Theoretical Study on the Influence of Degradation and Compression Parameters on Gas Pressure in Municipal Solid Waste Landfill

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ABSTRACT: Gas pressure is of great significance to the safe management and operation in a landfill. In this paper, a mathematical model for gas pressure simulation in a landfill was developed and the effects of degradation and compression parameters on gas pressure were studied. The results showed that gas pressure in landfill was continuously decreased under the action of extraction pressure. The internal gas pressure in horizontal direction was smaller than that in vertical direction at the same position due to the heterogeneity and anisotropy of refuse dump. Gas pressure in landfill increased with the increase of compression coefficient, biodegradation strain and biodegradation rate constant. The internal gas pressure was most significantly affected by compression coefficient, followed by biodegradation strain, and biodegradation rate constant had the least influence. The influence ranges were 60 kPa, 6 kPa and 3 kPa, respectively.

KEYWORDS: Landfill, Gas pressure, Mathematical model, Simulation rule.

1. INTRODUCTION

Domestic waste seems to be insignificant, but improper management and disposal will undoubtedly produce a lot of adverse effects (Chen et al., 2010). Timely, hygienic and safe disposal of domestic waste is of great significance to environmental protection (Zeng et al., 2019). Sanitary landfill is a widely and effective method to deal with domestic refuse because of its simple operation, large disposal capacity, low investment and fast efficiency (Liu et al., 2020; Zhang et al., 2019; Zheng et al., 2019). The essence of landfill is a multi-field coupled biochemical reactor. Its main input substances are domestic waste, and its main output substances are leachate and landfill gas (LFG) (Omar et al., 2015; Shu et al., 2021). LFG is one of the main pollutants generated by landfill, which is generated by the anaerobic degradation of organic substances. Its composition is mainly composed of methane, carbon dioxide and a small amount of trace gases (Zeng, 2019; Ma et al., 2020). Landfill gas has great greenhouse effect, inflammable and explosive hazards, but it is a new clean energy (Liu et al., 2018; Zeng et al., 2017; Dace et al., 2015). According to online reports, LFG explosions have been reported at landfills in Payatas, Chuxiong in Yunnan province, China, Wailingding island in Guangdong province, China and other landfills. The mechanism, prevention and control of LFG disaster has important practical significance, which is one of the scientific issues with high attention in the field of environmental geotechnical engineering (Xue et al., 2014). Gas pressure in landfill is closely related to gas migration, which has a great impact on the settlement, safety and stability of landfill (Chen et al., 2014; Li et al., 2009). It is particularly necessary to study the variation of gas pressure in landfill for the migration and collection of LFG.

Degradation and compression are important factors affecting the migration of LFG in landfill (Hossain et al., 2009; Stoltz et al., 2010). The degradation of organic matter determines the rate of gas generation and the decomposition of solid phase will change the pore structure of refuse. The solid phase compression changes the pore structure of refuse dump and causes the change of gas migration channel. A lot of scholars have carried out research work on landfill gas migration model and simulation of migration law. Chen et al. (2003) presented a two-dimensional steady-state mathematical model of LFG migration in polar coordinate system, and used the passive pumping well as the calculation model to predict the gas production law of a landfill site in New York City. Li et al. (2009) constructed a two-dimensional gas migration model combined with the traditional rheological model, and analyzed the influence of porosity and gas dispersion on the pressure distribution in landfill. Townsend et al. (2005) established the pressure distribution model of homogeneous landfill, and analyzed the gas production rate, landfill thickness and intrinsic permeability coefficient of landfill. Liu et al. (2014) developed a coupling model of the multicomponent gas flow and transport to describe methane oxidation in landfill cover. Feng et al. (2015) developed a two-dimensional analytical solution to enable the study of the gas pressure distribution, well pressure and recovery efficiency in layered landfills with horizontal wells.

The above literature could provide a reference for the establishment of this work. However, it was not difficult to find that there were few reports about the effect of degradation and compression parameters on gas pressure in landfill. In this paper, a mathematical model of gas migration in landfill was developed based on the knowledge of gas continuity equation, gas production equation and composite compression model. The effects of degradation and compression parameters on the distribution rule of gas pressure in landfill were analyzed by using the established model.

2. MATHEMATICAL MODEL

The following assumptions were made when establishing the coupling model: (a) LFG was considered as ideal gas, and gas flow in refuse dump obeyed Darcy's law; (b) Ignoring the dissolution of gas in the liquid, and the effect of liquids on gas migration was negligible; (c)The viscosity coefficient of LFG was constant, and refuse dump was isothermal state; (d) The compression of MSW occurred only in the vertical direction; (e) The flow rate of solid skeleton was much lower than that of gas.

Gas flow can be described by Darcy's law, and the expression of gas motion was shown in Eq. (1).

$$\nu = -\frac{k}{\mu}(\nabla P_g + \rho_g g) \tag{1}$$

where, ν was the absolute velocity of gas, m/s; k was the permeability of porous medium, m^2; μ was gas viscosity coefficient, Pa·s; P_g was gas pressure, Pa; ρ_g was gas density, kg/m^3; g was gravitational acceleration, m/s^2.

The continuity equation for LFG migration considered the source-sink term of gas generated by degradation written in divergence form was shown in Eq. (2).

$$\nabla \cdot (\rho_g v) + \frac{\partial(\rho_g \varphi)}{\partial t} = F_g \tag{2}$$

where, F_g was the total gas production rate, kg · m^{-3} · s^{-1}; ϕ was the porosity of the refuse dump.

F_g was the biochemical degradation that transformed the biodegradable organic matter in refuse from solid state to LFG. Gas generation rate of LFG could be described by the first-order kinetic model, and the expression was shown in Eq. (3) (Li et al., 2009).

$$F_g = G_T \sum_{i=1}^{3} A_i \lambda_i e^{-\lambda_i t} \tag{3}$$

where, G_T was the total gas production potential per unit volume of waste, is generally 502 kg/m^3; i was three organic substances that were easily degraded, moderately degraded and difficult to degrade in waste; A_i was the percentage of organic matter with different degradation capacity in refuse; λ_i was the degradation rate constant, and the value for the three organic compounds of easy degradation, moderate degradation and refractory degradation were 0.1386, 0.0231, 0.017328, respectively; t was the time after landfill.

Marques et al. (2003) proposed a composite compression model, which divided the settlement deformation of landfill into three parts: the instantaneous settlement related to load, the mechanical creep settlement related to time and the biochemical degradation settlement related to time. The expression of composite compression model was shown in Eq. (4).

$$\varepsilon = \frac{\Delta H}{H} = C_c' \cdot log(\frac{\sigma_0+\Delta\sigma}{\sigma_0}) + \Delta\sigma \cdot b \cdot (1-e^{-ct'}) + E_{dg} \cdot (1-e^{-dt''}) \tag{4}$$

where, ε was the strain; H was the landfill height; ΔH was the sedimentation; C_c' was the compression coefficient; Δσ was the vertical direction stress increment; b was the mechanical creep coefficient; c was the mechanical creep rate constant; E_{dg} was the total strain deformation caused by biochemical degradation; d was the biochemical degradation rate constant; t' was the time to apply stress; t'' was the time when the waste begins to landfill.

The relationship between porosity and strain can be expressed by Eq. (5).

$$\varphi = \frac{\varphi_0-\varepsilon}{1-\varepsilon} = \frac{\varphi_0-1}{1-\varepsilon} + 1 \tag{5}$$

where, ϕ_0 was the initial porosity of refuse.
Eq. (6) was obtained by substituting Eq. (4) into Eq. (5).

$$\varphi(P_g, t) = \frac{\varphi_0-1}{1-[C_c' \cdot log(\frac{\sigma_0+\Delta\sigma}{\sigma_0})+\Delta\sigma \cdot b \cdot (1-e^{-ct'})+E_{DG} \cdot (1-e^{-dt''})]} + 1 \tag{6}$$

Eq. (7) was obtained by taking a first order partial derivative of Eq. (6).

$$\frac{\partial\varphi}{\partial t} = h(P_g, t)\frac{\partial P_g}{\partial t} - g(P_g, t) \tag{7}$$

where,

$$h(P_g, t) = \frac{(1-\varphi_0)[C_c' \cdot \frac{\sigma_0+\Delta\sigma}{\sigma_0}+b \cdot (1-e^{-ct'})]}{\{1-[C_c' \cdot log(\frac{\sigma_0+\Delta\sigma}{\sigma_0})+\Delta\sigma \cdot b \cdot (1-e^{-ct'})+E_{DG} \cdot (1-e^{-dt''})]\}^2}$$

$$g(P_g, t) = \frac{(1-\varphi_0)(\Delta\sigma \cdot b \cdot c \cdot e^{-ct'}+E_{DG} \cdot d \cdot e^{-dt''})}{\{1-[C_c' \cdot log(\frac{\sigma_0+\Delta\sigma}{\sigma_0})+\Delta\sigma \cdot b \cdot (1-e^{-ct'})+E_{DG} \cdot (1-e^{-dt''})]\}^2}$$

Eq. (8) could be obtained by substituting gas ideal state equation, gas motion equation Eq. (1), gas production rate equation Eq. (3) and partial derivation of porosity for time Eq. (7) into gas continuity equation Eq. (2).

$$\nabla\left(\frac{P_g M v}{RT}\right) + \frac{M}{RT}[\varphi + P_g \cdot h(P_g, t)]\frac{\partial P_g}{\partial t} - \frac{M}{RT}P_g \cdot g(P_g, t)] = F_g \tag{8}$$

The governing mathematic model of LFG migration could be obtained for the deformation of Eq. (8), which was shown in Eq. (9).

$$\frac{\partial^2 P_g}{\partial z^2} = \frac{\alpha}{\beta}P_g \cdot g(P_g, t) - \frac{\alpha}{\beta}[\varphi + P_g \cdot h(P_g, t)]\frac{\partial P_g}{\partial t} + \frac{1}{\beta}F_g \tag{9}$$

where, $\alpha = \frac{M}{RT}$, $\beta = -\frac{MK}{2\mu RT}$.

3. SIMULATION AND ANALYSIS

The simulation method used to analyze gas pressure in landfill could provide technical support for LFG resource utilization in the practical project.

3.1 Simulation Model and Parameters

3.1.1 Simulation Model

The simulation model for LFG migration was established and simulated by COMSOL Multiphysics software. The schematic diagram is shown in Figure 1. The length and height of the model were 80 m and 14 m, respectively. The mathematical model was used to simulate the influence of compressibility coefficient, biodegradation strain and biodegradation rate constant on gas pressure in landfill under the condition of extraction pressure at 2 kPa and anisotropic ratio at 3:1.

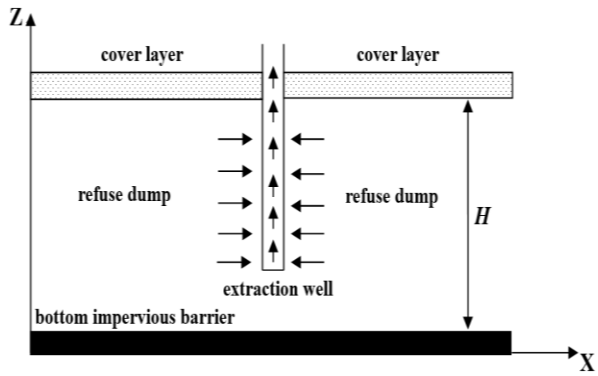

Figure 1 Schematic diagram of gas pressure simulation in landfill

3.1.2 Initial Conditions

The initial condition was that the initial pressure inside the landfill $P|_{t=0} = P_0$. The upper boundary of the landfill was constant pressure. That is, the gas pressure was equal to the standard atmospheric pressure $P = P_{atm} = 101325$ Pa, $z = H$. The bottom boundary of landfill was impermeable $\frac{\partial P}{\partial z}\Big|_{z=0} = 0$. The wall pressure was equal to the extraction pressure $P = P_e$.

3.1.3 Values of Model Parameters

The calculation parameters and values were shown in Table 1, which mainly included basic characteristics of refuse dump, extraction well, cover layer and composite compression model.

3.2 Simulation Results and Analysis

The variation rules of gas pressure in landfill closure for 1 year and 10 years were compared and analyzed. The simulation results are shown in Figure 2 to Figure 7. In the horizontal direction Z = 7 m was selected as the analysis profiles, while in the vertical direction X = 40 m was selected as the analysis profiles.

3.2.1 The Influence of Compression Coefficient on Gas Pressure in Landfill

The variation rules of compression coefficient on gas pressure in the horizontal and vertical directions of landfill are shown in Figure 2 and Figure 3, respectively.

Table 1 Values of Model Calculation Parameter

Model Calculation Parameter	**Values**
Density of refuse (kg/m^3)	900
Landfill height (m)	14
Radius of pumping well (m)	0.5
Buried depth of extraction well (m)	7
Cover thickness (m)	1
Ideal gas constant J/(mol*K)	8.314
Density of refuse (kg/m^3)	900
Molar mass of landfill gas (g/mol)	28.6
Gas temperature (K)	310
Atmospheric pressure (Pa)	101325
Content of easily degradable refuse A_1 (%)	15(Li et al., 2009)
Content of medium degradable refuse A_2 (%)	55(Li et al., 2009)
Content of refractory degradable refuse A_3 (%)	30(Li et al., 2009)
Gas viscosity coefficient (Pa·s)	0.000017
Biodegradation rate constant of easily degradable waste λ_1 (yr^{-1})	0.1386 (Li et al., 2009)
Biodegradation rate constant of medium degradation waste λ_2 (yr^{-1})	0.0231(Li et al., 2009)
Biodegradation rate constant of refractory waste λ_3 (yr^{-1})	0.017328 (Li et al., 2009)
Total gas production per unit mass of waste (m^3/kg)	502 (Li et al., 2009)
Horizontal gas permeability (m^2)	3.0×10^{-12} (Chen et al., 2003)
Vertical gas permeability (m^2)	1.0×10^{-12} (Chen et al., 2003)
Compression coefficient	0.1 (Marques et al., 2003)
Biodegradation strain	0.15(Marques et al., 2003)
Mechanical creep coefficient (kPa^{-1})	5.27×10^{-4} (Marques et al., 2003)
Mechanical creep rate constant (d^{-1})	1.50×10^{-3} (Marques et al., 2003)
Biodegradation rate constant (d^{-1})	1.14×10^{-3} (Marques et al., 2003)
Gas permeability of cover layer (m^2)	1.0×10^{-13} (Chen et al., 2003)
Extraction pressure (kPa)	2

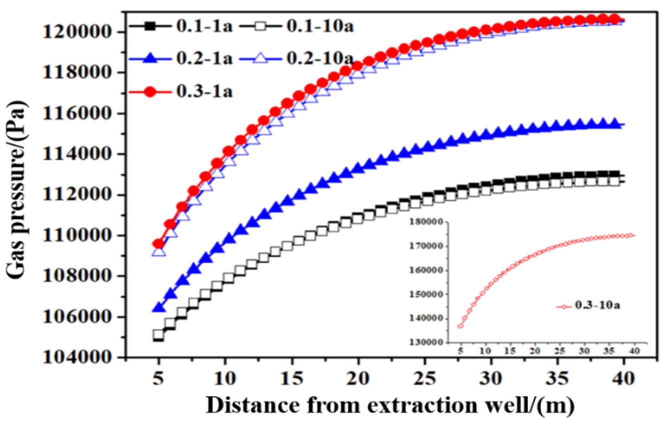

Figure 2 Effect of compression coefficient on gas pressure of landfill in horizontal direction

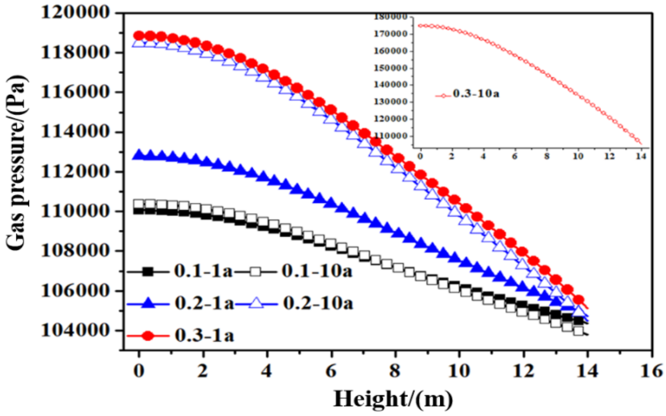

Figure 3 Effect of compression coefficient on gas pressure of landfill in vertical direction

In Figures 2 and 3, 0.1-1a refers to compression coefficient of 0.1, landfill age of 1 year, and other abbreviations. Landfill gas was continuously pumped away under the action of extraction pressure, and gas pressure was continuously reduced in landfill. Figure 2 showed that the farther away from the extraction well, the greater gas pressure inside the landfill. This was because the farther away from the extraction well, the less gas affected by the pumping effect, and the less gas was pumped away.

From Figure 3, it could be seen that gas pressure in landfill decreased gradually with the increase of the height under extraction pressure, and gas pressure at the bottom of the landfill was the largest.

It can be seen from Figure 2 and Figure 3 that gas pressure at the same position in the horizontal direction was lower than in the vertical direction, which was mainly because of the heterogeneity and anisotropy of refuse dump. When the compressibility coefficient was 0.1, 0.2 and 0.3, gas pressure in landfill was close to that in the 10th and 1st year, which was 5 kPa and 60 kPa higher, respectively.

Gas pressure in landfill increased with the increase of compression coefficient and closing time. The main reason was that the greater the compression coefficient was, the more compacted the refuse dump would be. And the longer the closing time was, the smaller the mineralization of the refuse particles would be. The pore passage became narrower with the increase of compression coefficient and closure time, which led to the decrease of the porosity of refuse dump and was not conducive to the migration of landfill gas.

3.2.2 The Influence of Biodegradation Strain on Gas Pressure in Landfill

The variation rules of biodegradation strain on gas pressure in the horizontal and vertical directions of landfill are shown in Figure 4 and Figure 5, respectively.

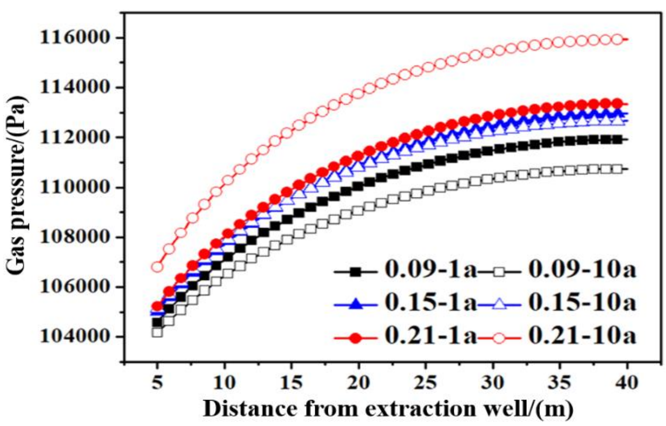

Figure 4 Effect of biodegradation strain on gas pressure of landfill in horizontal direction

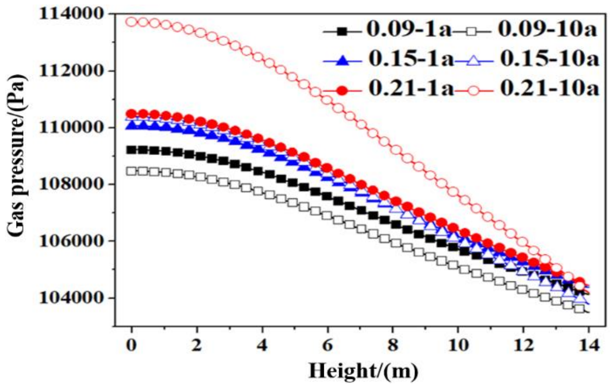

Figure 5 Effect of biodegradation strain on gas pressure of landfill in vertical direction

In Figure 4 and Figure 5, 0.09-1a meant that the biochemical degradation strain was 0.09, the landfill age was 1 year, and the rest were abbreviated as follows. As can be seen from Figure 4 and Figure 5, gas pressure in landfill gradually increased with the increase of biodegradation strain. The main reason was that the gas permeability of refuse dump decreased with the increase of biodegradation strain, which caused the migration of landfill gas slowing down in landfill. The influence of biodegradation strain on the internal gas pressure of landfill increased with the closure time. In the first year, the influence range of biodegradation strain on the internal gas pressure of landfill was 2 kPa, while the influence range of biodegradation strain on the internal gas pressure of landfill was 6 kPa in the tenth year.

3.2.3 The Influence of Biodegradation Rate Constant on Gas Pressure in Landfill

The variation rules of biodegradation rate constant on gas pressure in the horizontal and vertical directions of landfill are shown in Figure 6 and Figure 7, respectively.

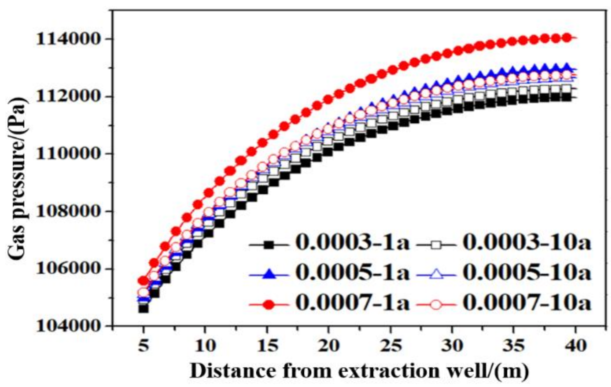

Figure 6 Effect of biodegradation rate constant on gas pressure of landfill in horizontal direction

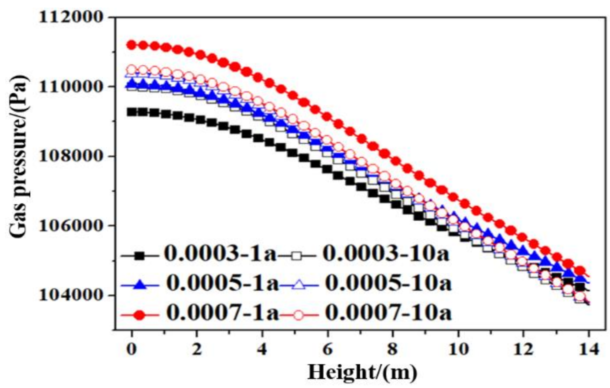

Figure 7 Effect of biodegradation rate constant on gas pressure of landfill in vertical direction

In Figure 6 and Figure 7, 0.0003-1a meant that the biodegradation rate constant was 0.09, the landfill age was 1 year, and the rest were abbreviated as follows. According to Figure 6 and Figure 7, gas pressure in landfill gradually increased with the increase of the biodegradation rate constant. The main reason was that the landfill gas source increased with the increase of biodegradation rate constant and the amount of landfill gas produced increased. The biodegradation rate constant had little influence on the change of gas pressure in landfill. The reason was mainly because it had little influence on the settlement of landfill, which made the gas permeability of refuse dump decreased less. The effect of biodegradation rate constant on the internal pressure of landfill decreased with the increase of closure time. The influence range of biodegradation strain on gas pressure of landfill was 3 kPa in the first year, while the influence range of biodegradation strain on gas pressure of landfill was 0.5 kPa in the tenth year. The effect of biodegradation rate constant on gas pressure in landfill was smaller than that of compression coefficient and biodegradation strain.

4. CONCLUSIONS

A mathematical model was developed to simulated change rule of gas pressure in landfill based on gas continuity equation, gas production equation and composite compression model. The effects of degradation and compression parameters (such as compressibility coefficient, biochemical degradation strain and biodegradation rate constant) on gas pressure was simulated by COMSOL Multiphysics were studied in this work. The main conclusions were obtained as follows.

1) Landfill gas migrated to gas well under the action of extraction pressure, and the gas pressure in landfill was released continuously during the extraction process. Because of the heterogeneity and anisotropy of refuse dump, gas pressure in horizontal direction inside the landfill was smaller than in vertical direction at the same location.
2) Gas pressure in landfill increased with the increase of compressibility coefficient, biochemical degradation strain and biodegradation rate constant. The compression coefficient had the most significant effect on the gas pressure inside the landfill, followed by biochemical degradation strain, and biochemical degradation rate constant was the smallest. The maximum values were up to 60 kPa, 6 kPa and 3 kPa, respectively.
3) Landfill was a gas-liquid-solid three-phase coupled system with temperature, degradation, stress and other fields. Gas pressure distribution in landfill was influenced by many factors, so it was necessary to consider comprehensively in the design, construction and management of landfill in order to seek the best landfill gas collection efficiency, which will be the next research work.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

Chen, X.D., Geng, Y., and Fujita T. (2010) "An overview of municipal solid waste management in China", Waste Management, 30, Issue 4, pp716-724.

Chen, Y.M., and Zhan, T.L.T. (2009) "Environmental geotechnics related to landfills of municipal solid wastes", Proceedings of Int. Symposium on Geoenvironmental Engineering, Hangzhou, pp132-152.

Chen, Y.C., Chen, K.S., and Wu C.H. (2003) "Numerical simulation of gas flow around a passive vent in a sanitary landfill", Journal of Hazardous Materials, 2003, 100, Issues 1-3, pp39-52.

Dace, E., Blumberga, D., Kuplais, G., Bozko, L., Khabdullina, Z., and Khabdullin, A. (2015) "Optimization of landfill gas use in municipal solid waste landfills in Latvia", Energy Procedia, 72, pp293-299.

Feng, S.J., Zheng, Q.T., and Xie, H.J. (2015) "A model for gas pressure in layered landfills with horizontal gas collection systems", Computers and Geotechnics, 68, pp117-127.

Hossain, M.S., Penmethsa, K.K., and Hoyos, L. (2009) "Permeability of municipal solid waste in bioreactor landfill with degradation", Geotechnical and Geological Engineering, 27, pp43-51.

Liu, C., Shi, J., Lv, Y., and Shao, G. (2020) "A modified stability analysis method of landfills dependent on gas pressure", Waste Management & Research, DOI:10.1177/0734242X20944479

Liu, L., Ma, J., Xue, Q., Wan, Y., and Yu, X. (2018) "Modeling the oxygen transport process under preferential flow effect in landfill", Environmental Science and Pollution Research, 25, Issue 19, pp18559-18569.

Liu, L., Xue, Q., and Xu, Y., et al. (2014) "Numerical simulation of dynamic processes of the methane migration and oxidation in landfill cover", Environmental Progress & Sustainable Energy, 33, Issue 4, pp1419-1424.

Li, Y., Francisco, B., and Jesus, C., et al. (2009) "Gas flow to a vertical gas extraction well in deformable MSW landfills". Journal of Hazardous Materials, 168, Issues 2-3, pp1404-1416.

Ma, J., Liu, L., Yu, X., Fei, X., Zhang, X., Zeng, G., and Bi, Y. (2020) "Simulation of gas concentration during the process of air injection and extraction in a landfill", Environmental Progress & Sustainable Energy, DOI:10.1002/ep.13406.

Marques, A.C.M., Filz, G.M., and Vilar, O.M. (2003) "Composite compressibility model for municipal solid waste", Journal of Geotechnical and Geoenvironmental Engineering, 129, Issue 4, pp372-378.

Omar, H., and Rohani, S. (2015) "Treatment of landfill waste, leachate and landfill gas: A review", Frontiers of Chemical Science and Engineering, 9, Issue 1, pp15-32.

Shu, S., Li, Y., Sun, Z., and Shi, J. (2021) "Effect of gas pressure on municipal solid waste landfill slope stability", Waste Management & Research, DOI: 10.1177/0734242x211001414.

Stoltz, G., Gourc, J.P., and Oxarango, L. (2010) "Liquid and gas permeabilities of unsaturated municipal solid waste under compression", Journal of Contaminant Hydrology, 118, pp27-42

Townsend, T.G., Wise, W.R., and Jain, P. (2005) "One-dimensional gas flow model for horizontal gas collection systems at municipal solid waste landfills", Journal of Environmental Engineering, 131, Issue 12, pp1726-1723.

Xue, Q., and Liu, L. (2014) "Study on optimizing evaluation and recovery efficiency for landfill gas energy collection", Environmental Progress & Sustainable Energy, 33, Issue 3, pp972-977.

Zeng, G., Ma J., Hu, D., and Wang, J. (2019) "Experimental study on compression and intrinsic permeability characteristics of municipal solid waste", Advances in Civil Engineering, doi.org/10.1155/2019/3541635.

Zhang, C., Xu, T., Feng, H., and Chen, S. (2019). "Greenhouse gas emissions from landfills: A review and bibliometric analysis", Sustainability, DOI: 10.3390/su11082282.

Zheng, Q.T., Reddy, K.R., and Feng S.J. (2019) "Design of horizontal landfill gas collection wells in non-homogeneous landfills", Waste Management, DOI: 10.1016/j.wasman.2019.08.017.

Zeng, G. (2019) "Study on landfill gas migration in landfilled municipal solid waste based on gas-solid coupling model", Environmental Progress & Sustainable Energy, DOI: 10.1002/ep.13352.

Zeng, G., Liu, L., Xue, Q., Wan, Y., Ma, J., and Zhao, Y. (2017) "Experimental study of the porosity and permeability of municipal solid waste". Environmental Progress & Sustainable Energy, 36, Issue 6, pp1694-1699.