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Numerical simulation of gas flow around a passive vent in a sanitary landfill

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Abstract

A numerical model, based on the Darcy law, was used to simulate the two-dimensional gas flow around a passive vent in a sanitary landfill. We follow Findikakis and Leckie [ASCE J. Environ. Eng. 105 (1979) 927] in modeling the biodegradation of the solid waste and assume the first-order biodegradation kinetics. The numerical results from the Fresh Kills landfill, New York, show that the well's ability in extracting the landfill gas by the passive vent decays quickly with the increase of the radial distance from the well. The influence radius of the well is generally less than 20 m. The effects from the final soil thickness, well depth, and other parameters on the gas flow are also discussed.

Keywords: Numerical simulation; Gas flow; Sanitary landfill; Passive vent

1. Introduction

Sanitary landfilling is a common method for the disposal of solid waste. Concerns about the pollution and hazard problems it may bring have, however, increased with the use of such a disposal. Two major pollution issues associated with the landfill are the leachate and gases. The gases produced in the landfills are mainly the methane and carbon dioxide. Methane in volumetric concentration of 5–15% is explosive. In order to control the air pollution and hazard from the gases produced from the solid waste in the landfills, gas collection systems are installed. There are two kinds of gas collection systems, the passive venting system and the active gas pumping system [2]. The passive venting system is a system in which

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Nomenclature

a	thickness of the final soil cover (m)
A_i	fraction of waste component i
b	well depth (m)
C	mass of total gas produced per volume of waste (kg/m^3)
g	acceleration of gravity (m/s^2)
h	total landfill depth (m)
K	permeabilities of the final soil or refuse (m^2)
M	mean molecular weight of gas mixture (kg/mol)
P	gas pressure (Pa)
P_{atm}	atmosphere pressure (Pa)
Q_{w}	gas flow rate at well exit (m^3/s)
r	radical distance from the center of the well (m)
r_{w}	well radius (m)
R	computational domain in the r-direction (m)
R_{u}	universal gas constant (J/(kmol K))
t	time (year)
t_0	time elapsed after the closure of the landfill (year)
t_{f}	total time to fill the landfill (year)
T	gas absolute temperature (K)
u_r	gas velocity in the r-direction (m/s)
u_z	gas velocity in the z-direction (m/s)
z	vertical distance from the landfill surface

Greek symbols

α	overall gas generation rate of the waste (kg/m^3)
λ_i	reaction rate constant of the waste component i (per year)
μ	viscosity of gas mixture (Pa s)
ρ	gas density (kg/m^3)
ϕ	$=P - \rho g z - P_{\mathrm{atm}}$ (Pa)

perforated venting pipes are installed within the landfill or the soil surrounding the landfill. The well depth ranges from 50 to 90% of the landfill depth. The wells collect gas by natural pressure difference and convection inside the landfill. In general, these wells are equipped with flares to burn off the gas. The advantages of the passive venting systems are simple to install, less expensive to operate, and easy to maintain, but its drawback is not effective in removing the landfill gas that may escape from landfill surface or from the underground soil surrounding the landfill into the nearby buildings. Another system is the active gas pumping system, which collects gas by using the vacuum pumps. A pipe network is built to the interconnect wells and blower equipment, which direct the collected gases to an energy recovery system. This system remove the landfill gas effectively but the installation and maintenance fees of such a system are pretty high.

In the modeling of the gas flow in the landfill, Esmaili [3] proposed a single-well model to analyze the gas flow rate from well in a landfill equipped with an active gas pumping system. The model assumed that: (1) the top surface of the soil formation is impermeable; and (2) the well is also located at the surrounding soil outside the landfill limits. His results, thus, cannot apply to the place inside the landfill. Lu and Kunz [4] developed a one-dimensional radial-flow model which calculates the landfill's methane production rate and gas-flow permeability by measuring of landfill gas pressures and pressure changes caused by the withdrawal of gas. Findikakis and Leckie [1] developed one-dimensional numerical model to simulate the gas pressure and concentration profiles in landfills. Arigala et al. [5] developed a model to describe the gas generation, transport, and extraction in a landfill. The wells are assumed to be one-dimensional line sinks with uniform gas extraction rates.

The well spacing is a critical issue in the passive venting system design. The influence radius is generally used in determining the well spacing. If the flow motion of gases produced from the solid waste is well understood for an influence radius, this may provide a useful information for the passive venting system design. The different influence radii (45–50 m for the Taipei Sanjuku landfill [6], and 30–35 m for the Taichung landfill [7]) were estimated in the designing of the passive venting system in Taiwan. It is also expensive to measure gas flow from a large area of landfill. These motivate the study of the gas-flow modeling in landfills.

2. Mathematical model

The sanitary landfill is composed of the solid waste and the final soil cover. The biodegradation of the solid waste is based on the approach by Findikakis and Leckie [1], in which the refuse is classified into three categories: readily biodegradable, moderately biodegradable and slowly biodegradable. Since the time scale of gas-flow dynamics within the landfill can be neglected, the gas flow can be approximated as a quasi-steady state, once the landfill gas is sufficiently mature. The landfill gas is assumed to be an equimolar mixture of CH_4 and CO_2. The variation of gas flow in the azimuthal direction is also neglected. A schematic of this flow system is given in Fig. 1. The governing equation of mass conservation can be written as:

$$\frac{1}{r}\frac{\partial}{\partial r}(r\rho u_r) + \frac{\partial}{\partial z}(\rho u_z) = \alpha, \tag{1}$$

where ρ is the gas density, r the radial distance from center of the well, z the vertical distance measured from top of the landfill, u_r and u_z the gas velocity in the r- and z-directions, respectively, and α the overall gas production rate for the solid waste layers. Gas production rate in the soil layers is zero. The gas production rate for all of the three components is assumed as follows [1,5]:

$$\alpha = C\sum_{i=1}^{3} A_i\lambda_i\, e^{-\lambda_i t}, \tag{2a}$$

$$t = t_0 + \frac{z}{h}t_{\mathrm{f}}, \tag{2b}$$

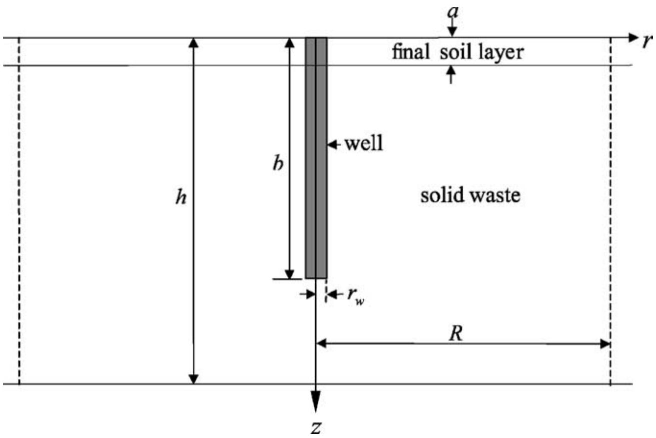

Fig. 1. The schematic of the landfill geometry and coordinate system.

where $C = \rho_{\text{refuse}}[\rho_{CH_4}(V_{CH_4})_{\text{refuse}} + \rho_{CO_2}(V_{CO_2})_{\text{refuse}}]$ is the mass of total gas produced per unit volume of refuse (ρ_{refuse}, ρ_{CH_4} and ρ_{CO_2} are the refuse, methane and carbon dioxide densities, respectively, and $(V_{CH_4})_{\text{refuse}}$ and $(V_{CO_2})_{\text{refuse}}$ the methane and carbon dioxide gas production potentials per unit mass of refuse (m^3/kg), respectively), A_i fraction of waste component i, λ_i the reaction rate constant of waste component i, t the time measured since the first layer of refuse was placed in the landfill, t_0 the time elapsed since the landfill was capped, t_f the total time to fill the landfill, and h the total landfill depth. The Dracy law is employed for the gas flow through the landfill including the soil and refuse layers. An ideal gas model is assumed for the gas mixtures:

$$u_r = -\frac{K_r}{\mu}\frac{\partial P}{\partial r}, \tag{3a}$$

$$u_z = -\frac{K_z}{\mu}\left(\frac{\partial P}{\partial z} - \rho g\right), \tag{3b}$$

$$\rho = \frac{PM}{R_u T}, \tag{3c}$$

where P is the gas pressure, μ the viscosity of gas mixture, g the acceleration of gravity, K_r and K_z the horizontal and vertical permeabilities of waste or soil layers, respectively, T the gas absolute temperature, M the mean molecular weight of gas mixture, and R_u the universal gas constant. In the waste layer, different horizontal and vertical permeabilities are used. In the final soil cover, the horizontal and vertical permeabilities are assumed to be the same. A new function can be defined as:

$$\phi = P - \rho g z - P_{\text{atm}}, \tag{4}$$

where P_{atm} is the atmosphere pressure. By substituting Eqs. (3) and (4) to Eq. (1), it yields:

$$\frac{1}{\mu}\frac{1}{r}\frac{\partial}{\partial r}\left(r\rho K_r\frac{\partial\phi}{\partial r}\right) + \frac{1}{\mu}\frac{\partial}{\partial z}\left(\rho K_z\frac{\partial\phi}{\partial z}\right) = -\alpha. \tag{5}$$

The associated boundary conditions are:

$$\phi = 0, \quad \text{at}\, z = 0, \quad r_w \le r \le R, \tag{6a}$$

$$\frac{\partial \phi}{\partial z} = 0, \quad \text{at}\, z = h, \quad 0 \le r \le R, \tag{6b}$$

$$\frac{\partial \phi}{\partial r} = 0, \quad \text{at}\, r = 0, \quad b \le z \le h, \tag{6c}$$

$$\frac{\partial \phi}{\partial r} = 0, \quad \text{at}\, r = R, \quad 0 \le z \le h, \tag{6d}$$

where r_w is the well radius, r the computational radius, b the well depth, and h the total depth of the landfill. The pressure on the top surface of the landfill is equal to the atmosphere pressure, P_{atm}. It is assumed that the bottom surface of the landfill is impermeable and the gas velocity in the radial direction is negligible at $r = R$. Boundary condition (6c) stands for the symmetric condition of the gas flow. The one-dimensional Bernoulli equation is assumed for the gas flow within the well, that is:

$$\phi_w + \tfrac{1}{2}\rho u_w^2 = \text{constant}, \quad \text{for}\, r < r_w, \quad 0 \le z \le b, \tag{7a}$$

where the subscript ‘w’ refers to the quantity within the well. The gas velocity distribution inside the well is obtained by using the mass conservation as shown in the following:

$$\frac{\mathrm{d}u_w}{\mathrm{d}z} = 2\pi r_w u_r|_{r=r_w}, \tag{7b}$$

where $u_r|_{r=r_w}$ is the gas velocity at the well boundary and is calculated from the Eq. (3). It is noted that the pressure on the top of the well is also the atmosphere pressure as is shown in boundary condition (6a). The governing Eq. (5) and associated boundary conditions are solved by the finite-difference method. The Tri-Diagonal Matrix Algorithm is used to solve the discretized equations. The numerical details can be found in the book of Patankar [8]. In this study, the grid points in the r- and z-directions are 74 and 72, respectively. The criterion used for the iteration convergence is:

$$\max|\phi^{n+1} - \phi^n| \le 0.01, \tag{8}$$

where ϕ^n is the values at the iteration number n.

3. Result and discussion

The landfill side for this study is the Fresh Kills landfill, which is one of the world’s largest landfill [9]. The Fresh Kills landfill is located at Staten Island, a borough of the city of New York. The total area covered by the municipal waste is 426.5 ha, and the mounds of waste extend up to 46 m or more in height. The landfill is divided into four sections designated as 3/4, 2/8, 6/7, and 1/9. Sections 3/4 and 2/8 no longer accepted trash. The northwest portion of the landfill is designated as Section 3/4 and covers approximately 57.2 ha (141 acres). The waste in this section dates from when the section was open in 1955 until it was closed in 1992. The details of the description of the landfill side can be found in the Report EPA902-R-95-001a [10].

A short-term intensive measurement on the landfill gas composition and pollutant emission rates was performed by the US Environmental Protection Agency Region II (assisted by the Radian Corporation). Hundred of gas samples were collected at the landfill over a 3-week period in June and July of 1995. In Section 3/4, most (119) of the passive vents had already been installed at the time of the field sampling. Only those vents above the 42.7 m elevation were not in place. The impermeable clay cap with thickness of 0.30–0.46 m on the toe covers approximately 9.1 ha. Approximately 8.2 ha were being capped with a PVC cover. The remaining 39.9 ha were capped with a soil cover. The details of the measurement data can be found in [10]. Since this report indicated that approximately 10% of the vents did not have flow, but it (Tables 4–8 of [10]) only had the flow rate records of 78 vents. The average of the flow rates of 78 vents is 52.8 m^3/h. Thus, we assume that the upper limit of the flow rate average is about 47.5 m^3/h and the lower limit (assuming the flow rates of the remaining vents are zero) is about $52.8 \times 78/119 = 34.6\,m^3$/h. The mean value of the upper limit and the lower limit of the flow rate for passive vent is 41 m^3/h.

Table 1 lists all input landfill parameters for the numerical model, including the soil and refuse permeabilities and other refuse properties used by Findikakis and Leckie [1] and Arigala et al. [5]. Since the final soil thickness generally ranges between 0.5 and 2 m, and the well depth generally ranges from 50 to 90% of the landfill depth [2], the final soil thickness

Table 1
Values of landfill parameters (data adopted from [1,5,10])

Landfill data	Value
Well diameter (m)	0.1
Landfill depth (m)	46
Final soil thickness (m)	1
Well depth (about 70% of landfill depth) (m)	32.5
Fill period (year)	37
Time elapsed since closure of landfill (per year)	3
Refuse density (kg/m^3)	880
Gas temperature (K)	310
Viscosity of gas mixture (Pa s)	1.54×10^{-5}
Permeability of final soil cover (m^2)	1.0×10^{-13}
Horizontal permeability of refuse (m^2)	3.0×10^{-12}
Vertical permeability of refuse (m^2)	1.0×10^{-12}
Methane gas generation potential per unit mass of refuse (m^3/kg)	0.178
Carbon dioxide gas generation potential per unit mass of refuse (m^3/kg)	0.178
Refuse composition	
Readily biodegradable (%)	15
Moderately biodegradable (%)	55
Slowly biodegradable (%)	30
Reaction rate constant of refuse	
Readily biodegradable (per year)	0.1386
Moderately biodegradable (per year)	0.0231
Slowly biodegradable (per year)	0.017328

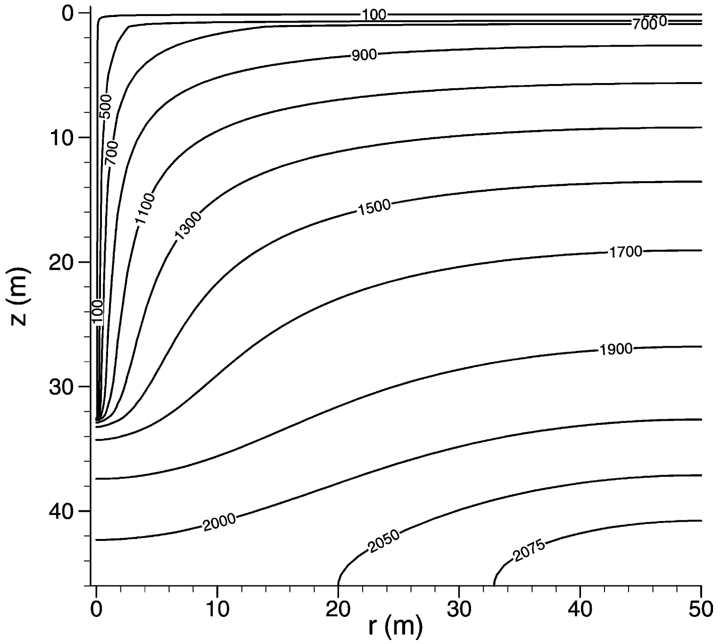

Fig. 2. The pressure contour, ϕ, with the input landfill parameters shown in Table 1.

of 1 m and the well depth with 70% of the landfill depth are also assumed in Table 1. The numerical result of the flow rate from a passive vent is 36.0 m^3/h. This indicates that the computed flow rate is in the reasonable range as compared with the landfill experimental data.

The pressure field, ϕ $(=P - \rho gz - P_{atm})$, for the above landfill parameters (Table 1) is plotted in Fig. 2. The results show that the constant pressure lines near the well are close to each other and the curves stand almost vertically. This indicates that the gas moves almost horizontally and will be collected by the well. But if the radial distance from the well is increased, the interval between two curves will increase quickly and the slope of the curve decline quickly. This implies that the well's ability in capturing the far-away landfill gas decays quickly with the increase of the radial distance from the well in the passive venting system. When the distance from the well is greater than 20 m, the constant pressure lines are close horizontal. It suggests that a high proportion of the landfill gas produced by the waste for $r \geq 20$ m could not be collected by the well and could emit out from the landfill surface. It can also be seen that the slope of the constant pressure line is smaller, when the curve is closer to the top surface. This indicates that the gases produced by the top refuse layers are easy to escape from the landfill surface. From the above discussions, it indicates that the well's ability in collecting the landfill gas by the passive vent is limited to a small area around the vent.

Fig. 3 shows the effect of the final soil cover thickness, a, on the gas flow rate at the well exit, Q_w (m^3/h). It is noted that, except the final soil thickness, all other input landfill parameters are the same with those listed in Table 1. Fig. 3 indicates that the gas flow rate from the well increases with increasing final soil thickness. This is because the permeability of final soil is much smaller than that of the refuse, the increase of the final soil thickness will

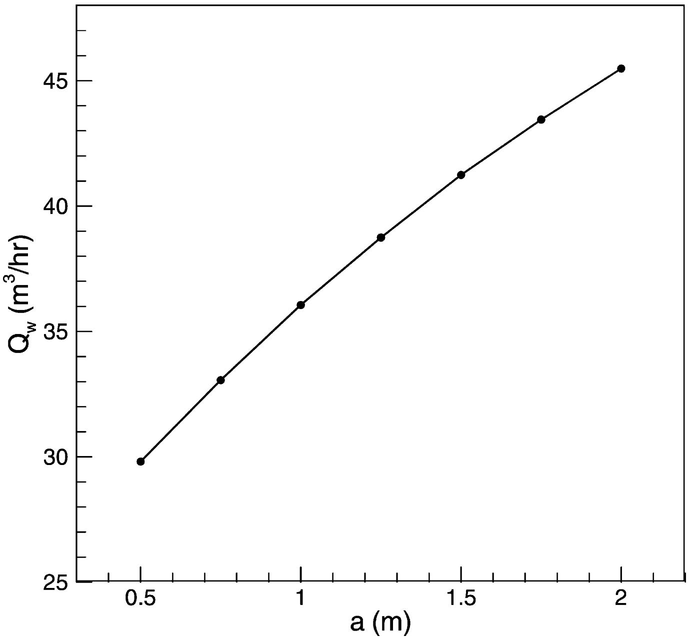

Fig. 3. The variation of flow rate, Q_w, with the final soil thickness, a (except the final soil thickness, all other input landfill parameters are the same with those in Table 1).

increase the flow resistance for the gas to go through the final soil layer. Thus, the landfill gas will move along the refuse layers with less flow resistance and is easy to be captured by the well. The flow rate for $a = 2$ m is 45.5 m^3/h, which is 53% higher than that (29.8 m^3/h) for $a = 0.5$ m. To show the effect on the flow pattern for the thicker final soil layer, the pressure contour, ϕ, for $a = 2$ m is plotted in Fig. 4. When it compares to the pressure contours in Fig. 2, the density of the curves near the well region in Fig. 4 is much higher than that in Fig. 2. This means that more landfill gas will move towards the well direction and will consequently be collected by the well. The curve inside the final soil in Fig. 4 is crowded, meaning that the final soil cover acts to retard the gas flow toward the landfill surface.

The effect of well depth, b, on the gas flow rate at well exit, Q_w, is plotted in Fig. 5. The well depth generally ranges from 50 to 90% of the landfill depth [2]. The Q_w increases with increasing well depth. The Q_w for the $b = 41.5$ m (90% of the landfill depth) is 44.6 m^3/h, which is 77% higher than that (25.2 m^3/h) for the $b = 23$ m (50% of the landfill depth). This indicates that the well depth has an important effect on the flow rate. Fig. 6 presents the pressure contour, ϕ, for a shorter well depth of 23 m. It shows that the flow pattern is affected by the well depth. The curves for the depth $z \geq 27$ m or for the radius $r \geq 18$ m are almost horizontal. This indicates that the well's ability in extracting on those gases, which are produced in the refuse for the regions of $z \geq 27$ m or for the radius $r \geq 18$ m, is rather limited. Thus, large amount of the landfill gases produced in these regions could escape from the landfill surface. From the above results, it is suggested that the well depth should be deeper as possible as it can be.

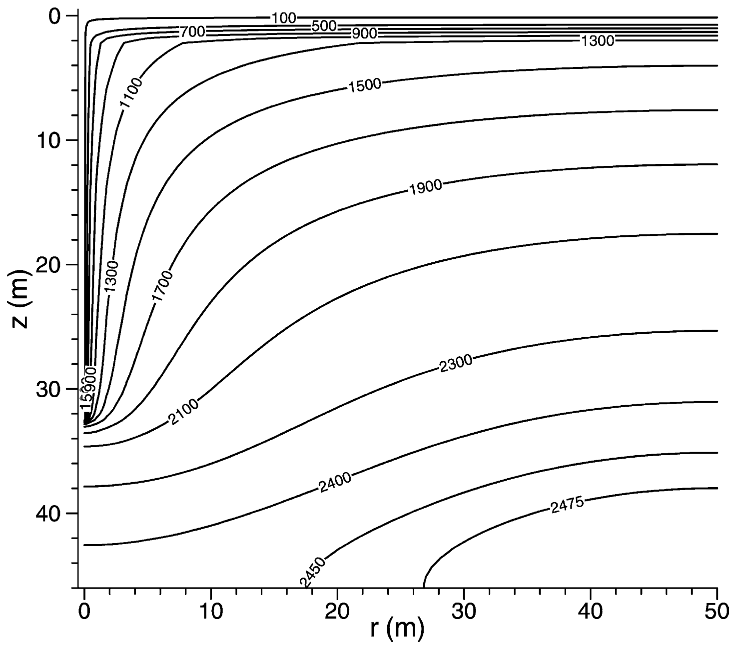

Fig. 4. The pressure contour, ϕ, for the final soil thickness, $a = 2\,\mathrm{m}$.

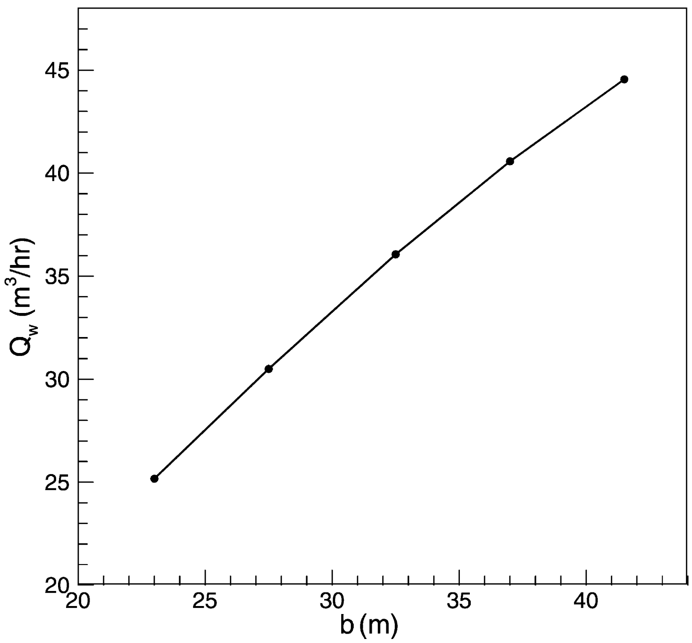

Fig. 5. The variation of flow rate, Q_w, with the well depth, b.

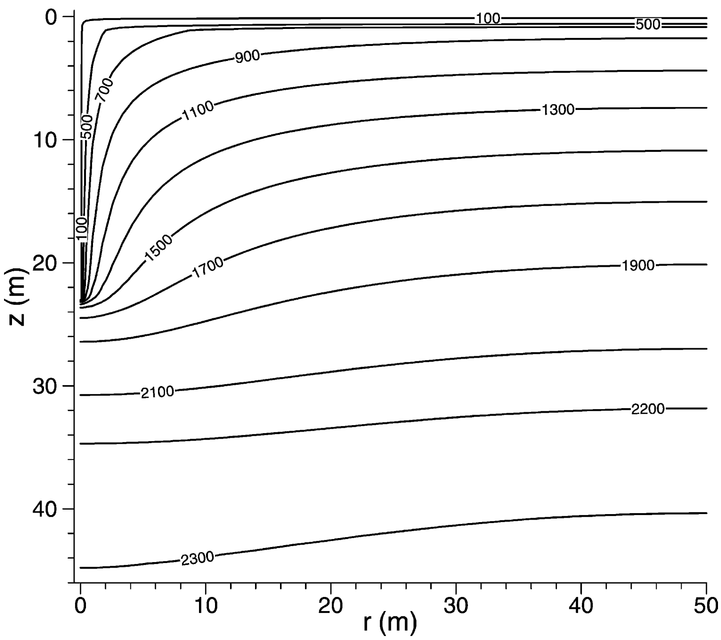

Fig. 6. The pressure contour, ϕ, for the well depth, $b = 23$ m.

The effect of the final soil permeability, K_f, on the gas flow rate from well, Q_w, is plotted in Fig. 7. The Q_w increases with the decreasing final soil permeability and its increases more quickly when the permeability of the final soil is small. The gas flow rate Q_w for $K_f = 6 \times 10^{-14}$ m^2 is 44.8 m^3/h, which is 72% higher than that (26 m^3/h) for $K_f = 30 \times 10^{-14}$ m^2. The pressure contour, ϕ, for small final soil permeability of 6×10^{-14} m^2 is shown in Fig. 8, and it shows that the curves in the final soil layer are close to each other, indicating that the flow resistance for the gas to go through the final soil layer is high. The above results show that the mechanisms on the flow patterns by increasing the final soil thickness or by choosing a lower permeability for the final soil are basically the same; that is, they increase the gas flow resistance through the final soil layer so that the landfill gas is difficult to penetrate this layer.

A sensitivity analysis of time, t_0 (year), elapsed since the landfill was capped is plotted in Fig. 9. It is reminded that, except the parameter of t_0, all other input landfill parameters are the same with those listed in Table 1. It shows that the flow rate gradually decays when time, t_0, is longer. Fig. 10 plots the pressure contour for $t_0 = 10$ years. As compared with Fig. 3 for $t_0 = 3$ years, both pressure patterns are similar, but the curves of Fig. 3 are more crowded. The flow rate (28.6 m^3/h) for $t_0 = 10$ years is 79% of that (36.1 m^3/h) for $t_0 = 3$ years. It is seen that most portions of the curve of $\phi = 1650$ in Fig. 10 coincide with those of the curve of $\phi = 2050$ in Fig. 3. Its ratio is 1650/2050 = 80%, which is very close to 79%. Thus, the magnitude of flow velocity in Fig. 3 is about 79% of that in Fig. 3. This indicates that the time age of t_0 has limited effect on the flow pattern, but it affects the magnitude of flow velocity in the landfill.

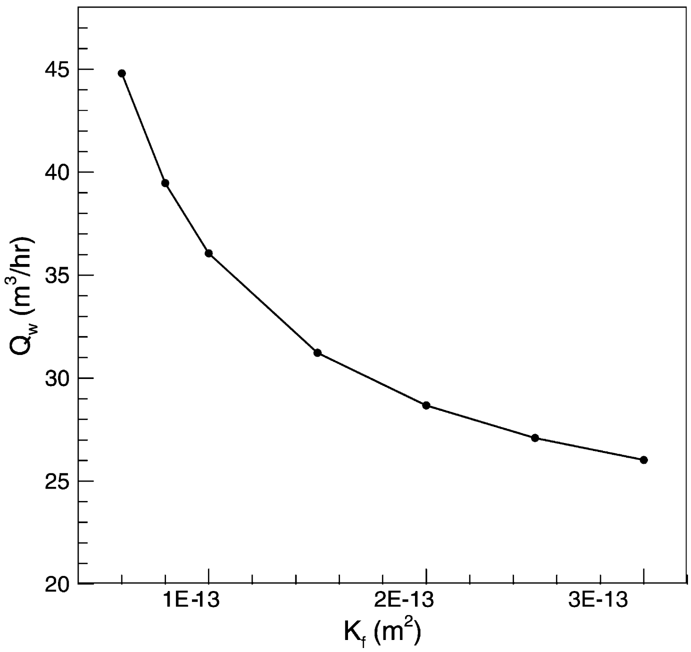

Fig. 7. The variation of flow rate, Q_w, with the final soil permeability, K_f.

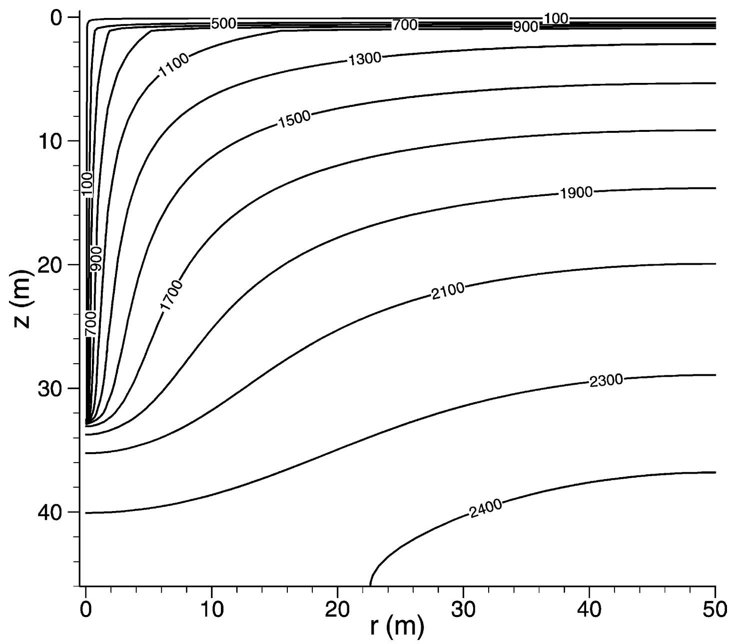

Fig. 8. The pressure contour, ϕ, for the final soil permeability, $K_f = 6 \times 10^{-14}\,m^2$.

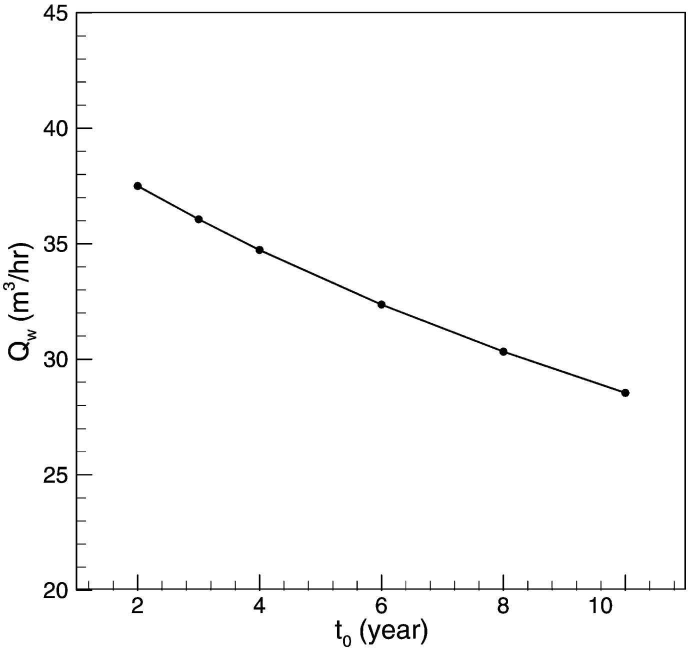

Fig. 9. The variation of flow rate, Q_w, with time elapsed since landfill was capped, t_0.

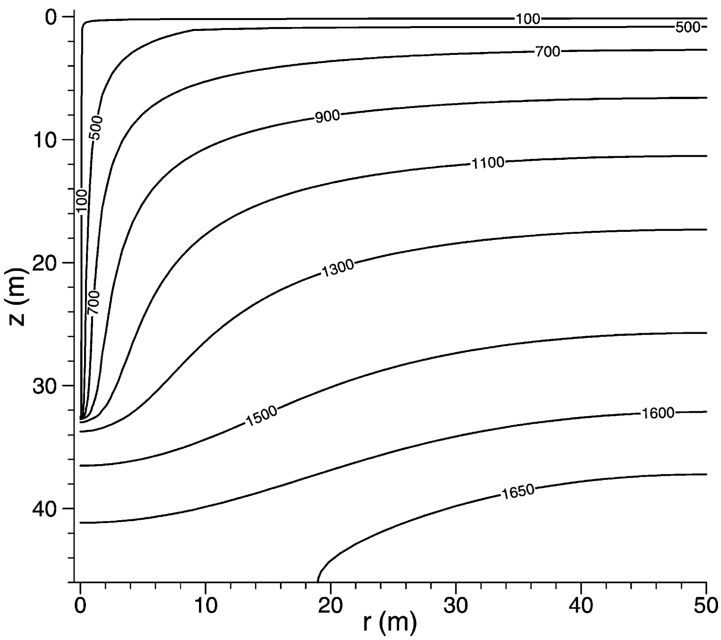

Fig. 10. The pressure contour, ϕ, for time, $t_0 = 10$ years.

4. Conclusion

The two-dimensional gas flow around a passive vent in a landfill was investigated numerically. The Darcy law was employed in modeling the flow motion. The one-dimensional Bernoulli equation was assumed for the gas flow within the well. The field data from the Fresh Kills landfill, New York, was used for the numerical model verification and the studies of the different landfill parameter effects on the gas flow. The numerical results show that the well's ability in extracting the landfill gas in the passive venting system is limited to a small area around the well and its gas collection ability decays quickly with the increase of the radial distance from the well. The result from the Fresh Kills landfill also shows that when the distance from the well is greater than 20 m, the slopes of constant pressure curves are generally small. It suggests that a high proportion of the landfill gas in the region with its radial distance from the well greater than 20 m may emit out from the landfill surface. This indicates that the influence radius of the passive vent is generally less than 20 m.

The landfill parameter studies also show that the flow rate from the well increases with increasing the final soil thickness or by choosing final soil with lower permeability. This is due to the fact that they increase the flow resistance through the final soil layer so that gas is difficult to penetrate it. The flow rate from the well is increased 53%, when the final soil thickness is increased from 0.5 to 2.0 m. The flow rate is increased 72%, when the final soil permeability is reduced from 30×10^{-14} to $6 \times 10^{-14}\,m^2$. The flow rate also increases for the deeper well depth. When the well depth is 90% of the landfill depth, its flow rate is 77% higher than that for the well depth equal to 50% of the landfill depth. The time age, elapsed since the closure of the landfill, has a limited effect on the flow pattern, but it affects the magnitude of flow velocity and the flow rate. Those imply that the gas flow can be significantly effected by the final soil thickness and its permeability, and the well depth.

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References

[1] A.N. Findikakis, J.O. Leckie, Numerical simulation of gas flow in sanitary landfills, ASCE J. Environ. Eng. 105 (1979) 927–945.
[2] P. O'Leary, P. Walsh, Landfill gas movement, control, and uses, Waste Age 114 (1991) 114–124.
[3] H. Esmaili, Control of gas flow from sanitary landfills, ASCE J. Environ. Eng. 101 (1975) 555–566.
[4] A.H. Lu, C.O. Kunz, Gas-flow model to determine methane production at sanitary landfills, Environ. Sci. Technol. 15 (1981) 436–440.
[5] S.G. Arigala, T.T. Tsotsis, I.A. Webster, Y.C. Yortsos, J.J. Kattapuram, Gas generation, transport, and extraction in landfills, ASCE J. Environ. Eng. 121 (1995) 33–44.

[6] Chung-Hsing Engineering Consulting Corp., Planning Report of Sanjuku Sanitary Landfill of Taipei City, 1992.
[7] Hwan-Chi Engineering Consulting Corp., The Planning Project of Gas and Leachate Pollution Prevention for the Taichung City Sanitary Landfill, 1994.
[8] S.V. Patankar, Numerical Heat Transfer and Fluid Flow, Hemisphere, New York, 1989.
[9] J.M. Suflita, C.P. Gerba, R.K. Ham, A.C. Palmisano, W.L. Rathje, J.A. Robinson, The world's largest landfill, Environ. Sci. Technol. 26 (1992) 1486–1495.
[10] Radian Corporation, Determination of landfill gas composition and pollutant emissions rates at Fresh Kills landfill, USEPA Project Report No. EPA902-R-95-001a, 1995.