased by a factor of 5, the gas flow rate can be increased by a factor of 4–4.4. The gas flow rate can be increased by a factor of 3 when the fracture and matrix ratio is increased by the same factor. The gas flow rate decreased with the increase of the cover layer coefficient. The gas flow rate is reduced by 75% when the cover layer coefficient increased by a factor of 5. The mass exchange coefficient has almost no effect on the gas flow rate.

Under the first type boundary condition, the gas flow rate can quickly reach its peak value and become stable under each case. However, under the boundary of the second type, the gas flow rate will increase over time for a period of time before it reaches steady state. The greater anisotropy, pumping pressure and fracture matrix ratio can induce the larger pumping flow. This is also consistent with the results in Fig. 11.

Conclusions

A field gas extraction experiment was carried out at a large-scale high kitchen waste landfill with high-leachate level in north-west of China. The leachate level was decreased to improve the gas extraction efficiency. A transient dual-porosity model was then developed to analyze the gas pressure distribution in the landfill obtained by the field tests under different drawdown conditions. Parametrical analyses were carried out to investigate the factors affecting the performance of gas extraction well. The main conclusions are as follows:

1. The gas pumping efficiency can be improved by the drawdown of leachate level. Under the same pumping pressure, the pumping flow rate of the case with active drawdown can be 1.37 times higher than that without drawdown. The increase was not obvious when the drawdown increases from 7 to 15 m. Because the landfill gas was mainly produced in the shallow layer with the age of 2–3 months.

2. The potential LFG generation capacity was determined to be 163.2 m³/t, which is 1.63–3 times larger than that of a landfill in Europe. This is induced by the greater high-kitchen food contents of the MSWs.

3. The distribution of gas pressure observed in the field test can be better fitted by the dual-porosity gas transport model than the single porosity model, especially when the drawdown is relatively small (i.e., < 12 m). This indicates that there was preferential flow in the landfill due to the heterogeneity and anisotropy of the MSWs. When the drawdown is larger than half of thickness of the waste, the preferential flow is not obvious due to the fact that the effect of water on gas transport was reduced.

4. The leachate drawdown has great effect on the volume of fractures divided by the total pores. It can be increased by a factor of 8.4, when the thickness of the unsaturated waste increased by a factor of 2.5 due to the decrease of the leachate level. This indicates that water content of the MSWs has great effect on the distribution of the fractures and matrix in them.
5. The pumping pressure and the anisotropy value of the MSWs have the greater influence on the radius of influence of the pumping well and the gas flow rate. The mass exchange coefficient has almost no influence on the influence radius of the extraction well.

6. The experimental results can provide scientific guidance for the deployment of pumping wells at landfill sites. The proposed model can be used for effective design of the field gas pumping experiments. The obtained gas generation rate, gas permeability of the dual porosity MSWs can be useful for gas transport analysis and gas pumping well design for the high-kitchen food landfills.

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