Research Article

Assessment of Landfill Odorous Gas Effect on Surrounding Environment

Si-liang Shen , Bin-hai Wu , Hui Xu , and Zhen-ying Zhang

School of Civil Engineering and Architecture, Zhejiang Sci-Tech University, Hangzhou 310018, China

Correspondence should be addressed to Hui Xu; xuhui@zstu.edu.cn

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Landfill odorous gas emission has been a serious environmental problem, especially for the residents or passersby on the road near the landfill. In this paper, in situ monitoring and the numerical CALPUFF model were adopted to analyze the odor nuisance problem caused by municipal solid waste (MSW) degradation in a large landfill. The static chamber technique was used to measure the odorous gas emission rate on the working area, temporary cover area, and final cover area of the landfill during Dec. 2016 and Apr. 2018. The results showed that the emission rate of H_2S on the working area varied from $0.003 \text{ mg/m}^2/\text{min}$ to $0.98 \text{ mg/m}^2/\text{min}$, and it was positively correlated with the ambient temperature. The emission of H_2S varied between 0.125 kg/h and 1.09 kg/h on the working area, and it varied between $9.2 \times 10^{-6} \text{ kg/h}$ and $6.8 \times 10^{-4} \text{ kg/h}$ on the temporary cover when considering the impact of the holes in a high-density polyethylene (HDPE) membrane, and it was negligible on the final cover. The contribution rates of H_2S emission in the whole landfill were $90.79\% \sim 98.59\%$ and $0.0008\% \sim 0.52\%$ for the working area and the temporary cover area, respectively. The numerical simulation showed that wind velocity and gas emission rates were the critical factors that affect odor dispersion. To limit the H_2S -influenced area within the landfill site, proper engineering measures should be taken to ensure the H_2S emission rate of lower than 15% of its original value.

1. Introduction

With the increasing of urbanization, a large number of transportation infrastructures with tremendous traffic and human flow (e.g., highways and tunnels) appear around the municipal solid waste (MSW) landfill. The degradation of MSW would generate less than 1% v/v nonmethane compounds, which are considered to be one of the primary sources of odor emissions [1]. The formation of these odorous gases originated from the secondary product during the waste degradation or strip of the mixed materials existed in the MSW. Compared with the MSW in developed European and American countries, the kitchen waste accounts for 40%~85% (wet basis) of the MSW in China, and the initial water content varies from 30% to 70% (wet basis) [2]. Thus, a greater variety of odorous gases could be measured around the landfill in China [3–5]. The health of the residents and passersby in and around the landfill site will be significantly influenced by the harmful odorous gases. The odor-related nuisance has become the major cause of

complaints to the local authorities [6]. The high concentration of H_2S could be measured in all the landfills monitoring at home and abroad, ranging from 0.004 ppm to 0.64 ppm [7–9]. Besides, the olfactory threshold of H_2S is only 0.41 ppb, which caused the H_2S chosen as the representative odor gas of landfills [5].

The gas migration in the air directly related to the local meteorological conditions [10]. Some specific weather conditions, including low mixing height or low wind speed could severely affect the odor dispersion process. Landfills are often located in complex terrain areas. The meteorological conditions are challenging to predict, which leads to the complexity of odor prediction. To assess the individual's perception of the odorous material, the quantification of compounds concentration, which is perceived by receptors, could be the most effective way [11]. Capelli et al. indicated that dispersion models had become a valuable tool to evaluate odor pollution [12]. Some air dispersion models, such as AERMOD and CALPUFF, recommended by the National Standard (HJ2.2-2008) could analyze the gas

migration in the range of tens of meters to tens of kilometers [13]. The existing research studies prefer to use the CALPUFF to assess the gas migration due to the limitations of the AERMOD model, including the incapability of handling the calm wind condition and steady-state assumption [14].

This paper mainly focused on the impact of the air pollution caused by the MSW degradation on the residents or passersby on the road near the landfill. In situ monitoring and the CALPUFF model were used to evaluate the long-term H₂S emission rate and the key factors which may affect the gas diffusion in the air. A proper method should be adopted to reduce the H₂S fugitive emission in the working area. The result could be used to improve landfill operations and management.

2. Materials and Methods

2.1. Site Description. The investigated MSW landfill is located in the northern part of Hangzhou City (120°12'E, 30°23'N). It is the first standardized valley-type sanitary landfill in China. The area of the landfill is 700,000 m². It was designed to contain 22 million m³ of MSW. The site does not accept medical, industrial, and hazardous waste. The daily amount of landfilled MSW increased to 6655 t/d since 2017 [15].

The total surface area of the landfill is 438,000 m² and comprises three parts: working area, temporary cover area, and final cover area. 1.5 mm thick high-density polyethylene (HDPE) was used as the only temporary cover material. Gas wells were installed to collect landfill gas (LFG) for electricity generation. The size of the working area is approximately 6000 m². There are many municipal structures scattered around the landfill within a radius of 5 km.

2.2. Gas Sampling and Analysis. As shown in Figure 1, sampling points were distributed on the landfill working area, temporary cover area, and final cover area. Twelve sampling points for each campaign were randomly arranged on the working area in each campaign following US EPA requirements. The monitoring above the temporary cover focused on the gas emission from the leakage point.

The static chamber and 10 ml syringe were used to collect landfill gas from selected locations. The chamber used in this study consists of a glass cylinder and a steel pedestal. The chamber is 550 mm in height and 500 mm in diameter. Once the chamber was placed on the sampling location, the groove in the steel pedestal was filled with water to keep the chamber sealed. All the valves were then shut off to allow the gas to accumulate into the chamber. The gas was sampled for 1 hour every 4 hours. A 1-L empty aluminum bag was connected to the chamber to equilibrate inner pressure. The gas emission rate was determined by equations (1) and (2) [16]:

$$VC_{t+\Delta t} = VC_t + j' S \Delta t, \quad (1)$$

$$j' = \frac{V}{S} \frac{\Delta C}{\Delta t}, \quad (2)$$

where V is the volume of the chamber (m³); C is the H₂S concentration (mg/m³); S is the area of the chamber base

(m²); j' is the gas flux (mg/m²/h); t is the time (min); ΔC is the gas concentration difference between time t and time $t + \Delta t$.

The sulfur-containing gas analysis was carried out by using a gas chromatograph with a flame photometric detector (FPD, HC-3, Hubei, China shafts Technology Co., Ltd.). FPD conditions were as follows: nitrogen was used as the carrier gas at the pressure of 0.1 MPa; the pressure of hydrogen and oxygen was adjusted to 0.04 MPa to form a hydrogen-rich flame; the temperature of the column and detector was held at 125°C and 100°C, respectively; 1 mL sample from anaerobic tubes was directly injected into the injection port during the measurement; the detection limit is 0.05 ppm for hydrogen sulfide.

2.3. The CALPUFF Model. The CALPUFF model was approved by the US Environmental Protection Agency (EPA) as a useful tool to determine atmospheric dispersion, especially in areas with pollution sources such as landfills. It combines three major components: CALMET, CALPUFF, and CALPOST. A detailed description of the CALPUFF model could be found in a study by Scire et al. [17].

2.3.1. Meteorological Data. Due to the difficulty of the upper-air meteorological data acquisition in the selected area, the meteorological data simulated by the mesoscale meteorological model (MM5) were used as the initial guess wind field of the CALMET meteorological model.

The MM5 model's domains for the processing of the meteorological parameters in the study area consisted of a main domain (Domain 1) with a resolution of 1 km per point and a nested domain (Domain 2) with a resolution of 1 km per point. The integration step was 9 s.

Using the MM5 as the initial guess wind field has been proven to be trustful in different research studies [18]. The validity of calculated meteorological data was verified by comparing them with the measured data from the meteorological station in the landfill (Figure 2).

2.3.2. Odor Threshold Regulations. The odor annoyance criterions of different countries are also rather diverse [19]. Mostly are based on the 98th percentile method proposed by the Lombardia region guidelines [20]. In odor diffusion modeling, very short averaging times (e.g., a few minutes) must be used [21]. Odors can be smelt intermittently for short periods. In the CALPUFF model, the averaged 1-h odor concentrations are converted to shorter averaging periods based on the power-law equation of the form:

$$C_s = C_h \left(\frac{T_h}{T_s} \right)^p, \quad (3)$$

where C_s is the required shorter time average concentration; C_h is the hourly average concentration calculated by the CALPUFF model; T_h is the 1-h period expressed in minutes; T_s is the short-term period in minutes; exponent (p): the CALPUFF manual advises the use of 1/5th power relationship. Nagata and Takeuchi showed that the olfactory

FIGURE 1: Gas sampling on the different areas of the landfill. (a) Working area. (b) Temporary cover area. (c) Final cover area.

threshold of H_2S was 0.41 ppb ($0.62 \mu\text{g}/\text{m}^3$) [22]. Therefore, the H_2S 1-h average limited concentration was $0.34 \mu\text{g}/\text{m}^3$.

2.4. Operation of CALPUFF. Figure 3 illustrates this study's diagram for CALPUFF operation. The spatial scale for analysis is $10 \text{ km} \times 10 \text{ km}$, and the mesh accuracy is 100 m. The map used in this study was a Universal Transverse Mercator (UTM) Reference Ellipsoid WGS-84, Global Coverage, UTM Zone 11 with coordinates 30.38°N and 120.21°E . The mesh used was $10 \text{ km} \times 10 \text{ km}$ and 11 vertical levels for meteorology. The topography and land use were defined using the preprocessors "Terrel" and "CTGPROC."

3. Results and Discussion

3.1. The Emission Rate of Odorous Gas. All dispersion models need reasonably accurate emission data to produce reliable results. The H_2S emission rate on the working surface and temporary area during the monitoring period is shown in Figure 4. It is estimated that 20% of the landfill gas released directly from the landfill working area [23]. For the monitoring of H_2S in this site, the statistical data shown in Figure 4(a) indicated that the H_2S flux rate varied from $0.003 \text{ mg}/\text{m}^2/\text{min}$ to $0.98 \text{ mg}/\text{m}^2/\text{min}$, equivalent to the annual H_2S emission varied between $1.57 \times 10^4 \text{ g/a}$ and $515 \times 10^4 \text{ g/a}$, which was comparable to the results measured in South Korean landfills ($0 \sim 13.6 \times 10^4 \text{ g/a}$) [24].

The arithmetic mean value of H_2S flux rate increased with the ambient temperature, reaching its peak value of $0.2502 \text{ mg}/\text{m}^2/\text{min}$ in June 2017. The maximum flux rate of $0.98 \text{ mg}/\text{m}^2/\text{min}$ was also monitored at a single point in June 2017. This rule has also been verified by other scholars. Kim indicated that the flux of sulfur-contained organic compounds would peak in summer and changed with seasons [24]. Ji reported the H_2S concentration peaked between July and September, which caused by the higher water content of MSW in summer. The field monitoring results found that the variation tendency of H_2S flux was consistent with that of moisture content [25].

3.2. The Analysis of the Critical Factors Affecting H_2S Diffusion. Set a fixed point at the height of 10 meters, which was 1.7 km to the northwest from the landfill center to be analyzed. The initial ambient temperature was 21°C , the ambient air pressure was 101.3 kPa, and the wind speed was 5.2 m/s.

Several factors that may influence the gas diffusion in the air were analyzed by the CALPUFF model.

3.2.1. Wind Velocity. The wind velocity degree was categorized by wind speed at 10 meters high off the open ground. The average wind speed varies with the altitude which is usually described by the logarithmic law or exponential law [26]. The regulation named "Load Code for the Design of Building Structure" (GB 50009-2001) adopts the exponential law [27]:

$$\frac{V(z)}{V_{10}} = \left(\frac{z}{10}\right)^\alpha, \quad (4)$$

where Z is the height to the ground; α is surface roughness; V_{10} is the average wind velocity at 10 meters above the ground. The wind velocity at 10 meters above the ground was revised in accordance with the wind velocity level 1~7.

The variation of H_2S concentration with wind velocity is shown in Figure 5(a). Wind velocity played a very significant role in gas diffusion. The concentration appeared to significantly increase at initial and then decrease in the process of wind velocity variation from calm to level 3.

3.2.2. Air Pressure. Considering the amplitude of the atmospheric pressure fluctuation [28], the pressure variation was set as 0, $\pm 3 \text{ kPa}$, and $\pm 6 \text{ kPa}$. The variation of H_2S concentration with atmospheric pressure is shown in Figure 5(b). The result of the gas concentration at the fixed point indicated that amplitude of concentration change caused by the air pressure variation was 0.3%. The pollutant concentration is negatively correlated with the increase in atmospheric pressure. The stronger turbulence caused by the higher atmospheric pressure will increase the regional wind speed and therefore reduce the pollutant concentration. Sadowska-Rociek et al. indicated that the variation of odorous gas concentration was directly related to air pressure [29]. The results of field monitoring showed that gas emission would increase during the low pressure in one day [30, 31].

3.2.3. Air Temperature. The variation of air temperature would affect the H_2S migration rates directly. Set the air temperature to 0°C , 20°C , and 35°C ; the variation of H_2S concentration with air temperature is shown in Figure 5(c). The results indicated that the H_2S concentration was changed positively with the air temperature variation, and the amplitude

FIGURE 2: The comparison of measured and calculated meteorological data (Aug. 2016).

of concentration change was 0.6%. The rise of temperature would reduce the atmospheric stability which may weaken the pollutant vertical convection in the air. Qiang et al. reported that the concentration of odorous gas in spring and summer was significantly higher than that in autumn and winter [32].

3.2.4. Emission Rates. The gas emission rate would be affected by several factors such as the composition, fill age, saturation, and mechanical movement of MSW. The measured H_2S emission rate is set to F_0 (0.125 kg/h); the variation of H_2S concentration with emission rate is shown in

Figure 5(d). The emission rate varied in the scope of $0.5 F_0$ to $1.5 F_0$, and the calculated results indicated that the H_2S concentration was linearly positively correlated with the variation of gas emission rate in the origin. The equation of the CALPUFF model also proved the linear positive correlation between the pollutant flux and concentration.

3.2.5. Surface Parameters. For the surface parameters of one landfill, the heat flux caused by human activity could be ignored; theoretical analysis and experiment proved that Bowen ratio and surface roughness are two sensitive

FIGURE 3: The distribution of the complained point (the numbers denote the different position; surface denotes the landfill working area and the origin of odor emission; MS denotes the meteorological station in the landfill).

parameters affecting surface gas concentration [33]. However, the geographical environment around the landfill site would keep constant. Therefore, the surface parameters would be regarded as constant values that would not be analyzed separately when analyzing the dynamic factors.

From the parametric analysis, it can be concluded that each parameter has a certain effect on the H_2S diffusion in the air; however, the influence of air temperature and air pressure could be ignored. The variation of gas emission rate was positively correlated with the change of gas concentration in fixed points. In addition, the variation of wind velocity was positively correlated with the H_2S concentration within a specific wind level range. This would imply that the high gas emission coupled with appropriate wind speed could cause a serious odorous problem in a certain range. Thus, it can be concluded that wind level and emission rate are the two key factors affecting H_2S diffusion in the air.

3.3. Assessment of Odor Influence by CALPUFF. Massive complaints against the odorous problems were investigated during 2016. The spatial distribution of complain points is shown in Figure 3. The complaints were concentrated in August, September, and October. No. 11 and no. 12 points occupied the major proportion of all the complaints, with 37 cases and 6 cases, respectively.

The no. 11 point was selected for further analysis. The detailed complaints which contain the specific date and time are listed in Table 1.

According to the 16-wind direction map, the no. 11 point was located 3.5 km south-southwest (SSW) to the landfill. The malodorous material released from the landfill could be directly blown to the no. 11 point when the wind direction was north-northeast (NNE), northeast (NE), and east-northeast (ENE). The CALPUFF model was used to analyze the percentage of wind that blew directly to the no. 11 point; the results are shown in Table 2. The percentage of wind that blew directly to no. 11 reached 27.9%, 7.86%, 20.9%, 58.32%, and 47.3%, respectively, during the 5 periods with massive complaints. The frequency of wind direction was consistent with the complaint occurrence.

The H_2S flux at the working area was assumed to be kept constant at 0.125 kg/h. According to the H_2S distribution calculated by CALPUFF (Figure 6(a)), the area within 5 km of the landfill would be interfered by the odorous problem. The averaged H_2S concentration at the no. 11 point reached $9.1 \mu\text{g}/\text{m}^3$, which is 15 times greater than the olfactory threshold. Therefore, proper engineering measures such as controlling the exposed area or increasing the gas collection should be taken to ensure the emission rate of H_2S decreases to 15% of its original value. Cai et al. reviewed nine LFG mitigation measures, including refinement process for MSW landfiling (RPL), LFG collection and flaring (LCF), and LFG collection and power generation (LCP) and found that the implementation of these methods could lead to the malodorous emission reduction of 90~95% theoretically [34].

FIGURE 4: H_2S emission rates in different covers. (a) H_2S emission rates on the working area. (b) H_2S emission rates on the leakage points.

FIGURE 5: The varied H₂S concentration with different factors. (a) Wind level. (b) Air pressure. (c) Air temperature. (d) Emission rate.

TABLE 1: A detailed complain inventory of no. 11 in August, September, and October.

Scenario	Time of complaint	The description of complaint	Analysis dates	Analysis periods
1	8.17	Odors from the Tianziling landfill occurred at 16:00 pm–8:00 am.	8.10~8.17	16 pm~8 am
	8.17	Odors from the Tianziling landfill occurred at about 21:00 pm in recent days.		
2	9.4	Odors from the Tianziling landfill occurred from wee hours to 8:00 am.	9.1~9.6	0~8 am
	9.6	Odors from the Tianziling landfill occurred at 8:00 am every day during half a year.		
3	9.7	Odors from the Tianziling landfill occurred in a rainy day recently.	9.6~9.7	Whole day
4	10.12	Odors from the Tianziling landfill occurred at 00:49 am in BanShan street and Tianyuan community.	10.10~10.13	18 pm~8 am
	10.12	Odors from the Tianziling landfill occurred at 0:00 am–1:00 am or 5:00 am–6:00 am every day.		
	10.13	Odors from the Tianziling landfill occurred at 20:30 pm on 12/10/2016 and complained by the residents of Tianyuan community.		
	10.13	Odors from the Tianziling landfill occurred in the afternoon on 10/10/2016.		
	10.13	Odors from the Tianziling landfill occurred at 6:00 am–8:00 am and 18:00 pm–23:00 pm. The situation lasted for a year.		
	10.13	Odors from the Tianziling landfill occurred severely at 18:00 pm–23:00 pm.		
	10.15	Odors from the Tianziling landfill occurred at 8:00 pm on 12/10/2016.		

TABLE 1: Continued.

Scenario	Time of complaint	The description of complaint	Analysis dates	Analysis periods
5	10.22	Odors from the Tianziling landfill occurred at 6:00 am, 8:00 pm, or even at midnight.	10.22~10.27	19 pm~7 am
	10.23	Odors from the Tianziling landfill occurred throughout the day irregularly.		
	10.23	Odors from the Tianziling landfill occurred at 22:00 pm on 10/23/2016, which was severe since 2016.		
	10.27	Odors from the Tianziling landfill occurred in the midnight recently.		

TABLE 2: The percentage of the wind that directly blew to the no. 11 area in different scenarios.

The scenario number	The percentage of the wind that directly blew to the no. 11 area (%)
1	7.86
2	20.9
3	58.32
4	21.5
5	47.3

FIGURE 6: Continued.

FIGURE 6: The comparison of H_2S -influenced area sizes with different gas emission rates (surface denotes the landfill working area and the origin of odor emission; MS denotes the meteorological station in the landfill). (a) The H_2S -influenced area with the original emission rate on the site (0.125 kg/h). (b) The H_2S -influenced area with the reduced emission rate on the site.

4. Conclusions

The odorous gas H_2S was monitored and analyzed in a large-scale landfill in Hangzhou, China. The CALPUFF model was adopted to evaluate the odor influence to the surrounding residential areas. The main conclusions are drawn as follows:

- (1) The emission rate of H_2S varied from 0.003 mg/m²/min to 0.98 mg/m²/min on the working area of the landfill, and it was positively correlated with the ambient temperature. The emission of H_2S varied between 0.125 kg/h and 1.09 kg/h on the working area, and it varied between 9.2×10^{-6} kg/h and 6.8×10^{-4} kg/h on the temporary cover when considering the impact of the holes in the HDPE membrane, and it was negligible on the final cover. The contribution rates of H_2S emission in the whole landfill were 90.79%~98.59% and 0.0008%~0.52% for the working area and the temporary cover area, respectively.
- (2) The varied wind direction and speed are the key reasons of large-scale complaints against the odorous problems. The degree of coincidence between the point orientation and the wind direction reached 27.9%, 7.86%, 20.9%, 58.32%, 21.5%, and 47.3%, respectively, during

the six periods with high complaints occurrence. During that time, the prevailing wind speed varied from 1.6 m/s to 3.3 m/s; the increasing of wind speed within this range would promote the higher H_2S concentration.

- (3) Gas flux variation is another critical factor to affect the odor dispersion. Proper engineering measures should be taken to ensure the emission rate of H_2S lower than 15% of its original value, such as increasing the gas collection rate.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request

Disclosure

A part of the findings in this paper has been published in the Proceedings of 8th International Congress on Environmental Geotechnics (Volume 2).

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

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