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# 稼働中の準好気性廃棄物処分場における上昇温度とガス成分に関する研究



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# STUDY ON ELEVATED TEMPERATURE AND GAS COMPONENT WITHIN AN OPERATING SEMI-AEROBIC LANDFILL

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2020

# STATEMENT OF AUTHENTICITY

I hereby certify that all of the work described within this thesis is the original work of the author. Any published (or unpublished) ideas and/or techniques from the work of others are fully acknowledged in accordance with the standard referencing practices.

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Date: August 2020

## ABSTRACT

In this study, the performance of an operating semi-aerobic landfill in the northern part of Japan has been investigated. Observation and data analysis have been conducted simultaneously aiming to evaluate the performance of the operating semi-aerobic landfill based on the landfill gas (LFG) temperature and LFG concentration. This study is summarized as follows.

1. A series of surveys has been carried out on-site to collect the temperature distribution and gas concentration data of LFG venting pipes (VPs) in about 10 years (including 9 main LFGVPs, 39 branch LFGVPs, and 5 monitoring LFGVPs). The observation results showed that the average temperature at the exit of surveyed main LFGVPs, branch LFGVPs, and monitoring LFGVPs are >25ºC, 20ºC, and 20ºC, respectively. Especially, the highest LFG temperature was above 60ºC within the main LFGVP M2. Methane gas ($CH_4$) concentration of most of the main LFGVPs was below 10%, while others were above 10%. The distributions of LFG concentration and temperature showed the biodegradation by aerobic or anaerobic. For about 10 years those distributions changed largely by the aerobic or anaerobic biodegradation. Especially clogging resulted in the increase of $CH_4$. If the ratio of $CH_4$ to $CO_2$ is below 1, aerobic biodegradation is active. This ratio in all LFGVPs was below 1.0 and was below 0.5 in main LFGVPs. So this semi-aerobic landfill has been operated appropriately.

2. The temperature of geomembrane liner at the bottom of the semi-aerobic landfill was monitored continuously from 2002 to 2017. The geomembrane temperatures gradually rose up 30-35ºC and remained over 30ºC for 10 years (2006-2016) before dropping down less than 30ºC in 2017. The temperature rise was due to the biodegradation of organic solid waste or the heat of hydration of incinerated bottom ash which is the main factors caused the generation of heat in the landfill. Recently, the geomembrane temperatures are gradually decreasing year by year because less landfilling organic wastes for biodegradation results in a small amount of heat generation. The risk of a high-temperature effect on barrier systems may decrease.

3. The numerical simulation has been used for modeling the movement of gas flow within a semi-aerobic landfill. In addition, the influence of clogging phenomena on the gas flow has been also considered by using the numerical simulations.

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# CHAPTER 1: INTRODUCTION

Today, landfill sites still play an important role in solid waste management (SWM) system in all over the world. However, landfilling is facing some serious problems such as shortage of land, the need for long-term maintenance for stabilization and environmental pollution from its emissions (leachate, landfill gases…). The necessity of surveying the phenomena happening within a landfill is critical to give solutions dealing with its negative impacts on our environment.

## 1.1 Background

In recent years, landfill aeration has been considered to be one of the most important options for the concept of sustainable landfill. The conventional landfills are considered to be unsustainable. Landfill aeration is considered to be an indispensable tool for the controlled and sustainable conversion of conventional anaerobic landfills into a biological stabilized state.

The main benefits of landfill aeration are to reduce methane gas accumulation which causes the greenhouse effects, improve the leachate quality, accelerate biological stabilization of the organic fraction of waste, and decrease the period of time after closure.

Landfill aeration is mainly used in old landfills to convert conventional anaerobic landfills into biological stabilized state. However, landfill aeration is not widely applied so far, it has already been successfully applied to several landfills in Europe, North America and Asia (M. Ritzkowski, 2012). Landfill aeration concepts include high pressure aeration where air is supplied by a compressed air distribution network with operating pressure greater than 0.3 bars, low pressure aeration is implemented with the range of operating pressure from 20 – 80 mbar by air compressors and semi-aerobic uses the natural convection in order to supply air into the landfill.

The concept of high-pressure aeration is mainly associated with the implementation of landfill mining projects. Low pressure aeration aims to accelerate biological waste stabilization in situ and reduce the greenhouse gas emissions. And semi-aerobic concept is mainly used in Japan and some other Asian countries for long-term reduction of GHG emissions and improvement of leachate quality and for landfill remediation of old landfills. Furthermore, the cost of construction and operation of the semi-aerobic landfills is lower than other concepts because it uses no mechanical equipment for aeration.

Studies on landfill aeration began from the late 1990s. However, there is a little our understanding of the processes occurring inside the landfill implemented by aeration methods so far. Therefore, the necessary demand for surveying and collecting the data in full-scale is critical to evaluate what happens inside an aerated landfill.

## 1.2 Research Objectives

Heat, gas and leachate are the primary products of decomposition process of organic wastes due to physical, chemical and biological reactions that occur within the wastes. Temperature and gas components are the constituents that have an interaction.

In addition, temperature is a good index to evaluate or detect an aerobic biodegradation in semi-aerobic landfills which have been widely used in Japan from 1975. The Japanese guideline for MSW landfill revised in 1989 also states that stabilization of landfill may be confirmed by 4 indexes, which are settlement, quality of leachate, quality and quantity of landfill gas and temperature in landfills (M.O.E, 1989). Therefore, the purpose of this study focuses on surveying and monitoring the landfill gas components and temperatures in a semi-aerobic landfill.

## 1.3 Organization of the Dissertation

The thesis includes five chapters. Chapter one introduces the background and purposes of research. This research focuses on evaluating the stabilization of an operating semi-aerobic landfill based on surveying and monitoring landfill gas components and temperatures.

Chapter two summaries briefly the structure, mechanism, and our understanding of semi-aerobic concepts so far.

Chapter three presents the methodology, the surveyed site and how to survey and collect the data in-situ.

Chapter four analyzes the collected data and give the evaluation about what happens inside an operating semi-aerobic landfill.

Chapter five is to focus on making a numerical modeling. Based on the collected data, a simulation is proceeded in order to predict the trend of landfill gas components and temperatures in the future by COMSOL Multiphysics software. Then, comparing the modeling results to observed data.

Finally, chapter six sums up what the study got achievements and future plans.

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# CHAPTER 2: LITERATURE REVIEW

## 2.1 Introduction

Landfilling technology continues to be one of the main methods used in future modern municipal solid waste (MSW) strategies (Cossu, 2012), particularly in developing countries, because of low construction and operation costs as compared to other technologies. It is a necessary and unavoidable step in closing the material cycle (Cossu, 2009; Cossu et al., 2016). At present, there are 4 types of main landfilling concepts: anaerobic, aerobic, semi-aerobic, and hybrid. Each type has its own advantages and disadvantages. The choice of a specific type depends on many factors (i.e., cost, regulations, climate, waste characteristics). Also, the goals of waste treatment (i.e., energy recovery, increasing the waste stabilization) play a role in landfill type selection (Grossule et al., 2018). One of the biggest challenges of landfilling technology is to maintain the performance of a landfill as its initial design purposes to minimize the risks to the surrounding environment. A good design, together with an appropriate operation mode, will significantly reduce the negative impacts on the environment and public health (Hrad et al., 2013; Stegmann and Ritzkowski, 2007).

The rapid development of science and technology during the last decades helped researchers to propose the "sustainable landfill" concept (Antonis and Haris, 2009; Cossu, 2005) with the aim of (1) reducing waste volume, (2) accelerating the stabilization of waste, (3) minimizing landfill gas production which leads to greenhouse effect, (4) rapid biogas production, and (5) decreasing the leachate organic load. In 2002, a special Task Group of International Waste Working Group (IWWG) was established to achieve these targets through a project named "Landfill Aeration". By means of the research projects all over the world, researchers realized that aerobic conditions process faster the waste degradation and reduce more significantly emissions than the anaerobic environment. Besides, the "Landfill Aeration" project has paved the way for the recovery of valuable resources through landfill mining. Therefore, in recent years, in situ landfill aeration projects have received much attention. It has been considered as a useful tool for the sustainable conversion of conventional anaerobic landfills into a biologically stabilized state. It has also shown a minimized emission potential (Ritzkowski and Stegmann, 2012).

Many years ago, in some places in America, Europe and Japan the air and moisture have been added into a landfill to create the optimized aerobic conditions which help aerobic microorganisms degrade biodegradable organic matter. The concept of semi-aerobic landfill might be the oldest method for landfill aeration.

The semi-aerobic landfill concept is based on passive aeration. This concept was developed in 1975 by researchers at Fukuoka University, Japan, when it was given the name semi-aerobic landfill. In semi-aerobic landfills, waste is aerated naturally by atmospheric air via a network of horizontal leachate collection pipes (LCPs) connected to vertical landfill gas (LFG) venting pipes (VPs). The outlet of the main LCP in the leachate pond is always open. Air is drawn into the main LCP due to a buoyancy effect, and the LFG is discharged into the atmosphere (Matsufuji and Tachifuji, 2007). Because of both the limited strength of the passive aeration induced by natural ventilation and anaerobic zones remaining inside the semi-aerobic landfill, the process of biological stabilization occurs more slowly in semi-aerobic landfill than that in actively aerated landfill. For this reason, semi-aerobic landfill has partial aeration around the wells and pipes.

In Japan, the semi-aerobic landfill is the standard design for landfills. In this system, waste is naturally aerated by oxygen supplied through a network of leachate collection pipes (LCPs) and gas collection pipes.

Semi-aerobic landfill is an unique structure for landfill aeration. Landfill gas (LFG) extraction wells are connected to leachate collection pipes in a semi-aerobic landfill and air is induced to the landfill body through the wells and pipes passively because the top of those wells and the end of those pipes are always open to the air.

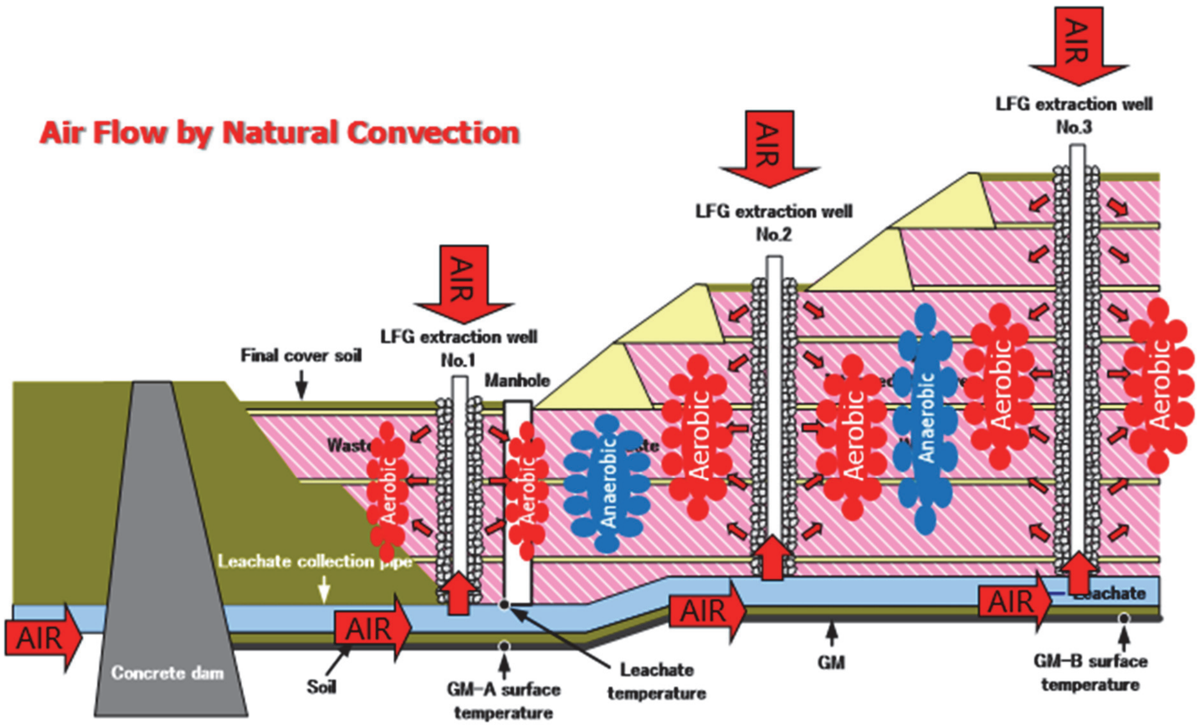


**Figure 1** Schematic diagram of semi-aerobic landfill

*Figure 1* shows the schematic concept of semi-aerobic landfill. Semi-aerobic landfill is a passive aeration system because it acts by means of air flow via LFG extraction wells and LCPs. Oxygen can be penetrated into waste layer from the top and bottom of landfill and results in aerobic biodegradation around the wells and pipes. Such aerobic biodegradation will generate a large amount of heat and then landfill temperature will increase. However, these zones where far away from LFG extraction wells and LCPs will become anaerobic conditions. That's why it is called the "semi-aerobic landfill".

Because the landfill layers are partially exposed to the air around the wells and pipes. Such aeration may contribute to reduction of leachate intensity and methane emission through the operation period of landfilling. However, passive aeration has lower performance than active aeration. Then semi-aerobic system should be characterized by monitoring data in landfill sites. Active aeration always produces heat by biological and chemical reactions and carbon dioxide. So temperature and gas component are appropriate indices for evaluating the performance of semi-aerobic landfill.

In semi-aerobic landfills, the leachate collection system consists of a central perforated pipe (main collection pipe) with perforated branch pipes on either side of it laid at a suitable interval. The pipes are embedded in graded gravel (5-15 cm) and installed with adequate slope.

The main collection pipe ends in open leachate collection pond. The pipes are designed in away that only one-third of the section is filled with liquid. At each intersection of the main collection pipe with the branch pipes, and at the end of each branch pipe, vertical gas ventilation wells enclosed in graded gravel (eventually packed inside a wire netting) are erected.

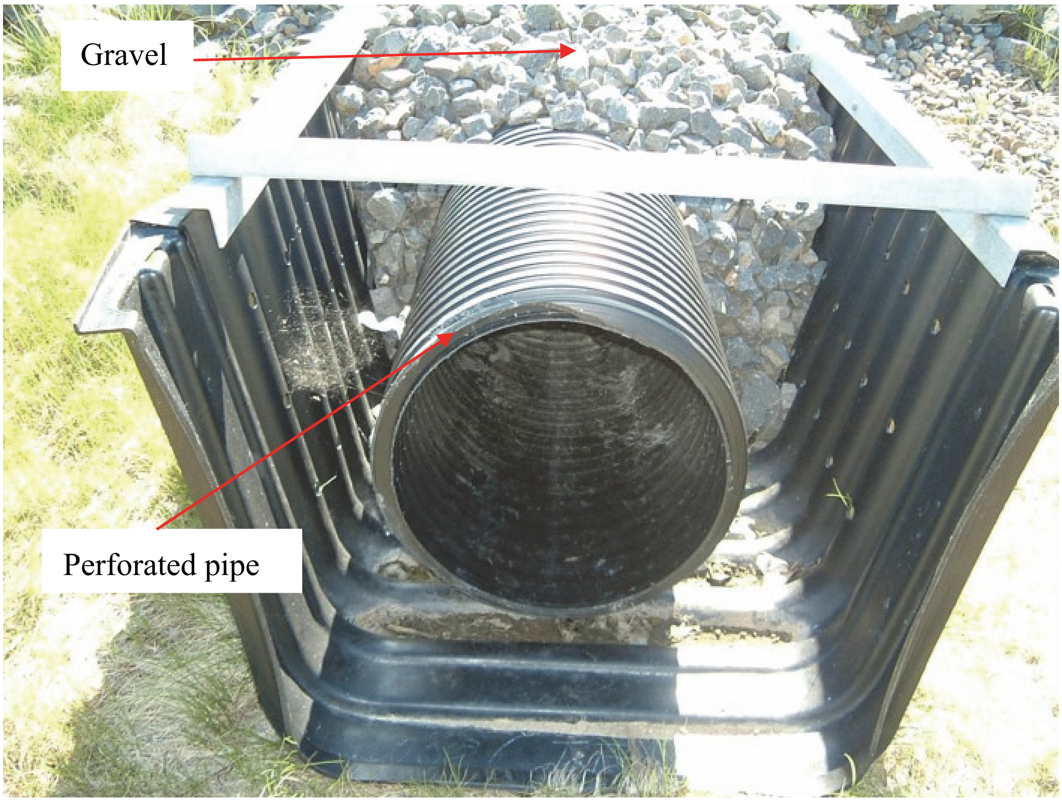


**Figure 2** Main leachate collection pipe


**Figure 3** A typical landfill gas venting pipe (venting pipe)

Since the two piping systems are connected, ambient air and landfill gas flows through the leachate collection pipes and the gas ventilation wells, thus, enhancing the intrusion of the air into the inner part of the landfilled wastes occasionally. Due to higher temperature in the waste (compared to the ambient air), the gas inside waste tends to rise and gets vented through the gas wells, thus, generating a negative pressure siphoning effect that draws more air into LCPs.

The majority of landfills in Japan, over half of the number of the landfills in Korea and a few landfills in Malaysia have been constructed and operating according to the semi-aerobic concept. Semi-aerobic landfills exhibit reduced methane gas generation rates and an enhanced leachate quality in comparison to anaerobic landfills. The key concept of a semi-aerobic landfill is the connection of a leachate collection pipe with gas vents that directly connect to the atmosphere. However, due to the limited intensity of aeration induced by natural ventilation and the remaining anaerobic zones inside the landfill waste, the biological stabilization occurs rather slowly in comparison to actively aerated landfills.

During recent years, the semi-aerobic concept has been recognized for its potential towards landfill remediation. As a part of remediation works, passive gas vents could be installed in closed landfills, however, each vent is installed separately, and they do not connect to each other. (H.Yoshida, 2007).

Although numerous studies have focused on the semi-aerobic landfill concept (Ahmadifar et al., 2016; Cossu et al., 2016; Grossule and Lavagnolo, 2017; Hanashima et al., 1981; Hirata et al., 2012; Huang et al., 2008; Matsuto et al., 2015; Morello et al., 2017; Ritzkowski et al., 2006; Shimaoka et al., 2000; Theng et al., 2005; Wu et al., 2017; Yang et al., 2012), most of them were conducted using a lysimeter either in a laboratory or at pilot scale. Those demonstrated significant achievements of the semi-aerobic landfill concept, including (1) accelerating the biodegradation of organic matter, (2) improving leachate quality, (3) reducing methane ($CH_4$) gas emission, and (4) entailing lower construction and maintenance costs (Ishigaki et al., 2011). The current study has been carried out over many years to monitor and evaluate the aerobisation within a full-scale operational semi-aerobic landfill based on measurements of the LFG temperature and concentration.

LFG temperature is regarded as a good index for assessing the decomposition of biodegradable waste. Both aerobic and anaerobic decomposition processes generate heat [see Equations (1) and (2)]. Rees (1980) measured a temperature range of 40°C–45°C in a waste layer that was 4 m thick. High temperatures, in the range of 60°C–90°C, have also been measured in other parts of the world (Bouazza et al., 2011; Yesiller et al., 2015, 2011; Yoshida and Rowe, 2003). Moreover, several studies have been aimed at determining the heat generation value through theoretical analyses of biochemical decomposition of waste. Pirt (1978) and Rees (1980) reported a heat generation value of 632 kJ/kg glucose for anaerobic digestion. Cooney et al. (1969) reported a heat generation value of approximately 110 kcal/mol oxygen (O2) (15,400 kJ/kg glucose) for aerobic digestion. Thus, it is clear that aerobic decomposition generates a larger amount of heat from waste decomposition than does anaerobic decomposition.

## 2.2 Biological Degradation Processes in MSW Landfill

Semi-aerobic is a combination of aerobic and anaerobic decomposition. Biological decomposition is classified into aerobic and anaerobic one. Glucose ($C_6H_{12}O_6$) is thought to be the most popular organic waste. The aerobic process may be expressed by:

$$\text{Degradable waste} + \text{Oxygen} \rightarrow CO_2 + H_2O + \text{biomass} + \text{heat} + \text{partially degraded materials}$$

The process of anaerobic decomposition may be expressed by:

$$\text{Degradable wastes} \rightarrow CH_4 + CO_2 + \text{organism growth} + \text{partially degraded organics}$$

### *2.2.1. Landfill Gas (LFG) Generation*

Landfill gas is a mixture of many gas components which results from the decomposition of wastes. The most common gas components including methane ($CH_4$), carbon dioxide ($CO_2$), oxygen ($O_2$), nitrogen ($N_2$). The amount of gas generated depends on the amount and composition of the organic content of the waste. The rate of gas generation depends on the composition of the organic waste and the biochemical environment in the landfill (plenty of water, no inhibitors present). The gas moves out of the waste by the pressure that it builds.

Inside the semi-aerobic landfills, there are always two reaction zones existing at various locations simultaneously which are aerobic zone and anaerobic zone. The areas around the perforated gas vents and leachate collection pipes are aerobic zone because the air flow (oxygen) is supplied from the bottom of LCPs and from the top of gas vents. Therefore, oxygen is utilized by aerobic microorganisms. At the locations which are far from LCPs and gas vents, oxygen cannot reach these points or be limited, the anaerobic reaction becomes dominant.

#### *2.2.1.1. Aerobic Decomposition*

Aerobic processes require the presence of oxygen. Thus, aerobic decomposition occurs on initial placement of the refuse, while oxygen is still available. In addition, the aerobic reactions also occur around the landfill gas venting pipes where oxygen is provided from the LCPs and from the top of gas vents. When there is enough oxygen for aerobic microorganisms, the aerobic reaction will happen until the organic matter disappears. During the stage of decomposition, aerobic microorganisms degrade organic materials to carbon dioxide ($CO_2$), water ($H_2O$), partially degraded residual organics, and considerable heat. Aerobic decomposition is characteristically rapid, relative to subsequence anaerobic decomposition.

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{Heat} \quad (1)$$

In this stage, the main gas components is $CO_2$ and water vapor.

*2.2.1.2. Anaerobic Decomposition*

As the biodegradation of the refuse progresses, the oxygen becomes depleted, the redox potential is reduced, and the anaerobic methanogenic bacteria becomes dominant. These organisms produce carbon dioxide, methane, and water, along with some heat. Characteristically, these organisms work relatively slowly but efficiently over many years to decompose remaining organics.

$$C_6H_{12}O_6 \rightarrow 3CH_4 + 3CO_2 + \text{Heat} \quad (2)$$

In this stage, nitrogen ($N_2$) and hydrogen sulfide ($H_2S$) may also be produced due to the microbial process of denitrification, in which the nitrate ion is reduced. Hydrogen sulfide is produced by sulfate-reducing microorganisms.

Landfill gas production rate gradually decrease over time due to the decrease of organic materials. Gas production rate (consumption) is the rate of oxygen in a landfill in the case of aerobic decomposition or the rate of production of methane in a landfill in the case of anaerobic decomposition. The rate at which landfill gas is generated depends on many factors, the most important factors are moisture content, nutrient content, bacterial content, pH level, temperature, particle size of waste. Therefore, a great deal can be learned about the status of landfill decomposition by monitoring the gas components and leachate.

In practice, LFG is considered to be a mixture of the gases $CH_4$, carbon dioxide ($CO_2$), $O_2$, and nitrogen ($N_2$). LFG is composed 45% to 60% methane and 40% to 60% carbon dioxide (ATSDR, 2001). In conventional sanitary anaerobic landfills operating under normal conditions, the ratio is typically from 0.8 to 1.4 (Benson, 2017). Theoretically, if the ratio of $CH_4$ to $CO_2$ is either greater than or equal to 1 [from Equation (1)], the anaerobic condition predominates (Barlaz et al., 2010; Jafari et al., 2017; Martin et al., 2013). Thus, it can be derived that if the $CH_4/CO_2$ ratio is less than 0.8, anaerobic and aerobic conditions are coexisting simultaneously within the landfill. Matsufuji et al. (1996) created a semi-aerobic landfill model in a lysimeter and found the $CH_4/CO_2$ ratio to be 1.0. IPCC (2006) calculated the ratio to be 0.33 by using default values. Kim et al. (2010) measured the ratio at 1.0 in a closed landfill site that had been undergoing remediation to accelerate landfill stabilization through installing numerous passive LFGVPs that were not connected to the LCPs. Yang et al. (2012) found the $CH_4/CO_2$ ratios for anaerobic landfills and semi-aerobic landfills to be 1.9 and 0.8, respectively. Zhang and Matsuto

(2013) reported a $CH_4/CO_2$ ratio between 1.0 and 1.5 for a semi-aerobic landfill site that was not being operated correctly. Jeong et al. (2015) measured LFG from VPs in five semi-aerobic landfills in South Korea. However, the ends of LCPs in all five landfill sites were closed, and the $CH_4/CO_2$ ratio ranged from 1.08 to 1.46, averaging 1.30. Thus, a $CH_4/CO_2$ ratio below 1.5 might be an indicator of landfills with a semi-aerobic design.

The $CH_4/CO_2$ ratio is regarded as an indicator for evaluating the proportions of anaerobic decomposition and aerobic decomposition. Semi-aerobic landfill is a partial aerobisation system because passive aeration works only around LFGVPs and LCPs, and there is limited penetration of $O_2$ into waste mass.

If the ratio of $CO_2/CH_4 > 1.0$, it means that the aerobic reactions become dominant than anaerobic reactions.

### *2.2.2. Heat Generation*

Significant amounts of heat are generated in MSW landfills due to the decomposition of the organic fraction of the waste mass. The heat generated results in long-term elevated waste temperatures with respect to local air and ground temperatures (Nazli Yesiller, 2015).

Heat is one of byproducts of waste decomposition process.

Heat generation due to biological processes was provided for varying phases of decomposition including aerobic phase, anaerobic phase and total decomposition. Rates of heat generation were higher for the aerobic phase than the anaerobic phase (H. Yoshida R. K., 2003).

Many researchers have been pointed out that temperatures is an important factor of chemical, physical and biological phenomena in a sanitary landfill. Ree (1980) proposed that methane production in landfills can be optimized by temperature control. Cecchi (1993) indicated that anaerobic digestion of MSW can be accelerated more actively in thermophilic condition than in mesophilic one. Collin (1993) indicated that the maximum temperature in the bottom of a landfill reached to about 65°C and such temperature rising may induce a crack in clay liners. Hasegawa (1979) indicated that gas temperature in the landfill rose up to about 70°C rapidly during landfilling. Then the temperature drops to 40-50°C gradually several months later and stabilized at 25-35°C five or six years later. It was concluded that the temperature rise was caused by the heat generation of aerobic decomposition. Nakamura (1987) observed that the temperature began to rise 50-100 days later after landfilling and methane gas produced actively at the same time.

However, if landfill temperature rise above 70-80°C, microbiology may become extinct. So, 70-80°C may be maximum for landfill temperature.

In this study, we surveyed several important indicators, including the LFG temperature and concentration and ratio of $CH_4$ to $CO_2$, of an operating semi-aerobic landfill at full-scale. Our observations indicated that the passive aeration happened effectively. The aerobic condition occurred around the main LFGVPs. The highest LFG temperature was over 60ºC and remained above 40°C for over 5 years. The average $CH_4$ concentrations were below 15%. These above analyses also showed that high temperature and the $CH_4/CO_2$ ratio less than 1.0 potentially are useful indicators of the type of landfill processes. They can help landfill operators realize the predominance of aerobic biodegradation within the landfill. Oxygen ($O_2$) is supplied naturally into the waste mass without the need for a blower, promoting aerobisation within the landfill through the buoyancy effect. This leads to significantly reducing the costs of construction and operation. The aerobic biodegradation performance of the branch LFGVPs was not as efficient as the main LFGVPs.

Although our study focuses only on the analysis of LFG components and LFG temperatures, these are useful indicators that can be measured easily on-site to identify the aerobic condition of operating semi-aerobic landfills. Besides analyzing the leachate quality, monitoring the LFG concentration and temperature periodically is required to detect the sudden rise in $CH_4$ concentrations in semi-aerobic landfills. This monitoring should play a key role in evaluating the passive aeration performance of semi-aerobic landfills.

This paper is the first step in a series of our research. We will develop the research in further works by conducting the coupling analysis. Next steps, the numerical simulations will be used for modeling the gas production, temperature distribution, gas concentrations and we will compare the numerical simulations with the real data and evaluate the gas and heat transport phenomena within the semi-aerobic landfill.

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# CHAPTER 3: METHODOLOGY

## 3.1 Introduction

This chapter introduces briefly an operating semi-aerobic landfill site in Hokkaido, Japan and the survey methods were implemented to collect the temperature and gas component data at the site.

## 3.2 Description of the landfill

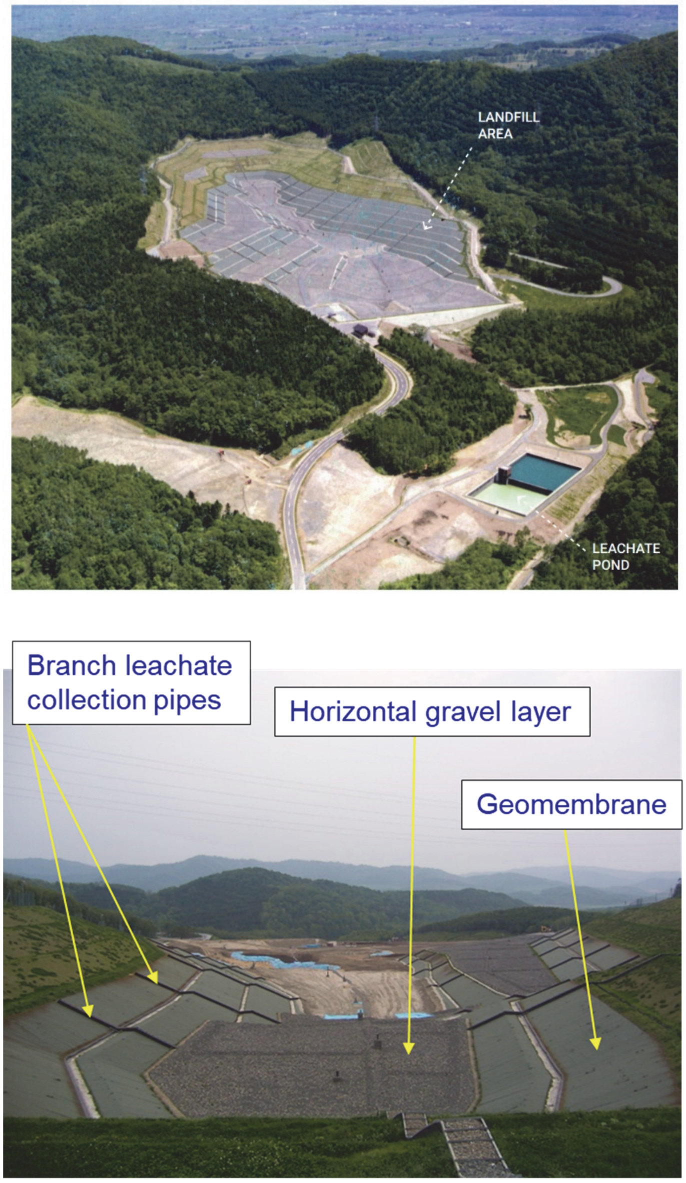



**Figure 4** Aerial view of the operating semi-aerobic landfill in the northern part of Hokkaido, Japan (in 2003)

This semi-aerobic landfill site is located in the northern part of Hokkaido, Japan (*Figure 4*). It has been designed following the canyon/depression method, and the waste is filled in multiple lifts (sandwiched method). The area of the landfill is 12.3 ha, and its volume is expected to reach 1,840,000 m3 over a 27-year period (2003–2030). Each waste type, such as mixed waste, incombustible waste, bottom ash, and fly ash, is placed into the site in different lifts. The operation began in 2003 and is expected to proceed until 2030.

***3.2.1. Gas venting pipes***

According to the design, the Asahikawa municipality will install 73 gas venting pipes classified three types including main wells, branch wells and monitoring wells. A typical gas venting pipe contains two main parts: a venting pipe and a gravel layer. The material used for venting pipes is high-density polyethylene (HDPE) and the venting pipes are perforated along the pipe body, the diameter of a small hole is from 5mm to 10mm. *Table 1* summaries the quantity of gas wells of Yoshino landfill and *Figure 6* shows the map of gas venting pipes at the site.

After that the perforated pipe is enclosed by a gravel layer with the average diameter of stones or gravel from 150 mm to 200 mm. The thickness of the enclosed gravel layer is about 300 mm. To fix the gravel layer embedding the venting pipe, a steel wire mesh is used. *Figure 8* presents the structure of a typical gas venting pipe at the site.

*Table 1* The quantity of gas venting pipes of the landfill

| | **Main wells** | **Branch wells** | **Monitoring wells** |
|---|---|---|---|
| Design | 9 | 59 | 5 |
| Installed | 9 | | 5 |

*Figure 3* shows a typical landfill gas venting pipe in the landfill site. The LFGVP arrangement consists of a 200 mm high-density polyethylene pipe surrounded by a vertical gravel layer measuring 1,200 × 1,000 mm. The VP is perforated along its length with small holes measuring 5–10 mm in diameter. The average diameter of the gravel (stone) is 15–20 cm. Wire netting is used to support and embed the vertical gravel layer. The purpose of surrounding the VP with this vertical gravel layer is to (1) protect the VP from deformation due to waste compaction and other external forces, (2) reduce clogging of the perforations on the body of

the VP, (3) enable the leachate head to quickly, and (4) create another pathway for ambient air to penetrate waste layers.

Apart from the monitoring LFGVPs, which are not connected to the LCP network, all the LFGVPs (e.g., main LFGVPs and branch LFGVPs) are connected to the LCPs to take the air flow into the waste layers. Currently, 53 of 73 LFGVPs have been installed, including 9 main LFGVPs, 39 branch LFGVPs, and 5 monitoring LFGVPs (*Figure 6*). The unique structure of the semi-aerobic landfill generates passive aeration because its mechanism is based entirely on the buoyancy effect resulting from the temperature difference between the waste mass and the outside air. Thus, a negative pressure siphoning effect is created to draw air into the pipes, and air penetrates the waste mass (Matsufuji and Tachifuji, 2007).

The leachate is collected via an LCP network at the bottom of the landfill and is conveyed to the leachate pond (*Figure 4* and *Figure 6*). The diameters of the main LCP and branch LCP are 700 and 400 mm, respectively. The average leachate discharge is 600 $m^3$/day, and the volume of the leachate pond is 12,700 $m^3$. As for the water quality of the leachate, the suspended solids' concentration is less than 890 mg/L, and the biochemical $O_2$ demand is less than 1,900 mg/L. As mentioned above, in addition to collecting leachate, LCPs convey air into the waste layers. Therefore, the main end of an LCP is always open to the atmosphere.

To date, 53 LFGVPs have been installed in the landfill site. Some of these LFGVPs were built when the landfilling began, whereas others have been installed more recently. Currently, the landfill site is divided into two zones: A and B.

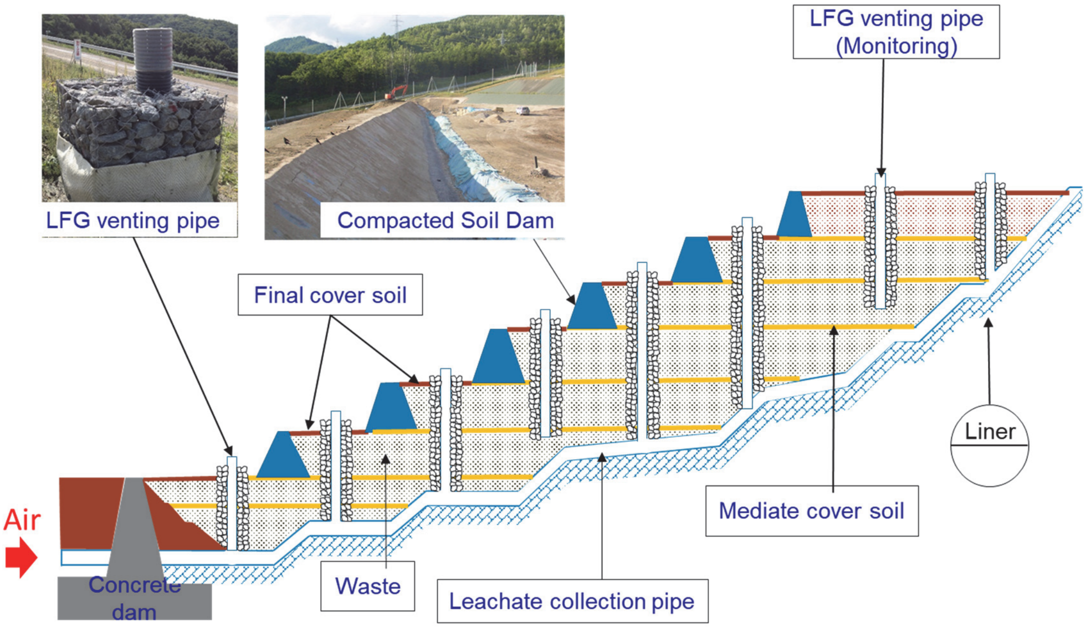



**Figure 5** Structure of the operating semi-aerobic landfill

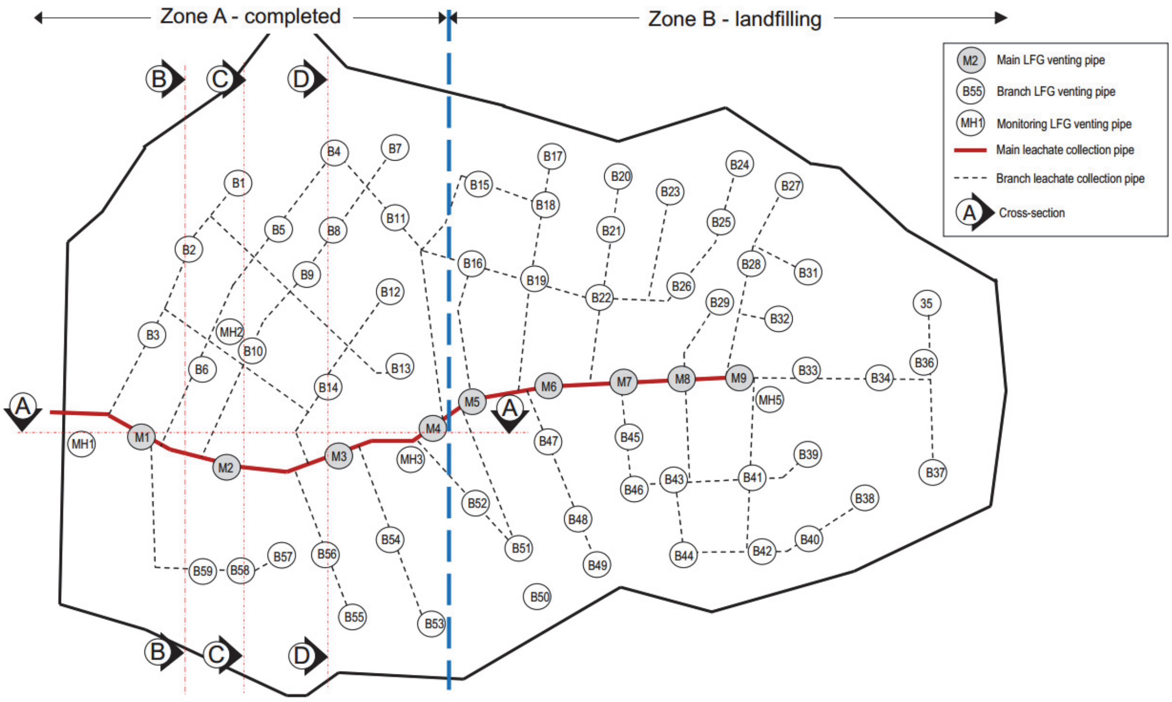



**Figure 6** The layout of landfll gas venting pipes and the leachate collection system in the surveyed operating semi-aerobic landfill.

In Zone A, the landfilling operation was completed in 2010 (*Figure 6*). By 2014, the volume of waste deposited was 730,550 $m^3$. Zone A contains 28 LFGVPs (4 main LFGVPs, 21 branch LFGVPs, and 3 monitoring LFGVPs), and the waste mass has reached the designed height. The heights of the waste at the main gas VPs M1, M2, M3, and M4 are 17.6, 26.6, 30.8, and 33.0 m, respectively. Waste is still being placed in Zone B. Consequently, our analysis focuses on the LFGVPs in Zone A. *Figure 7* is the cross-section through some LFGVPs in Zone A and depicts the waste layers buried from before 2005 to 2014. It should be noted that, before 2005, the landfill accepted organic waste because the city's incineration plant could not accept all combustible wastes. However, since 2005, the landfill has accepted only incombustible waste, bottom ash, and fly ash.

Ideally, we should consider all the LFGVPs in Zone A. However, we focus only on measuring the LFG temperature and concentration to identify whether aerobization is occurring within the semi-aerobic landfill. Therefore, the LFGVPs installed in cells containing only bottom ash and fly ash are not considered in this analysis. The monitoring LFGVPs are also not considered in this study because the bottom of these LFGVPs are not connected to the LCPs network and the positions of these LFGVPs are so close to the main LFGVPs or LCPs (i.e., MH2, MH3), the performance of monitoring LFGVPs can be affected by the main LFGVPs.

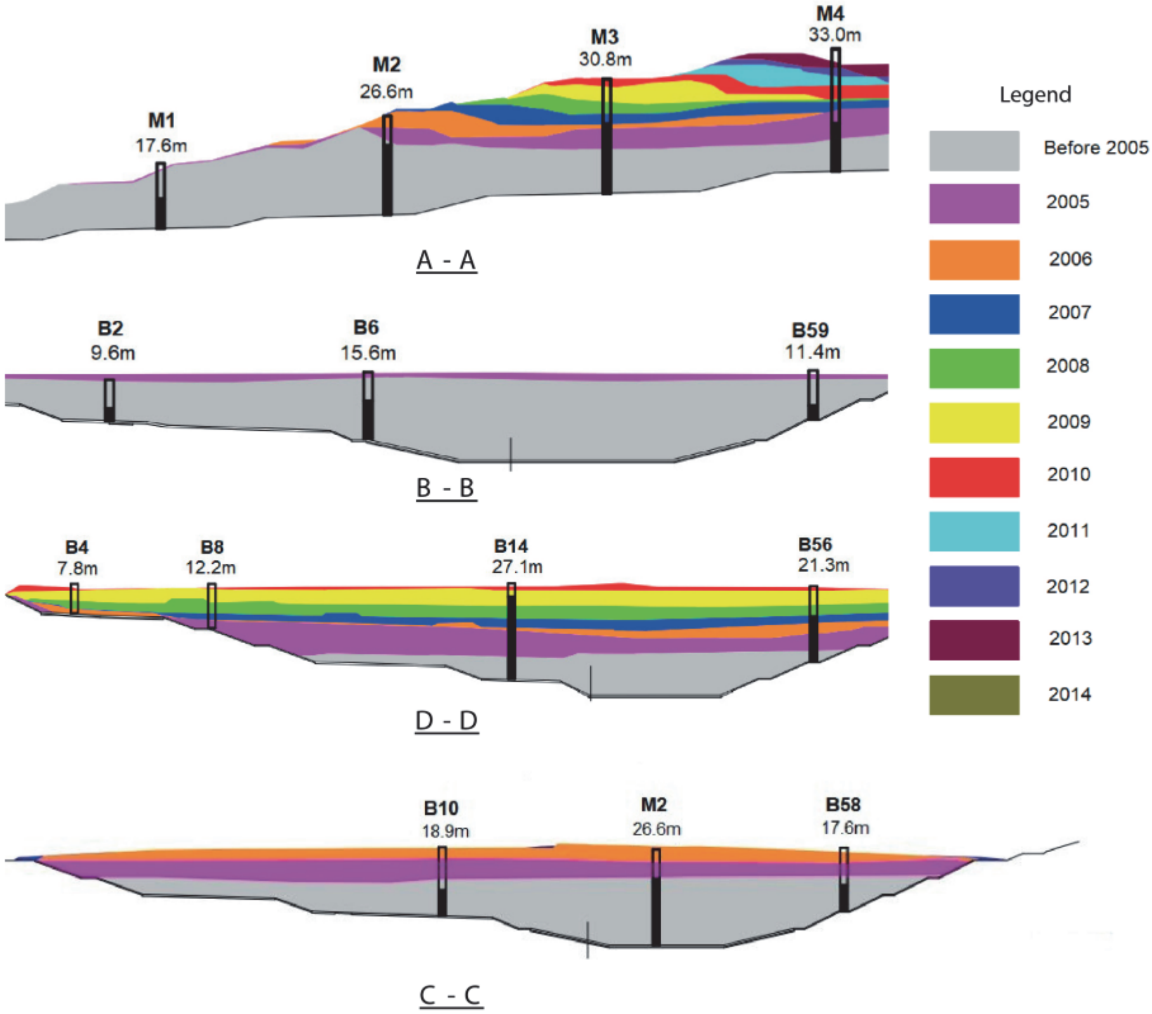



**Figure 7** Cross-section of waste layers through the landfill gas venting pipes.

The distance between the gas venting pipes is designed adequately in order that the natural aeration happens efficiently. Clearly, the distance is more short more efficient, however, the cost of construction also becomes higher.

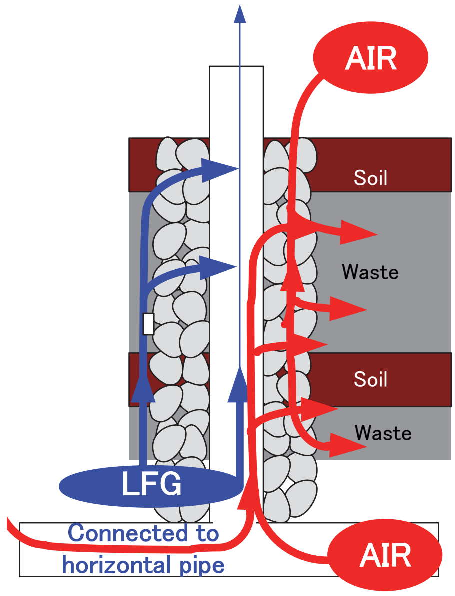



**Figure 8** A typical gas venting pipe

**Figure 9** Mechanism of a gas venting pipe

As mentioned above, the duty of a gas venting pipe is mainly to discharge the landfill gases generating during the waste decomposition into the atmosphere and supply oxygen for aerobic reactions caused by microbial activities.

### *3.2.2. Leachate Collection Pipes (LCPs)*

The leachate collection pipe network is designed to be responsible for the collection and transport of the leachate, which flows from the bottom of the landfill. Leachate is a byproduct of waste decomposition or percolation through waste. Rainwater percolates through the landfill cover into the waste playing an important role in leachate generation. The composition of leachate varies in each landfill depending on waste composition, amount of water available and landfill age.

The function of the LCPs is to lower the leachate mound, reduce hydraulic head on the liner system, and reduce the amount of contaminants available for transport through the barrier system.

**Figure 10** Base gravel layer

**Figure 11** Main leachate collection pipe (perforated pipe)

### *3.2.3. Leachate Pond*

Leachate pond is designed to store the liquids collected by leachate collection pipes before transporting to wastewater treatment plant. Treated leachate meets the requirements of environmental standard then could be discharged into local waterways or streams.

**Figure 12** Leachate pond in Yoshino landfill, Asahikawa City, Hokkaido

### *3.2.4. Barrier Systems*

*3.2.4.1. Cover Layer*

The cover is a material layer used to separate the waste with the environment for protection of public health. During landfill operation, there are two types of cover will be used. The one is daily cover used to cover the top of waste at the end of the working day to reduce odors and vermin. *Figure 13* shows the material used to be daily cover in Yoshino landfill.


**Figure 13** Daily cover by soil

The other is final cover which is a multilayer barrier, the function of the final cover is to reduce or prevent infiltration of precipitation into the landfill in order to minimize leachate generation.

*3.2.4.2. Liner*

Liner system is also a multilayer system to control contamination transport for protection of the subsurface water and soils. Advection and diffusion are the main mechanisms of contaminant transport through the liner. During advection, suspended solids or dissolved material moves with water or leachate and can be transported through pores of a liner based on the hydraulic head. Diffusion may be a significant transport process in low permeability liner systems. HDPE geomembrane is the main material used for liner system in Yoshino landfill.

The bottom barrier system of the semi-aerobic landfill was designed according to the regulation promulgating by the Ministry of Health and Welfare in 1998. The landfill used a single geomembrane with impervious soil layer and geotextiles used as a protection mat on the top of the geomembrane.

In Japan, the amount of natural clay is not available, therefore, to deal with the challenge, bentonite was mixed with soil to create two low-permeability material layers with the coefficient of permeability less than $10^{-7}$ cm/s. The thickness of each bentonite-soil layer is 250 mm. Sandwiched between two bentonite-soil mixture layers, a bentonite sheet with a thickness of 3.5 mm was placed for the protection. Upper of the bentonite-soil mixture layer is bentonite sheet (t=3.5 mm), geomembrane (t=1.5 mm) and geotextile (t=10 mm). The thickness of the protective soil layer and gravel layer are 700 mm and 300 mm, respectively (Fig.13).

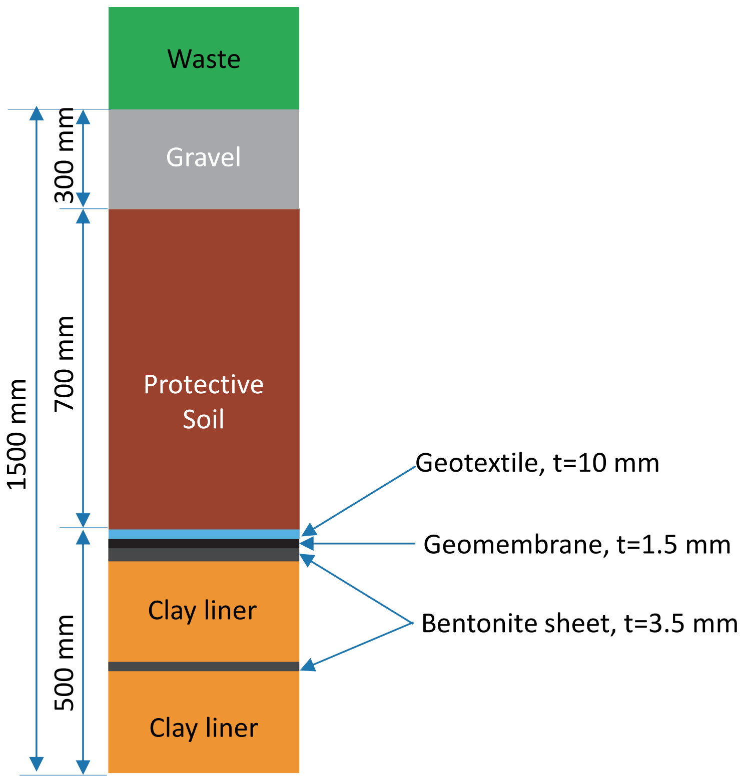



**Figure 14** A cross-section of the bottom barrier system

The municipal solid waste is directly above the gravel. Before 2005, the landfill accepted organic waste because the city's incineration plant could not accept all combustible wastes. However, since 2005, the landfill has accepted only incombustible waste, bottom ash, and fly ash.

The landfill site has been constructed in a temperate climate region. The air temperature fluctuates from −20°C in winter to 25°C in summer. The mean annual temperature is 6.7ºC. Precipitation is distributed throughout the year with maximum amounts of during the late summer. The mean annual precipitation for the region is 1103 mm. The yearly average amount of snowfall ranges widely from 300 cm to 750 cm.

## 3.3 Survey methods

### *3.3.1. LFG temperature and LFG concentration*

Temperatures at the Yoshino landfill were measured by lowering thermo-couple sensor into the vertical gas wells open to the atmosphere during specific monitoring events (*Figure 15)*. Gas concentrations also were measured at the same locations as the temperature measurements in the gas wells using a portable gas analyzer (*Figure 16)*.


**Figure 15** Temperature analyser

**Figure 16** Gas analyser

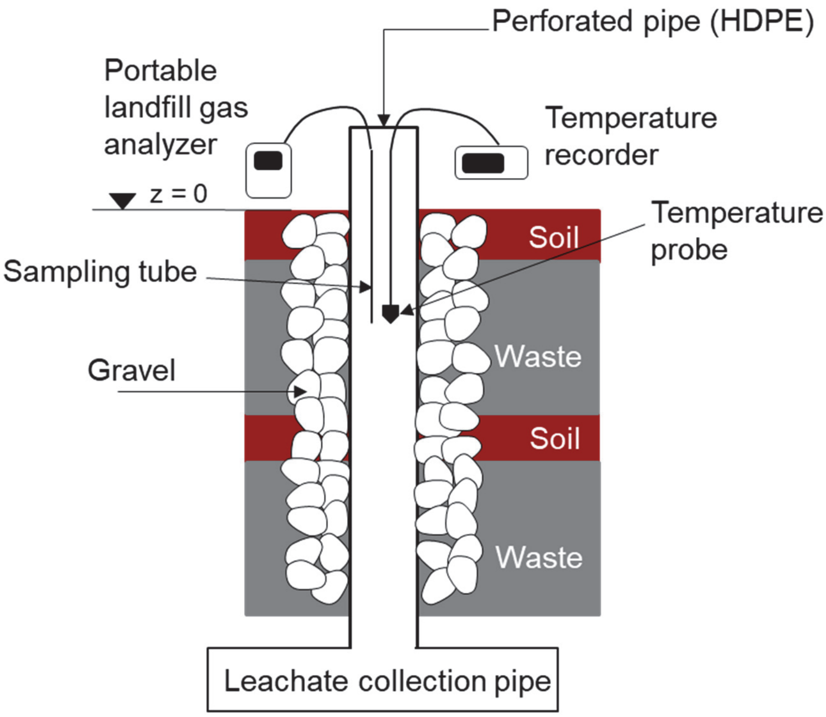



**Figure 17** Methods collecting the LFG temperature and LFG concentration

Air and gas movement occur in the gas wells and the measured temperatures may not fully represent the adjacent waste mass temperatures at a given measurement location. Nevertheless, these temperature measurements provide representation of temperature trends and variations in temperatures due to changing decomposition conditions in the waste mass and were used in the analysis presented herein (N. Ysiller, 2011).

As shown in *Figure 15* and *Figure 16*, the temperature was measured using a thermocouple recorder (Graphtec GL200A, measurement range of thermocouple type T), and the gas component was measured using a portable LFG analyzer (Geotech GA5000, Portable

Landfill Gas Analyzer). The analyzer was equipped with a pump working at a sampling rate of 550 mL/min. Typically, a gas sampling tube and a thermometer sensor were lowered into LFGVPs to sample the air at 1-m-depth intervals from ground level, and measurements were recorded after 90 s of sampling. Three different gases—$CH_4$, $CO_2$, and $O_2$—were detected occurring simultaneously. The $N_2$ content was determined from the balance of $CH_4$, $CO_2$, and $O_2$. The accuracy of the measurement after calibration for $CH_4$, $CO_2$, and $O_2$ was ±0.5%, ±0.5%, and ±1%, respectively.

**Figure 18** In-situ collecting data

Temperature and gas data at the Yoshino landfill have been obtained since 2010 in wastes with ages 2 years to over 13 years. The initial data set at each well represents temperature and gas conditions prior to the placement of the gas wells.

Since 2006, gas temperatures and gas component data have been measured in waste layers aged from 2 years to >11 years. There are movements of air and gases in the gas wells, and the temperatures measured may not fully represent the adjacent waste mass temperatures at a given measurement location. Nevertheless, due to employing a consistent measurement method, these temperature measurements are representative of temperature trends and variations in temperatures due to changing decomposition conditions in the waste mass and have been used in the analysis presented herein (Yesiller et al., 2011).

Carbon monoxide (CO) concentration was also measured by the Portable Landfill Gas Analyzer. The CO concentration was below 30 ppm. Therefore, the concern about the potential for subsurface combustion was not significant in this study (FEMA, 2002).

### *3.3.2. Geomembrane temperature*

Geomembrane temperature under the LFGVP M2 have been monitored for more than 10 years (*Figure 19*).

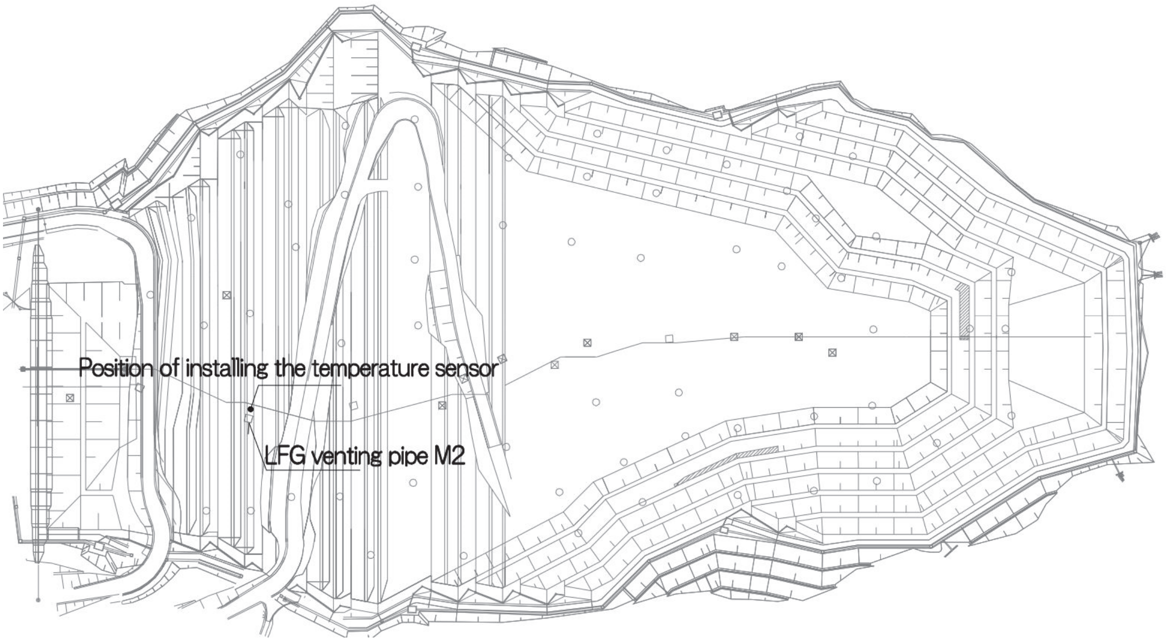
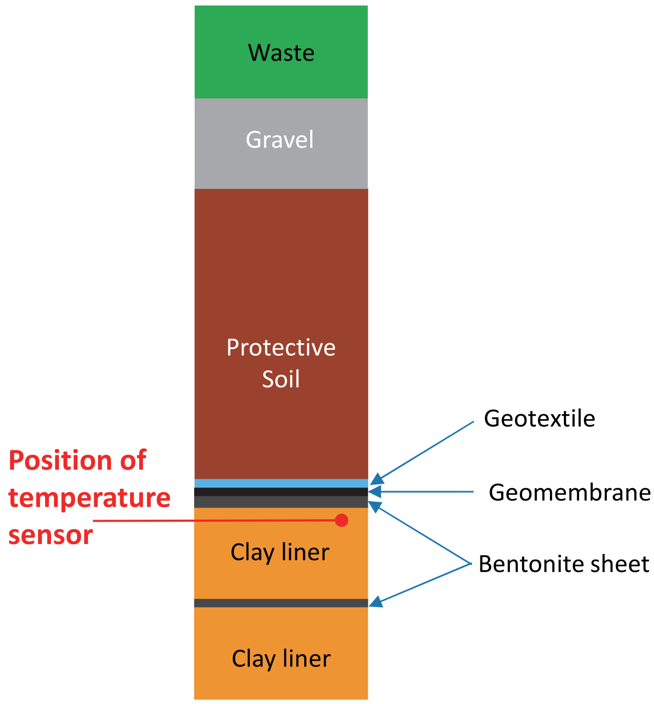



**Figure 19** The position of measuring the LFG temperature and liner temperature on site




(b)

**Figure 20** Scheme of measuring the liner temperature

Geomembrane temperature has been measured by using an integrated temperature sensor below the geomembrane. The Type T Thermocouple (BT-100) with a temperature range of -30ºC - 70ºC has been installed below the primary bentonite sheet in the liner system. The geomembrane temperature has been measured 4 times per day (6-hour intervals) and the temperature data have been collected 2 times per year from the data logger. The operation of the thermocouple bases on the thermoelectric effect which produces a temperature-dependent voltage. Then this voltage is interpreted to measure temperature. The temperature measurement has started since October 2002.

LFG temperature is measured by a temperature recorder (Graphtec GL200A, the measurement range of thermocouple type T). A temperature probe was lowered into the LFGVP M2 at 1-m-depth intervals from ground level, and measurements were recorded after 90 s of sampling. The measurement of LFG temperature has started since January 2006. However, the LFG temperatures only have been measured 4 times per year. The measured temperatures may not fully represent the adjacent waste mass temperatures at a given measurement location. However, these temperature measurements provide a representation of temperature trends and variations in temperatures due to changing decomposition conditions in the waste mass and were used in the analysis presented herein. Besides, air temperature also has been recorded at the same time as measuring the LFG temperature.

### 3.4 Numerical simulation

The finite element method (FEM) is the most widely used method for solving problems of engineering and mathematical models. Typical problem areas of interest include the traditional fields of structural analysis, heat transfer, fluid flow, mass transport, and electromagnetic potential.

COMSOL Multiphysics is a finite element analysis, solver and simulation software/ FEA software package which is used for various physics and engineering applications, especially coupled phenomena, or multiphysics.

In this study, a cross-platform finite element analysis named COMSOL Multiphysics Modeling was utilized to simulate the biodegradation process happening within the landfill which cannot be seen in reality.

#### *3.4.1. Basic goal of the simulation*

This part of research only focuses on simulating the transport of phenomena of landfill gas. A 2D model represents the venting pipe, gravel layer, cover soil and waste layer. Heat transport, mass transfer and momentum transport are considered as the main transport phenomena happening during the biodegradation of organic matter.

In addition, the simulation also considers the effects of clogging phenomena on the generation and distribution of LFG concentration, and temperature within the semi-aerobic landfill. As the venting pipe is clogged, the air cannot migrate into the venting pipe from the bottom of the LCP, therefore, there is no air flow at the bottom.

#### *3.4.2. Various properties needed for the simulation*

##### *3.4.2.1. Density*

The landfill gas is a mixture of many gases, however, the main gas components including methane gas ($CH_4$), carbon dioxide ($CO_2$), oxygen ($O_2$) and nitrogen ($N_2$). And the density of landfill gas is a function depends on the temperature, internal pressure, and gas concentration.

*3.4.2.2. Porosity*

Porosity is defined as the fraction of the control volume that is occupied by pores. Thus, porosity can vary from zero for pure solid regions to unity for domains of free flow.

*3.4.2.3. Permeability*

Permeability is defined as the ability of a porous material to allow fluids to pass through it. The unit for permeability is $m^2$

The permeability of a medium is related to the porosity, but also to the shapes of the pores in the medium and their level of connectedness.

***3.4.3. Governing equations and geometry***

Waste matrix is a heterogeneous porous medium. A detailed description down to every pore is not practical. Therefore, to simplify the problems, a combination of the porous (waste) and fluid (landfill gas) media into a single homogeneous medium is a common alternative approach.

The geometry of model is modeled including 3 blocks: waste block, gravel block and pipe block with the dimensions as follow:

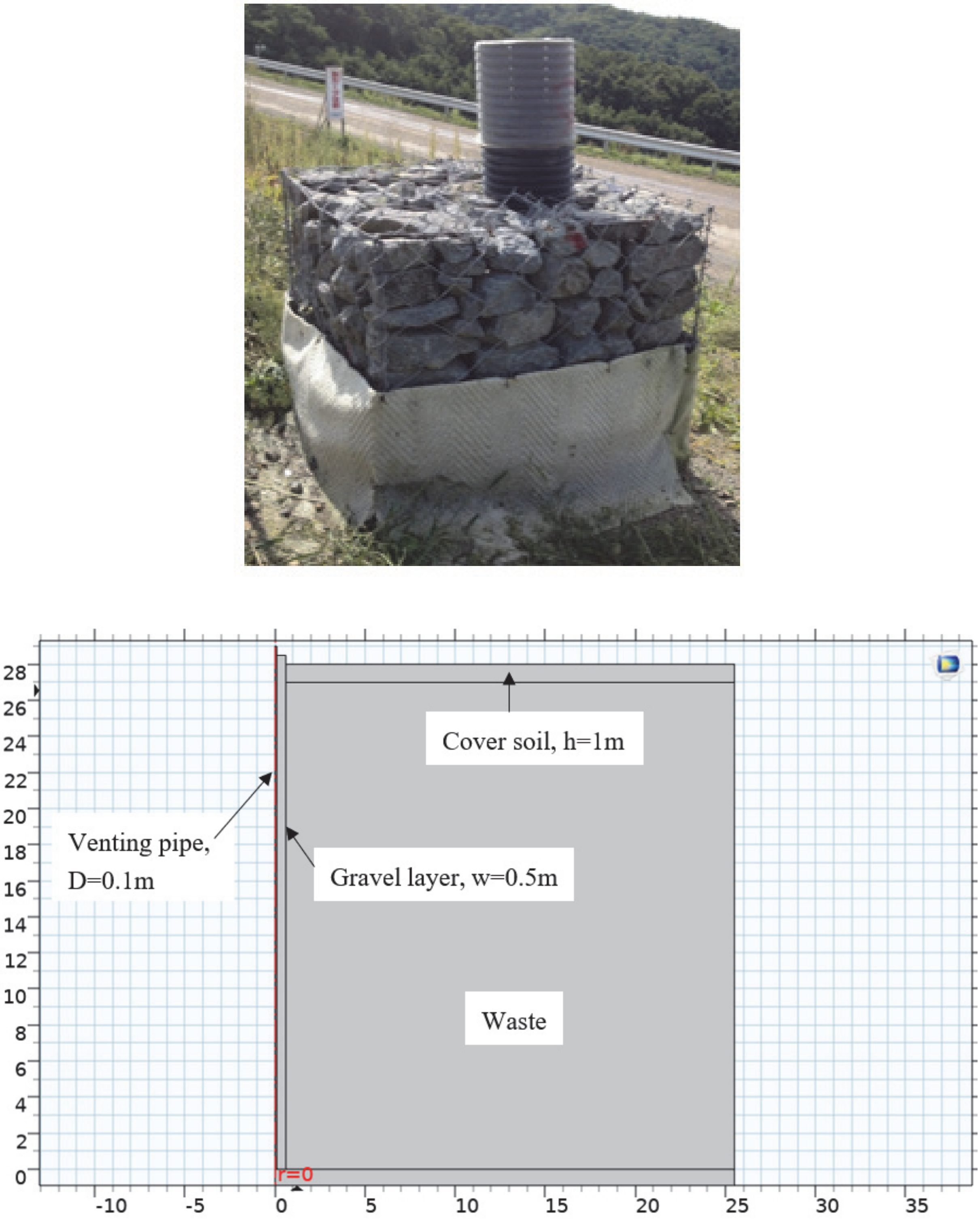



**Figure 21** The geometry of model

*3.4.3.1. Continuity equation*

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\nabla.(\rho\mathbf{u})=Q_m$$

*3.4.3.2. Darcy's Law equation*

To model low-velocity flows or media where the permeability and porosity are very small, and for which the pressure gradient is the major driving force and the flow is mostly influenced by the frictional resistance within the pores, Darcy's law together with the continuity equation and equation of state for the pore fluid (or gas) provide a complete mathematical model suitable for a wide variety of applications involving porous media flows. With Darcy's law, the momentum is so small it can be neglected, pressure alone drives the flow

Darcy's law states that the velocity field is determined by the pressure gradient, the fluid viscosity, and the structure of the porous medium:

$$\mathbf{u} = -\frac{\kappa}{\mu}\nabla p$$

Inserting Darcy's equation into the continuity equation:

$$\frac{\partial}{\partial t}(\rho\varepsilon) + \nabla.\rho\left[-\frac{\kappa}{\mu}\nabla p\right] = Q_m$$

where:

ρ = landfill gas density ($kg/m^3$)

μ = dynamic viscosity of LFG (Pa.s)

ε = porosity (a dimensionless number between 0 and 1)

κ = permeability of the media ($m^2$)

$Q_m$ = mass source ($kg/(m^3.s)$)

$p$ = LFG pressure (Pa)

$t$ = time (s)

In the landfill, the transformation of organic matter to the landfill gas component and other products mainly based on the aerobic and anaerobic reactions caused by microorganism activities. The consumption of organic matter and oxygen, the generation of methane gas and carbon dioxide have to be considered. Hence, mass source ($Q_m$) will be added into the above equation.

$$Q_m = (R_{CH4}+R_{CO2})*(xO_{2\_initial}/Kfactor)/[xO_{2\_initial}/Kfactor + wO_2]$$

Where:

$R_{CH4}$ = the methane gas generation rate from waste layer (kg/(m$^3$.s))

$R_{CO2}$ = the carbon dioxide generation rate from waste layer (kg/(m3.s))

$wO_2$ = mass fraction of oxygen (a dimensionless number between 0 and 1)

$xO_{2\_initial}$ = initial oxygen concentration (mol/m$^3$)

Kfactor = a coefficient (dimensionless)

*3.4.3.3. Heat transfer equations in fluid and solid*

The heat transfer equation for porous media is derived from the mixture rule on energies appearing in solid and fluid heat transfer equations. For solid medium:

$$\rho_s C_{p,s} \frac{\partial T_s}{\partial t} + \nabla \cdot \mathbf{q}_s = Q_s$$

where:

ρ = solid density (waste, soil, gravel) (kg/m$^3$)

$C_p$ = specific heat capacity of solid (waste, soil, gravel) (J/m$^3$/kg)

T = temperature (K)

q = conductive heat flux

Q = heat source or sink

For fluid medium:

$$\rho_f C_{p,f} \frac{\partial T_f}{\partial t} + \rho_f C_{p,f} \mathbf{u}_f \cdot \nabla T_f + \nabla \cdot \mathbf{q}_f = Q_f$$

where:

ρ = fluid density (kg/m$^3$)

$C_p$ = specific heat capacity of fluid (J/m$^3$/kg)

T = fluid temperature (K)

q = conductive heat flux

Q = heat source or sink

The local thermal equilibrium hypothesis assumes equality of temperature in both fluid and solid phases:

$$T_f = T_s = T$$

Heat source is the heat generation of biodegradation of organic materials within the landfill resulting from microorganism activities and chemical reactions. In this simulation, heat source is considered as a function mainly depending on the biological reactions.

$$Q_0 = R_{aero}*dH_{aero}*wO_2/(xO_{2\_initial}/Kfactor+wO_2)$$

where:

$R_{aero}$ = heat generation rate of aerobic decomposition (J/(m$^3$.s)))

$dH_{aero}$ = heat generation value aerobic decomposition (J/(m$^3$.s)))

*3.4.3.4. Transport of landfill gas concentration equations*

The basic equation for the conservation of mass of a species i is:

$$\frac{\partial}{\partial t}(\rho\omega_i) + \nabla \cdot (\rho\omega_i\mathbf{u}) = -\nabla \cdot \mathbf{j}_i + R_i$$

Where:

$\rho$ = the density of landfill gas mixture (kg/m$^3$)

$\omega_i$ = mass fraction of gas component i (dimensionless)

$\mathbf{u}$ = the mass averaged velocity of the mixture (m/s)

$\mathbf{j}_i$ = the mass flux relative to the mass averaged velocity (kg/(m$^2$.s))

$R_i$ = heat the rate expression describing its production or consumption (kg/(m$^3$.s))

3.4.3.5. *Organic matter (glucose) consumption equation*

To model the solid waste biodegradation (glucose), the Monod equation was used:

$$\frac{\partial u}{\partial t} = f$$

Where:

$$f = - R_{CH4}*xO_{2\_initial}/Kfactor/(xO_{2\_initial}/Kfactor+xO_2)/M_{CH4}$$

$$- R_{O2}*xO_2/(xO_{2\_initial}/Kfactor + x_{O2})/M_{O2}$$

$u$ = the concentration of the biodegradable of solid waste (kg/m$^3$)

$f$ = solid waste biodegradation rate (kg/(m$^3$.s))

$t$ = time (s)

$R_{CH4}$ = the methane gas generation rate from waste layer (kg/(m$^3$.s))

$R_{O2}$ = the oxygen consumption rate (kg/(m3.s))

$xO_2$ = mole fraction of oxygen (mol/m$^3$)

$xO_{2\_initial}$ = initial oxygen concentration (mol/m$^3$)

Kfactor = a coefficient (dimensionless)

$M_{CH4}$ = molecular weight of methane (kg/mol)

$M_{O2}$ = molecular weight of oxygen (kg/mol)

### *3.4.4. Input parameters*

| Input parameters | Unit | Value |
|---|---|---|
| Atmospheric pressure, $p_0$ | atm | 1 |
| Initial temperature, $T_0$ | K | 273.15 |
| Porosity, $\varepsilon$ | - | 0.1 |
| Tortuosity, $\tau$ | - | 1.5 |
| Density of landfill gas, $\rho_g$ | kg/m$^3$ | 1.293 |
| Density of waste, $\rho_w$ | kg/m$^3$ | 1200 |
| Density of soil, $\rho_s$ | kg/m$^3$ | 1800 |
| Permeability of waste, $\kappa_w$ | m$^2$ | 1e-13 |
| Permeability of soil, $\kappa_s$ | m$^2$ | 1e-12 |
| Permeability of gas, $\kappa_g$ | m$^2$ | 1e-4 |
| Dynamic viscosity of gas | Pa.s | 1.78e-5 |
| The methane gas generation rate, $R_{CH4}$ | kg/(m3.s) | 1.6e-7 |
| The oxygen consumption rate, $R_{O2}$ | kg/(m3.s) | 3.2e-8 |
| The carbon dioxide generation rate, $R_{CO2}$ | kg/(m3.s) | 2.93e-7 |
| Molecular weight of methane, $M_{CH4}$ | kg/mol | 0.016 |
| Molecular weight of oxygen, $M_{O2}$ | kg/mol | 0.032 |
| Molecular weight of carbon dioxide, $M_{CO2}$ | kg/mol | 0.044 |
| Molecular weight of nitrogen, $M_{N2}$ | kg/mol | 0.028 |
| Molecular weight of glucose, $M_{glucose}$ | kg/mol | 279 |
| Initial temperature, $T_{init}$ | $^oC$ | 20 |
| Thermal conductivity of waste, $k_w$ | W/(m.K) | 0.95 |
| Thermal conductivity of soil, $k_s$ | W/(m.K) | 0.86 |
| Thermal conductivity of gas, $k_g$ | W/(m.K) | 0.02 |
| The initial methane gas concentration, $xCH4_{\_initial}$ | mol/m$^3$ | 0 |
| The initial oxygen concentration, $xO2_{\_initial}$ | mol/m$^3$ | 0.21 |
| The initial carbon dioxide concentration, $xCO2_{\_initial}$ | mol/m$^3$ | 0 |
| The initial nitrogen concentration, $xN2_{\_initial}$ | mol/m$^3$ | 0.79 |
| The half saturation constant for the oxygen, K*factor* | kg/m$^3$ | 20 |
| The gas constant, $R_g$ | J/(mol.K) | 8.314 |
| Specific heat capacity of gas mixture, $C_{p,gas}$ | J/(kg.K) | 1524 |
| Specific heat capacity of waste, $C_{p,w}$ | J/(kg.K) | 1000 |
| Specific heat capacity of soil, $C_{p,s}$ | J/(kg.K) | 1109 |
| Heat generation rate of aerobic decomposition, $R_{aero}$ | J/(m$^3$.s) | 1e-6 |
| Heat generation value aerobic decomposition, $dH_{aero}$ | J/(m$^3$.s) | 4.67e5 |
| The effective specific capacity of gas, $C_{eff}$ | J/(kg.K) | 1939 |
| The effective density of porous media, $\kappa_{eff}$ | kg/m$^3$ | 1157 |
| The effective thermal conductivity of gas, $k_g$ | J/(kg.K) | 0.35 |

* These parameters are determined by the reference # H.Yoshida, doctoral degree dissertation, Hokkaido Univ. (1999). The reference shows the characteristics of the wastes which were not incinerated and landfilled.

As mentioned above, porosity is defined as the fraction of the control volume that is occupied by pores. Therefore, the porosity is one of the most representative parameters of void space structure. For natural media, porosity does not normally exceed 0.6 and for the experimented waste layers, porosity varied widely within the range 0.03 to 0.6 (Amjad Kallel N. T., 2004).

# CHAPTER 4: RESULTS AND DISCUSSION

## 4.1 Observation results

Temperatures at the Yoshino landfill were measured by lowering thermo-couple sensor into the vertical gas wells open to the atmosphere during specific monitoring events from 2010 until now.

### *4.1.1. Spatial distribution of LFG*

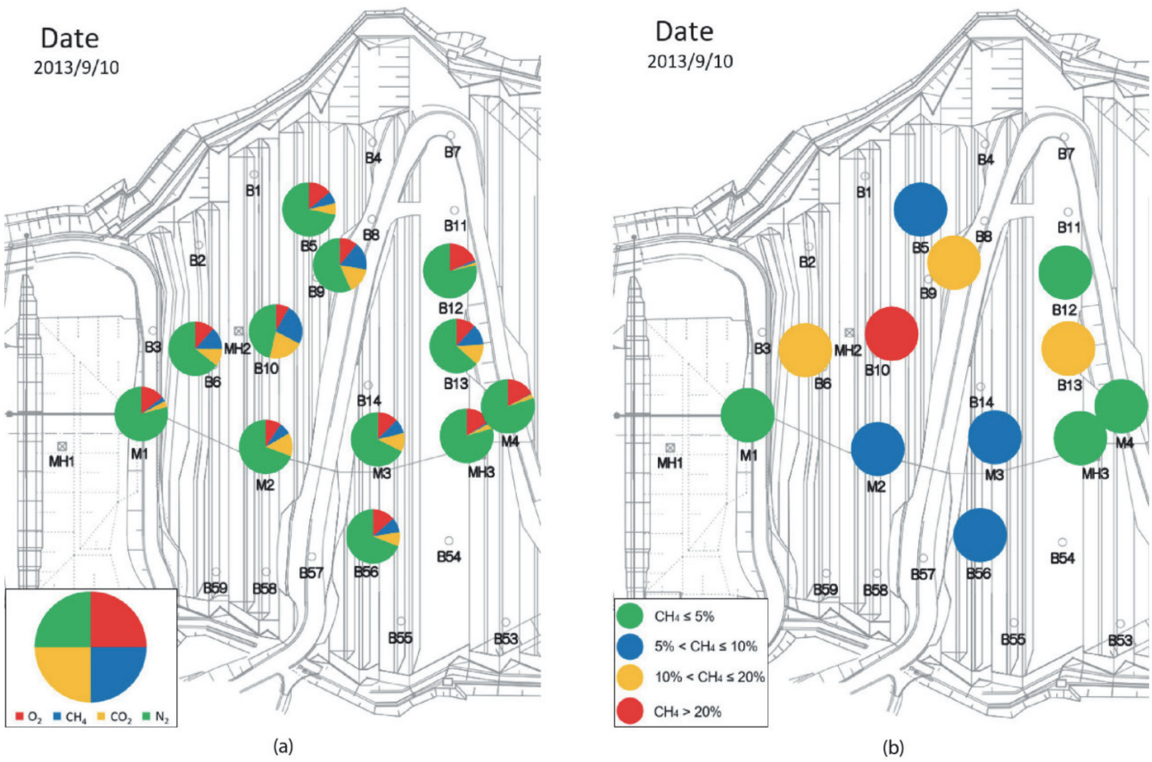



**Figure 22** (a) Gas components and (b) ranking map of $CH_4$ concentration at the exit of surveyed landfill gas venting pipes (Zone A) on September 10, 2013.

*Figure 22(a)* describes the main LFG components, including $CH_4$, $CO_2$, $O_2$, and $N_2$, at the exit of LFGVPs surveyed on September 2013. It can be seen that the $CH_4$ concentration at the exit of the surveyed LFGVPs is below 10% (blue color), apart from the case of the branch LFGVP B10 (24.4%). *Figure 22(b)* shows the range of $CH_4$ concentrations at the exits of the surveyed LFGVPs. Here, we rank the $CH_4$ concentration using four colors: green represents a $CH_4$ concentration either less than or equal to 5%, blue represents a concentration greater than

5% and either less than or equal to 10%, yellow represents a concentration greater than 10% and either less than or equal to 20%, and red represents a concentration greater than 20%. Most of the main LFGVPs (M1, M2, M3, and M4) have a $CH_4$ concentration below 10%, whereas the $CH_4$ concentration of branch LFGVPs ranges from 1.4% (B12) to 24.4% (B10). The ranking map of $CH_4$ concentration [*Figure 22(b)*] shows that most of the LFGVPs with high $CH_4$ concentration are branch LFGVPs (B6, B9, B10, and B13). This could be due to the branch LFGEWs are far away from the main LCP; the air flow is difficult to move to these branch LFGEWs through the main LCP at the bottom of the landfill.

#### *4.1.2. Influence of the type of gas VPs on LFG concentration and temperature*

#### *4.1.3. The main gas VP M2*

Zone A (landfilling completed) contains four main LFGVPs: M1, M2, M3, and M4. Our analysis focuses on the main gas VP M2, where the height of the organic waste (approximately 20 m) was the largest in the landfill site (see *Figure 7*).

*Figure 23* shows the LFG concentration and temperature and the $CH_4/CO_2$ ratio at the exit of the main LFGVP M2. The air temperature fluctuated from −20°C in winter to 25°C in summer. Though the air temperature was always below 0°C in the winter months, the high-temperature trend of LFG remained at >40°C for more than 5 years before declining to 20°C in the most recent observation. This means that there was a continuous active aerobic condition around this LFGVP. Over the observation period, the $CH_4/CO_2$ ratio was below 1.0 (from 0.34 to 1.04). This shows that aerobisation was active in this LFGVP, and the aerobic condition became dominant. The trend of this ratio increased slightly from the 1,200th day to the 2,450th day (from 2006 to January 2010) from the commencement of the landfilling operation and then declined gradually to less than 0.5 by the 3,800th day (February 2014). The $CH_4$ concentration at the exit ranged from 5% to 15%. The $CH_4$ concentration increased slightly, from 7% to 15%, in the early observation and then decreased gradually to 5%.

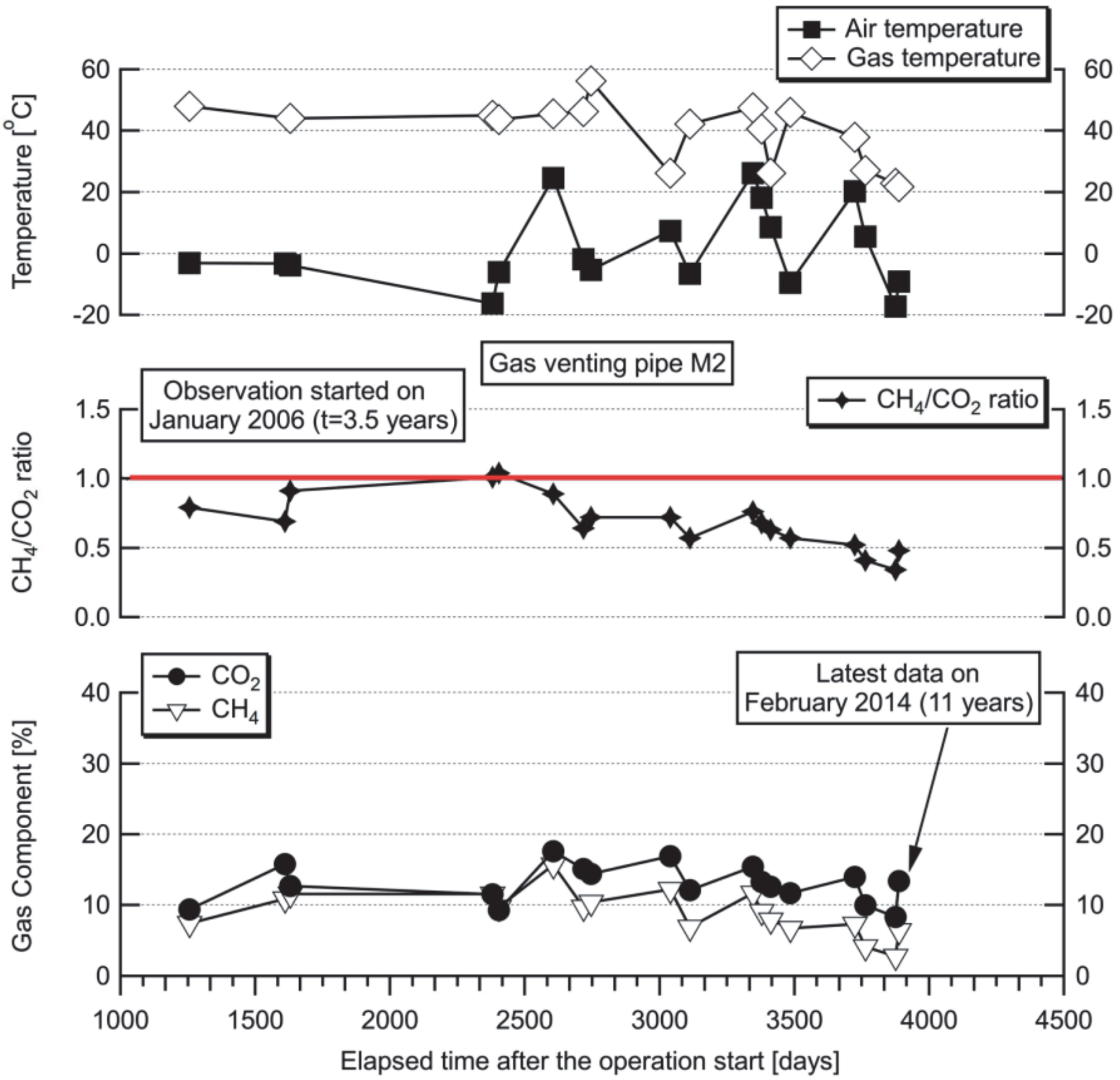



**Figure 23** Landfill gas concentration and temperature and the $CH_4/CO_2$ ratio at the exit of the main landfill gas venting pipe M2

The findings reveal that, during the 7 years from December 2006 (3 years after the landfilling operation commenced) to February 2014, the $CH_4$ concentration of the LFGVP M2 varied from ~7% to ~15% from December 2006 to August 2010 and then declined gradually. This decline may have been due to the gradual disappearance of organic waste. Obviously, the trend of reduction of LFG temperature, $CH_4$ concentration, and the $CH_4/CO_2$ ratio may be useful indicators of the landfill stabilizing.

As the $CH_4$ concentration data were recorded only at the exits of LFGVPs, the measured $CH_4$ content could be diluted by air. However, even when we measured the $CH_4$ and $O_2$ concentrations since 2010 along the depths of the LFGVP M2, the $CH_4$ concentration of this

LFGVP was always less 20% from 2010 to 2013, and it then declined to below 10% in 2014 [*Figure 24(a)*].

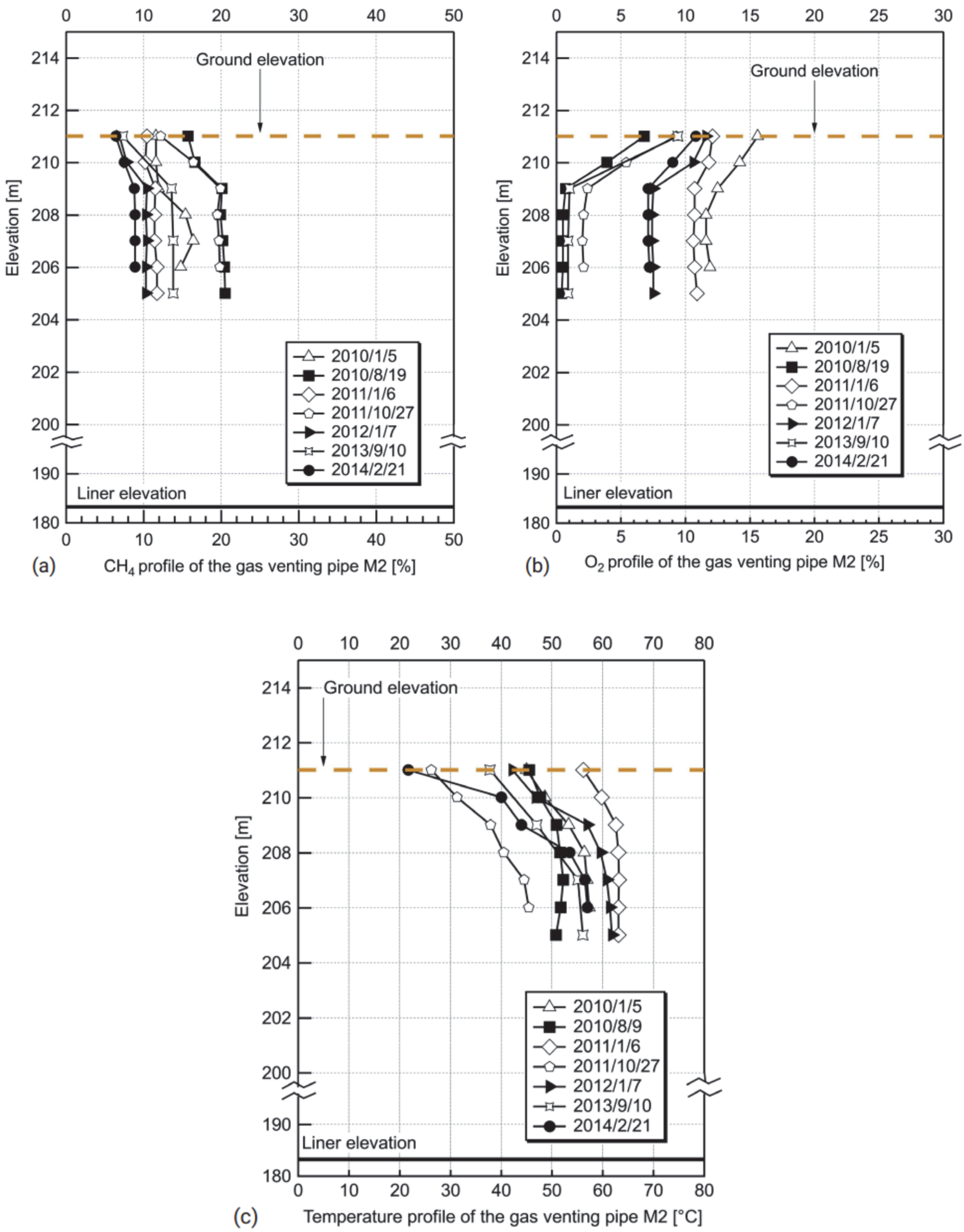



**Figure 24** (a) $CH_4$ concentration profile of the main landfill gas venting pipe M; (b) $O_2$ concentration profile of the main landfill gas venting pipe M2; (c) Temperature profile of the main LFG venting pipe M2.

The $CH_4$ concentrations were always below 20% at all depths, whereas the $O_2$ concentrations ranged from ~1% to ~15%. The waste mass at the LFGVP M2 reached the designed elevation of 211 m in 2008. Most of the measurements were obtained in winter (January and February), and the surface of the landfill was covered with a thick layer of snow (the average annual snowfall is around 0.8 m). This meant that it was impossible for air to migrate into the landfill body through the soil cover layers. However, the $O_2$ concentrations inside the VP fluctuated around 8–15%. During the summer and autumn months (August, September, and October), when there was no snow, the $O_2$ concentrations dropped to below 5%, and the $CH_4$ concentrations increased to 20% [*Figure 24(a,b)*]. Such phenomena proved that the semi-aerobic mechanism was functioning. $O_2$ is supplied into the waste mass from the LCPs at the bottom due to the buoyancy effect, which is a product of the temperature difference between the inside and outside of the landfill, and then it migrates to the waste layers near the LFGVPs. The more the temperature difference increases, the greater the amount of $O_2$ drawn into the pipe network. As a result, aerobisation happens strongly at the waste layers close to the LFGVPs.

The aim of semi-aerobic landfill is to promote aerobic biodegradation of organic wastes within the landfill. To assess the aerobization of the semi-aerobic landfill, LFG temperatures of LFGVPs should be measured. *Figure 24(c)* depicts the LFG temperature profiles of the main LFGVP M2. The LFG temperatures have been monitored since 2010 (7 years after the landfilling operation commenced).

The main LFGVP M2 showed the highest gas temperature of all the LFGVPs installed in the landfill area. The highest temperature recorded was 63.2°C at −4 m depth in January 2011, and the high-temperature trend continued until 2014. *Figure 24(c)* also indicates the elevated temperature of above 40°C from January 2010 to 2014. The high temperatures were observed particularly in early January and February. At that time, it was winter at the study site, and the average daily ambient temperature was from −20°C to −5°C. The temperature difference between the inside and outside of the LFGVP was greater than 60°C (*Figure 23*). This affirms that the driving force of air flow in the semi-aerobic landfill increases in winter. Yanase et al. (2010) measured the rate of air flow into the LCP for 1 year and found a high flow rate in winter and no air flow in summer. That explains why our measurements recorded high temperatures in the landfill over the observation period.

*4.1.4. The branch gas VP B10*

The branch LFGVP B10 is located near the main LFGVP M2. At this location, the height of the waste layers, including organic waste, was ~10 m. However, the average $CH_4$ concentration of this branch LFGVP was highest (18.9%) among the surveyed LFGVPs.

*Figure 25* shows that the gas temperatures at the exits were affected by air temperatures. The LFG temperatures ranged from 7.1°C to 32.4°C. Meanwhile, the $CH_4$ concentrations ranged from 15% to 38% at the exit during 2,000 days (approximately 6 years) before declining to 0% at the most recent observation. Clearly, the $CH_4$ concentration of the branch LFGVP B10 was 2–3 times higher than that of the main LFGVP M2 (see Figures 20, 21, and 22).

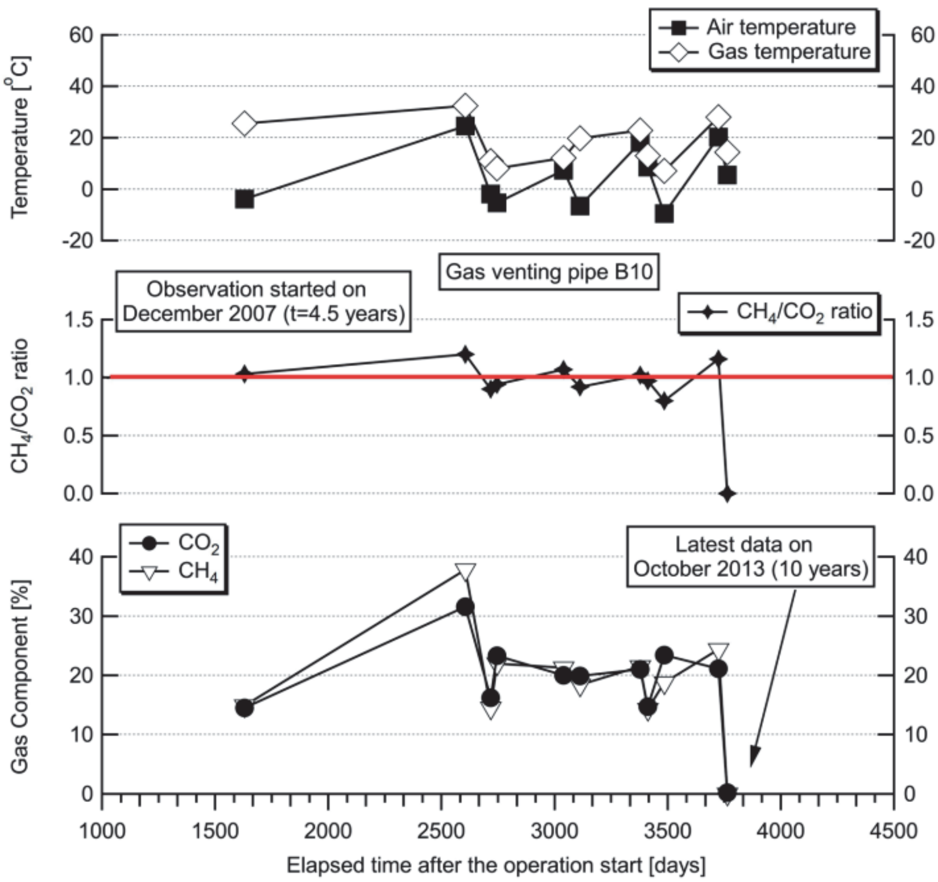
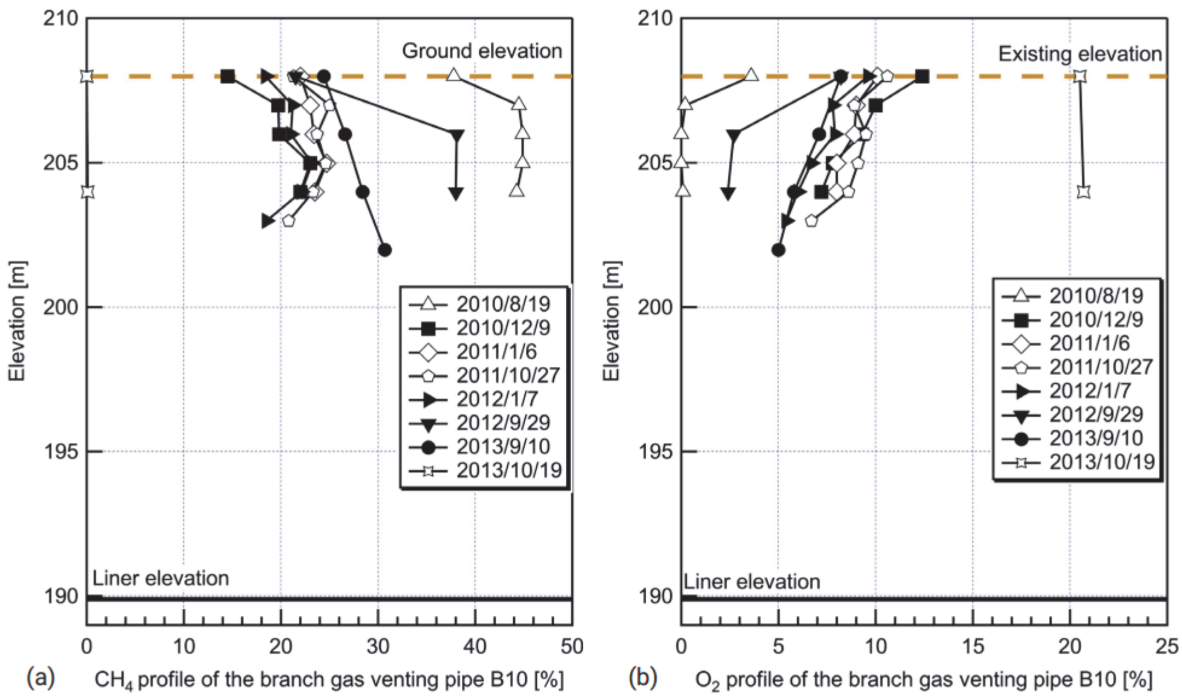



**Figure 25** The Landfill gas concentration and temperature and the $CH_4/CO_2$ ratio at the exit of the branch landfill gas venting pipe B10.

The ratio of $CH_4/CO_2$ ranged from 0.8 to 1.2 for 6 years before decreasing to 0. The fact that the LFG concentration was 0 in the most recent observation could be due to the disappearance of organic waste. In this case, the anaerobic condition could become more dominant than the aerobic condition.

*Figure 26(a,b)* shows the $CH_4$ and $O_2$ concentration profiles of the branch LFGVP B10. The $CH_4$ concentrations ranged from 20% to 45%, whereas the $O_2$ concentrations ranged, approximately, from 0% to 10%. Apart from the measurement obtained in August 2010, the $O_2$ concentration reached 0% and the $CH_4$ concentration reached 45%. In other measurements, the $CH_4$ concentration fluctuated from 20% to 38%, whereas the $O_2$ concentration ranged from 3% to 10%, and the temperature ranged from 10°C to 30°C [*Figure 26(c)*]. These indicators reveal that the anaerobic condition became dominant.



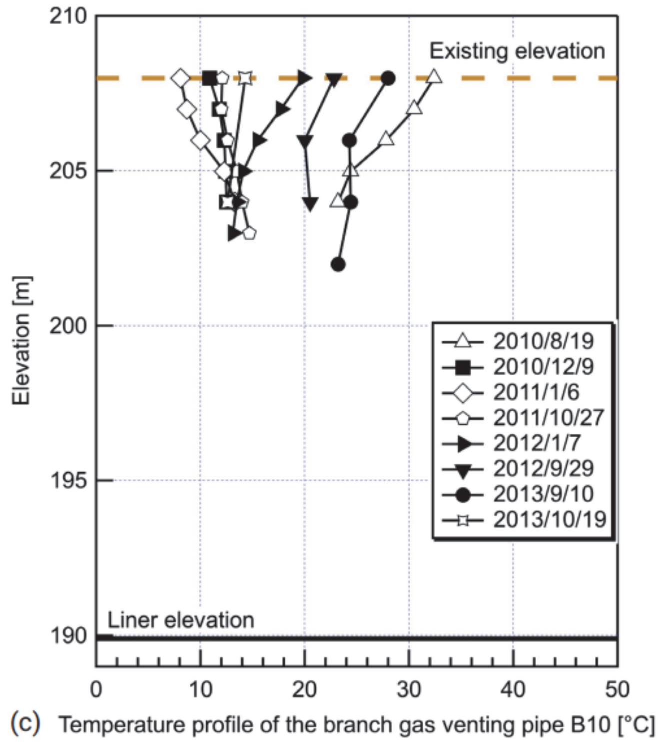
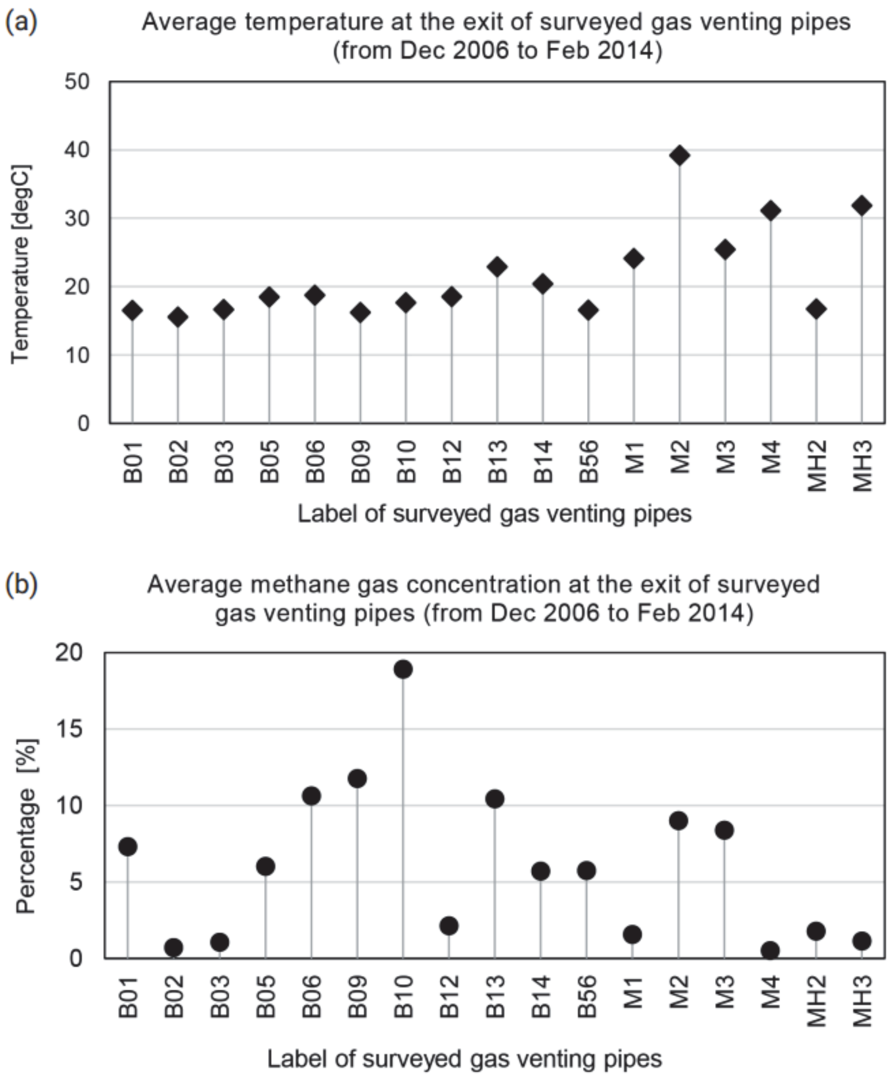



**Figure 26** (a) $CH_4$ concentration profile of the branch landfill gas venting pipe B10; (b) $O_2$ concentration profile of the branch landfill gas venting pipe B10; (c) Temperature profile of the branch landfill gas venting pipe B10.

*Figure 26(c)* depicts the temperature profile of the branch LFGVP B10. The highest temperature was 40°C at 0 m depth (at ground elevation) in September 2012, and a high-temperature trend was recorded in August 2010, when the gas temperature ranged from 22°C to 32°C, with the highest value being at ground level. In general, the shape of the gas temperature line of this LFGVP was different from the shape of the temperature line of the LFGVP M2 (see *Figure 24*). In this case, as the O2 concentration remained between 3% and 10% inside the LFGVP [*Figure 26(b)*], it may be that the organic wastes near the LFGVP were exhausted and the $CH_4$ moved to the LFGVP from distant areas where anaerobic conditions existed.

#### *4.1.5. The average values of the gas temperature, $CH_4$ concentration and the ratio of $CH_4/CO_2$*

*Figure 27* shows the average values of the gas temperatures, the $CH_4$ concentrations, and the $CH_4/CO_2$ ratios at the exits of the surveyed LFGVPs (from December 2006 to February 2014). The average LFG temperatures of the main LFGVPs (M1, M2, M3, and M4) were higher than those of the branch LFGVPs. The average $CH_4$ concentrations of the main LFGVPs were below 10%. In particular, the $CH_4/CO_2$ ratios of the main LFGVPs were below 0.8, whereas the $CH_4/CO_2$ ratios of the branch LFGVPs ranged from 0.9 to 1.1. This means that there was more effective aerobic biodegradation at the main LFGVPs than that at the branch LFGVPs.



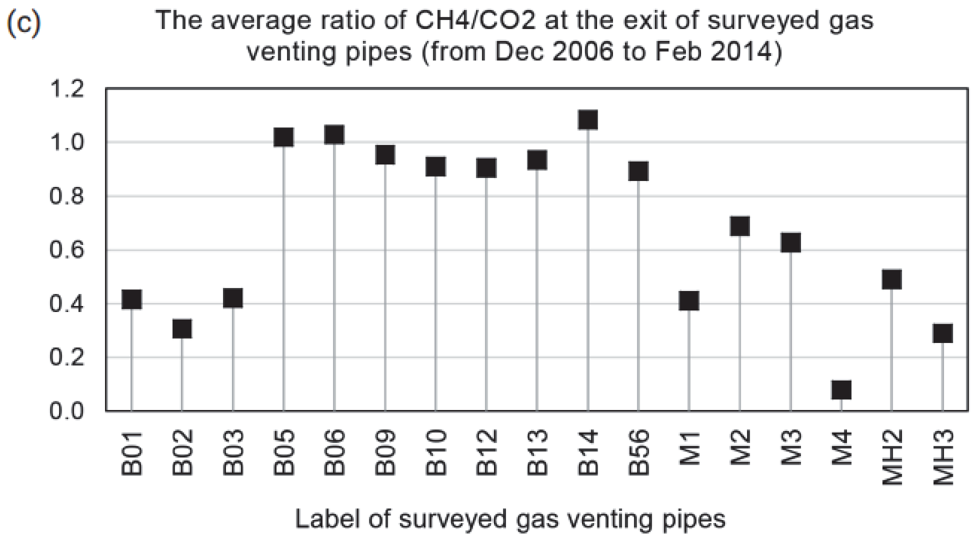



**Figure 27** The average values of (a) the gas temperature and (b) $CH_4$ concentrations and (c) the $CH_4/CO_2$ ratio at the exit of the surveyed landfill gas venting pipes during the period from December 2006 to February 2014.

Although the branch LFGVPs B1, B2, and B3 showed average $CH_4/CO_2$ ratios of below 0.4 and average $CH_4$ concentrations below 7%, the average LFG temperatures were below 20°C. Thus, it may be that the anaerobic condition was still dominant. Another reason could be due to the amount of organic matter within the waste mass exhausted.

#### *4.1.6. Long-term temperature monitoring of geomembrane liner*

In recent years, modern sanitary landfills have been designed with modern engineered facilities to reduce the negative impacts on the environment and community. A barrier system is one of the key components in waste disposal facilities. The main duties of the barrier system are to isolate waste from the surrounding environment. The top barrier is to minimize the nuisance of waste disposal facilities from the community. The bottom one helps to protect the groundwater and subsoil from contaminants of waste.

For modern waste disposal facilities, designing appropriately the bottom barrier (liner) is very important to prevent dissolved contaminants from migrating to the underneath. Materials for constructing the bottom liner could be low-permeability material layers such as natural clayey deposits, compacted clay liners, geosynthetic clay liners. Recently, geomembrane liners have been used in many applications over the world. Geomembranes (high-density polyethylene) have been used as bottom liners in landfills for almost 30 years because of their advantages such as extremely low permeability ($10^{-14}$ m/s), physical, biological and chemical resistance.

Using the geomembrane liner at the bottom barrier layers of landfills showed significant effectiveness in minimizing the migration of contaminants into groundwater. Nevertheless, if the geomembrane liners have not been installed properly, technical faults during construction lead to risks to the environment. In addition, geomembrane is a type of polymeric plastic material (e.g., high-density polyethylene (HDPE) and polyvinyl chloride (PVC)), its physical, mechanical and chemical properties are easily weakened as it exposed to high temperatures.

Heat is a primary byproduct of biodegradation of organic materials and also due to chemical and biochemical reactions occurring within the waste mass. The biological reactions happening inside a typical landfill are exothermic by virtue of mechanisms of aerobic and anaerobic decomposition processes and expressed as below:

Anaerobic condition: $C_6H_{12}O_6 \rightarrow 3CO_2 + 3CH_4 + \text{Heat}$ (1)

Aerobic condition: $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{Heat}$ (2)

Pirt (1978) and Rees (1980) reported a heat generation value of 632 kJ/kg glucose for anaerobic digestion. Cooney, Wang and Mateles (1968) reported a heat generation value of approximately 110 kcal/mol oxygen ($O_2$) (15,400 kJ/kg glucose) for aerobic digestion. Thus, it is clear that aerobic decomposition generates a larger amount of heat from waste decomposition than does anaerobic decomposition.

Heat or temperature affects engineering properties of wastes and properties and performance of earthen and geosynthetic components of cover and bottom liner systems. Temperatures within solid waste landfills in some areas with the different climatic conditions over the world were recorded up to 60-90ºC (Yesiller et al, 2015). Incineration and combustion ash-related reactions can generate temperatures up to 150ºC (Calder et al, 2010). Such elevated landfill temperatures also affect the chemical, physical and biological processes in the landfill and may have a significant impact on the service life of components of any engineered barrier system [(Southen and Rowe, 2004), (Rowe, 2005), (Jafari et al, 2013), (Rowe et al, 2009).

HDPE and PVC geomembranes are sensitive to high temperatures which make mechanical and chemical properties change. This leads to a decrease in the bending stiffness, reduction in resistance to chemicals, an increase in the process of thermo-oxidation which will cause antioxidant depletion in a geomembrane, potential desiccation in clay liners beneath a geomembrane, and an increase diffusion and/or moisture movement through liners (Rowe, 1998).

Koerner and Koerner (2006) monitored the in situ temperature of geomembrane liners at a dry cell and a wet cell of an MSW landfill in Pennsylvania, USA. The average temperature was from 20ºC – 30ºC for the dry cell. For the wet cell, the temperature ranged from 25ºC – 46ºC over a period of observation. Klein, Baumann, Kahapka and Niessner (2001) reported that the temperature of the geomembrane over clay (composite liner system) rose to 46ºC and the maximum temperature in the waste was 85ºC within an MSW incinerator bottom ash landfill in Ingolstadt, Germany. Yoshida and Rowe (2003) observed in situ landfill temperature of Tokyo Port Landfill where the waste was placed directly on the surface of a natural clayey liner without geomembrane liners. The temperature ranged from 25ºC – 50ºC. And there is evidence of landfill temperature above ambient temperature for more than 40 years. In some cases, temperatures up to 80ºC have been measured (Martin et al, 2013). The elevation of temperature from 25ºC to 90ºC in bentonite-sand mixture layer reduces free swelling potential and strain about 20 percent, this causes increasing in compressibility rate and quantities for this layer (Shariatmadari and Saeidijam, 2012).

In Japan, the first sanitary landfill with a geosynthetic liner was constructed in the Nakata landfill in Chiba City in 1977. However, the final regulations requiring the barrier systems for all new sanitary landfills promulgated in October 1998 (Imaizumi et al, 2006). The semi-aerobic landfill is a unique technology that was discovered in Fukuoka, Japan in 1975 (Shimaoka et al, 2000) and it became the compulsory standard for planning new landfills. There has been a dozen of researches on the effective performance of semi-aerobic landfill technology so far including both in lab-scale and full-scale. These advantages are (1) reducing methane emissions, (2) reducing leachate intensity, (3) aerobic biodegradation happens effectively, (4) high landfill temperature which could speeds up the stabilization process, (5) cost-effectiveness.

However, there have been not so many researches about the influence of liner temperature on the service life of the barrier system in semi-aerobic landfills. Therefore, this paper discusses the observed LFG temperature and the temperature of the landfill barrier system within an operating semi-aerobic landfill with the point of view of practical management of landfills.

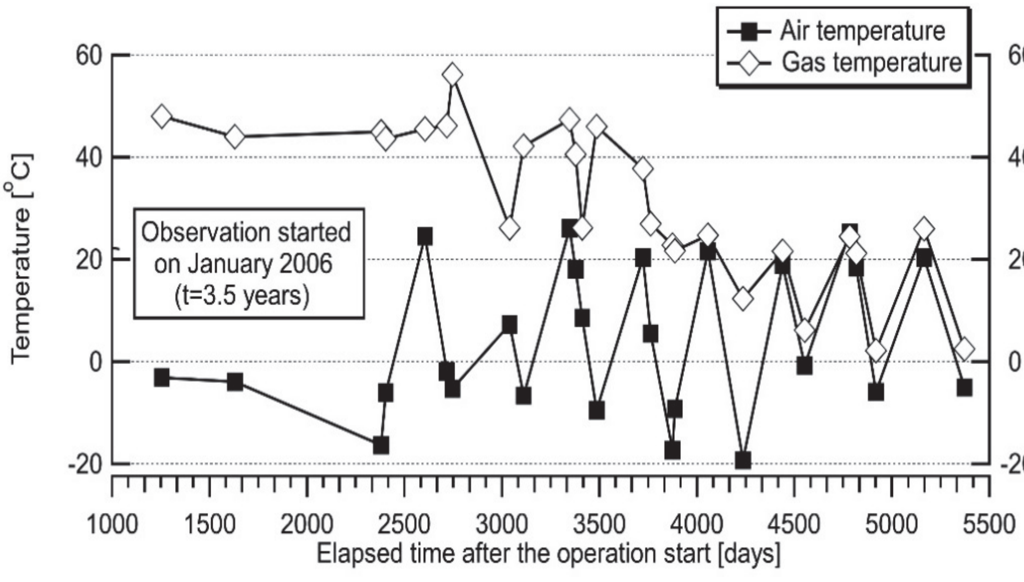



**Figure 28** Air temperature and LFG temperature at the exit of LFGVP M2 over the observation period

*Figure 28* shows the results of air and LFG temperatures at the exit of LFGVP M2 during 2006-2018. The air temperature fluctuated from −20°C in winter to 25°C in summer.

The LFG temperatures rose to over 50ºC (2 years after starting to place the waste) as a result of the biodegradation of wastes in the landfill.

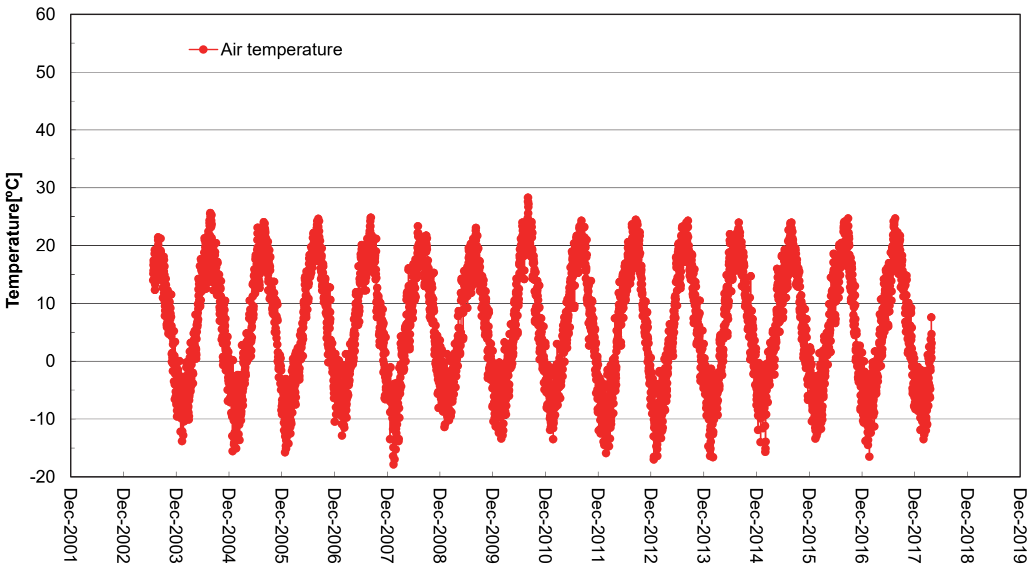



**Figure 29** Variations of average air temperatures

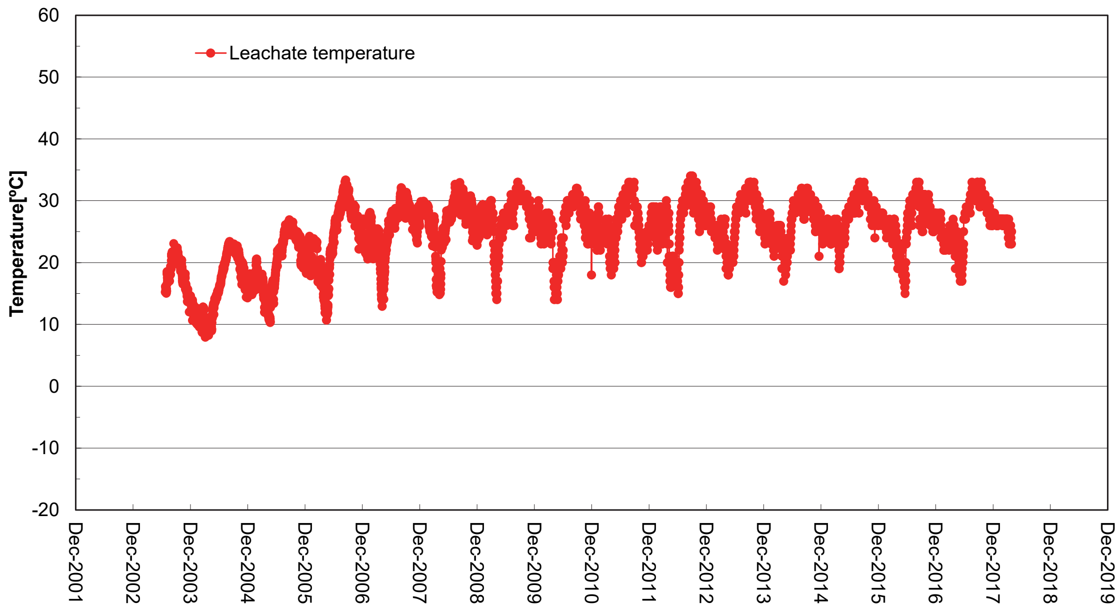



**Figure 30** Variations of average leachate temperatures versus time

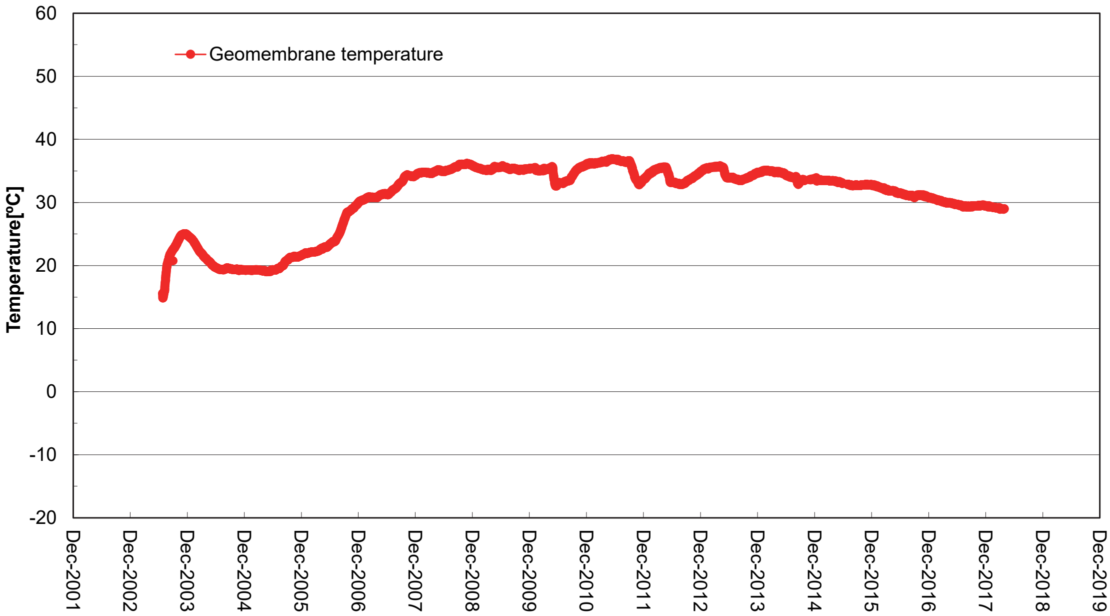



**Figure 31** The average observed geomembrane temperature under the LFGVP M2 with time

The measurement of temperatures (air, leachate, and geomembrane) has been started in early July 2003. That time was summer in the region; therefore the average air temperatures were from 12ºC – 22ºC. After that, the air temperature gradually decreased to less than -15ºC in winter (*Figure 28*). The lowest air temperature was -18ºC in January 2008 and the highest air temperature was 28ºC in August 2010. Although the differences in air temperatures between summer and winter were so large, there were no significant differences in temperature background among years.

*Figure 30* and *Figure 31* show the average temperatures of leachate and geomembrane over the observation period. The average leachate temperatures ranged from 8ºC (March 2004) to 34ºC (the end of August and early September 2012).

In the winters of the observation, the leachate temperatures and the geomembrane temperature still remained over 8ºC and 20ºC, respectively (*Figure 30* and *Figure 31*). During the first 3 months from the beginning of the measurements, the leachate temperature increased from 15ºC to 22ºC and the geomembrane temperature increased from 15ºC to 25ºC. The increase in temperatures could be due to the aerobic decomposition of organic wastes happening in the landfill.

During the first 3 years from July 2003 to June 2006, the leachate temperatures only fluctuated from 10ºC to 25ºC before increasing over 30ºC in August 2006. The leachate temperature often ranged from 20ºC – 25ºC in summers and from 8ºC – 12ºC in winters. It can be seen that the leachate temperatures were affected by the air temperatures.

From 2004, the geomembrane temperature gradually increased to 35ºC and remained stable over 8 years before declining to 30ºC in recent years. Obviously, the geomembrane temperatures varied without any effect by the air temperature. As the unique structure of the semi-aerobic landfill, the elevated temperature in the semi-aerobic landfill is a result of aerobic biodegradation of organic materials caused by the buoyancy effect (Shimaoka et al, 2000). The cause of the elevated temperatures in geomembrane is mainly due to the biodegradation of organic solid waste or the heat of hydration of incinerated bottom ash which is the main factors causing the generation of heat in the landfill [(Yesiller et al, 2015), (Koerner and Koerner, 2006), (Yoshida and Rowe, 2003)].

The aerobic decomposition within this semi-aerobic landfill strongly effected on waste layers and geomembrane. Barrier systems were exposed to high-temperature conditions. Such temperature rise may result in degradation of geomembrane made by plastic and desiccation of clay layer which composed of bentonite clay sheets. Elevated temperatures can reduce service life HDPE geomembranes by accelerating antioxidant depletion of geomembranes and polymer degradation. Rowe (2005) estimated the service life of HDPE geomembrane as exposed to high temperatures.

**Table 2** The service life of HDPE geomembrane based on an estimation of Rowe (2005)

| Temperature (ºC) | Service life (years) |
|---|---|
| 20 | 565 – 900 |
| 30 | 205 – 315 |
| 35 | 130 – 190 |
| 40 | 80 – 120 |
| 50 | 35 – 50 |
| 60 | 15 – 20 |

The temperature range under HDPE geomembrane at the operating semi-aerobic landfill has remained from 30-35ºC. Therefore, according to the estimations of Rowe (2005), the lifetime of the geomembrane is from 130 to 315 years (see Table 2). Recently, the geomembrane temperatures are gradually decreasing year by year because of less landfilling organic wastes for biodegradation. The risk of a high-temperature effect on barrier systems may decrease, however, monitoring temperatures in LFG extraction wells and geomembrane is very important for practical management of an operating semi-aerobic landfill.

The surveyed operating semi-aerobic landfill in Hokkaido shows the elevated temperatures in landfill gas and geomembrane under the LFGVP M2. The LFG temperature increased over 40ºC after 2 years from the beginning of placing the waste. The maximum of LFG temperature was approximately 60ºC. The high-temperature trend of LFG remained over 40ºC in 7 years (2006-2013) as a result of the aerobic biodegradation of organic wastes. The temperature of the geomembrane also rose to 30-35ºC due to the effect of aerobic biodegradation within the landfill. Such temperature rise may result in the risk of degradation of geomembrane made by plastic and desiccation of the clay layer of the barrier system. The lifetime of HDPE geomembrane composed of a bottom barrier system could be reduced significantly as exposed to high temperatures. Monitoring geomembrane temperature or the temperature of the bottom barrier is very important for semi-aerobic landfill management.

## 4.2 Simulation results

This simulation focusing on calculating the pressure distribution, landfill gas concentration and temperature distribution within the landfill body. To verify the quality of the simulation, the calculated results will be compared to the observation results, for example the landfill gas concentration at the exit of the landfill gas venting pipe M2.

### *4.2.1.1. Landfill gas pressure distribution*

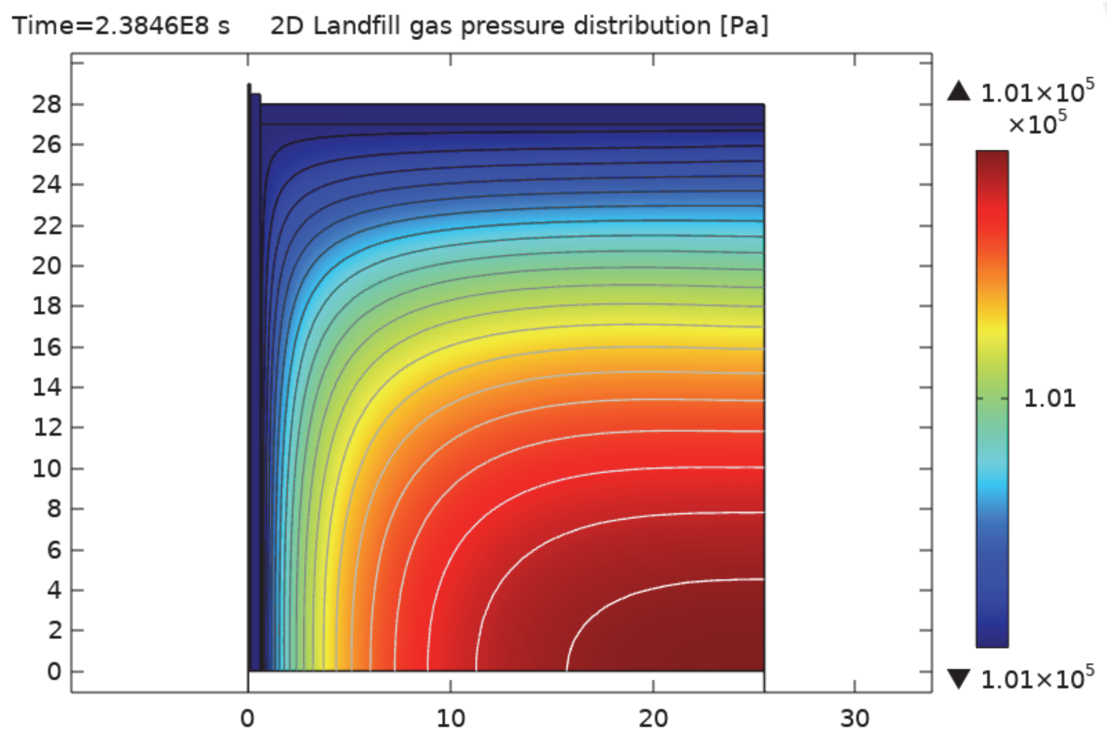



**Figure 32** Simulated landfill gas pressure distribution in August 2014 (t=7 years after starting the operation)

Gases accumulating in a landfill create areas of high pressure. Figure 32 indicated that the high LFG pressure is at the corner of the model, far awar from the surface and the gas well. The LFG pressure near the vertical venting pipe or vertical gravel layer and near the surface is equal to the atmospheric pressure.

*4.2.1.2. Landfill gas temperature distribution 2D*

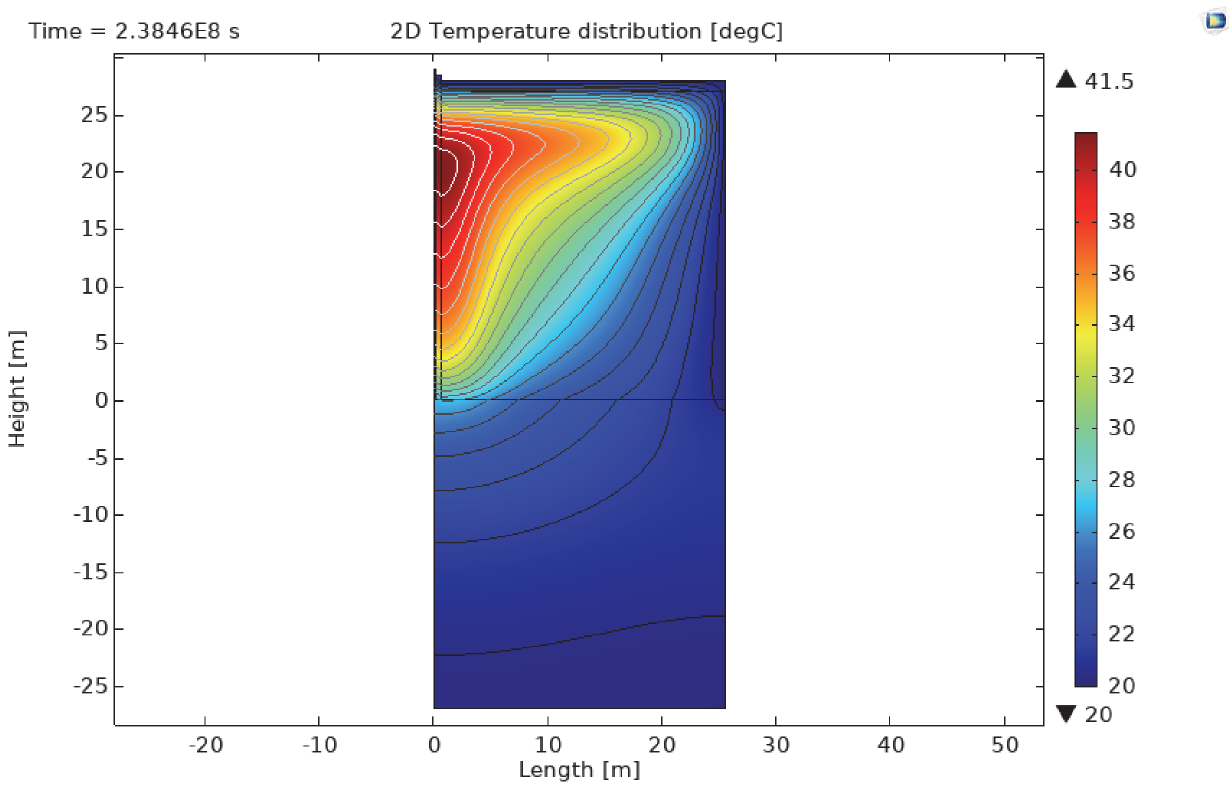



**Figure 33** Simulated temperature distribution in August 2014 (t=7 years after starting the operation)

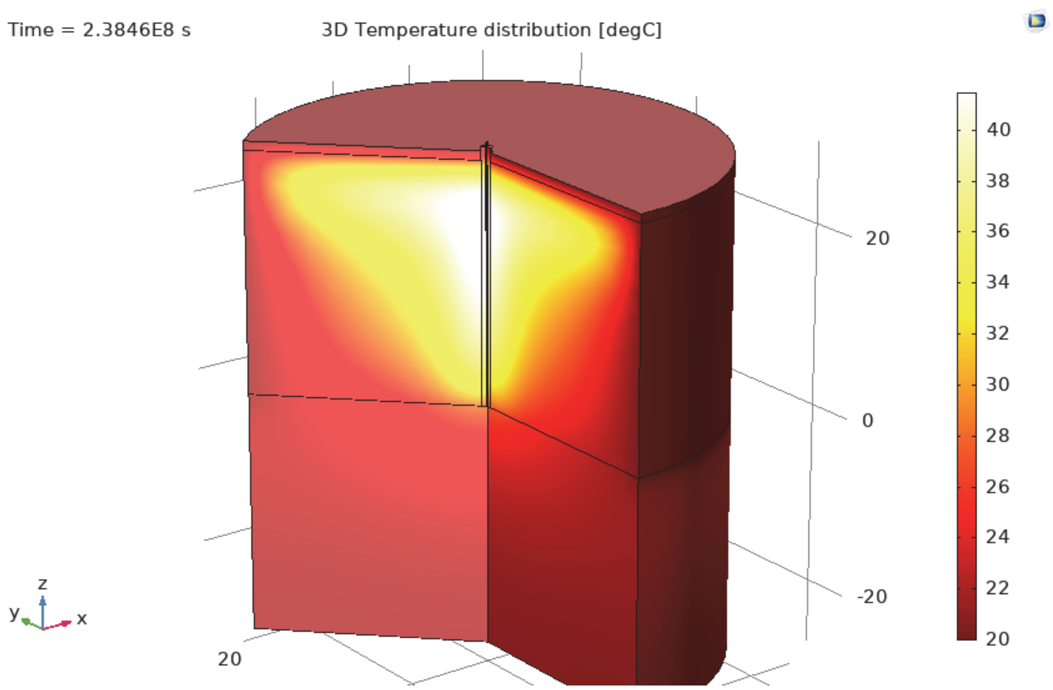



**Figure 34** Simulated landfill gas temperature distribution in 3D in August 2014 (t=7 years after starting the operation)

Figure 33 showed that high temperature area are along the venting pipe, the vertical gravel layer and areas near the surface. The maximum temperature is 41.5ºC. The aerobic biodegradation happen effectively near surrounding the gas venting pipe or the vertical gravel layer. Clearly, the imigration of oxygen concentration is the main driven promoting the aerobic bacteria activities.

#### *4.2.1.3. Gas concentration at the exit*

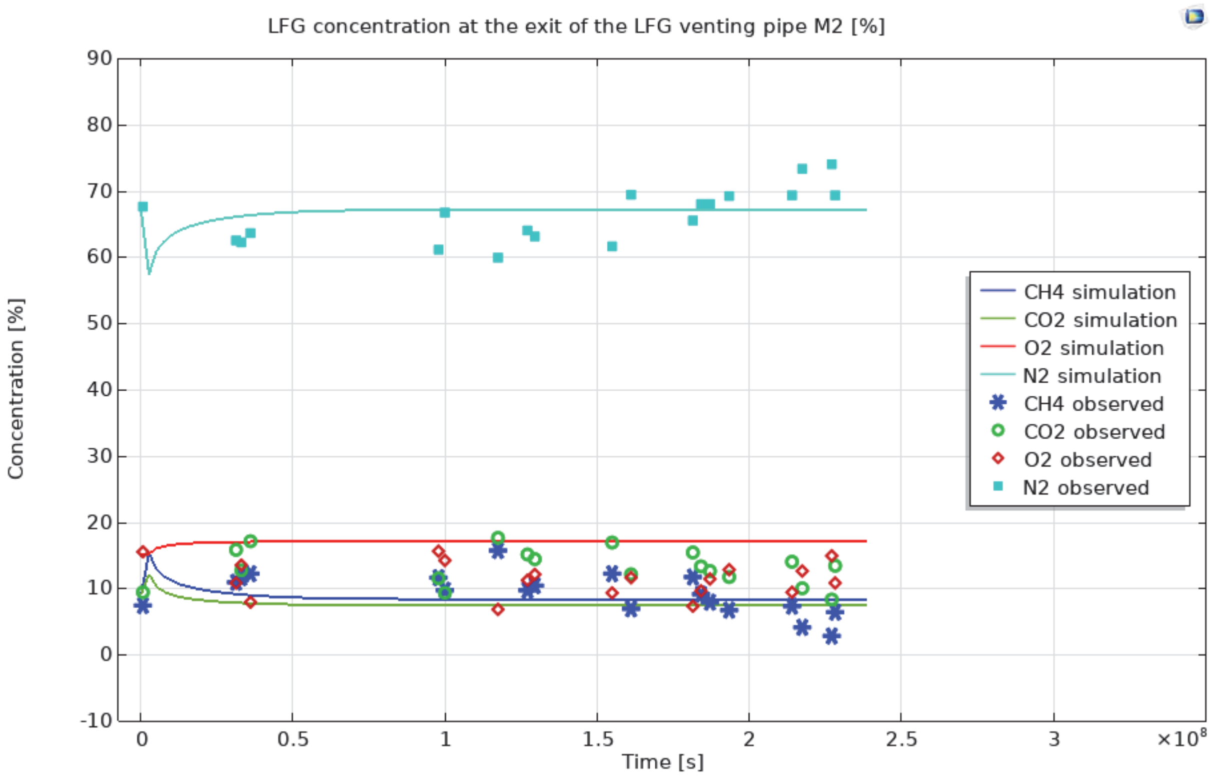
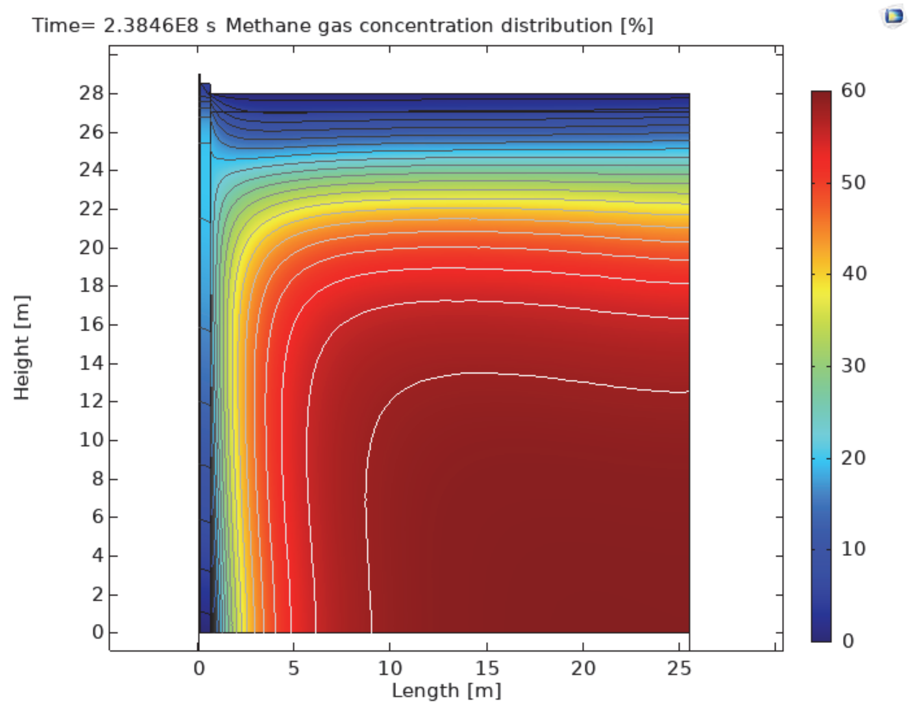
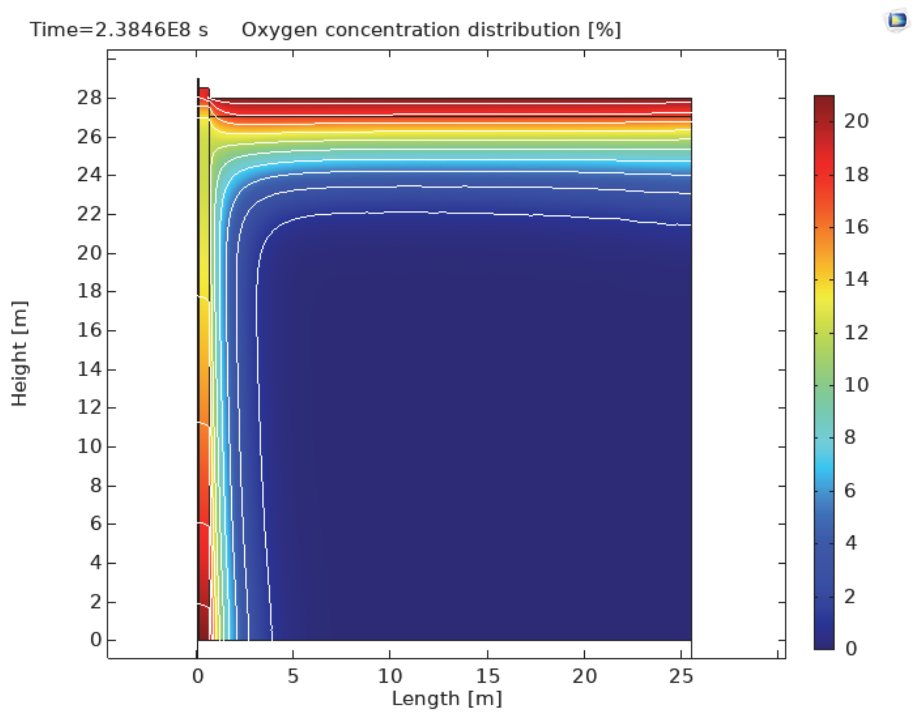


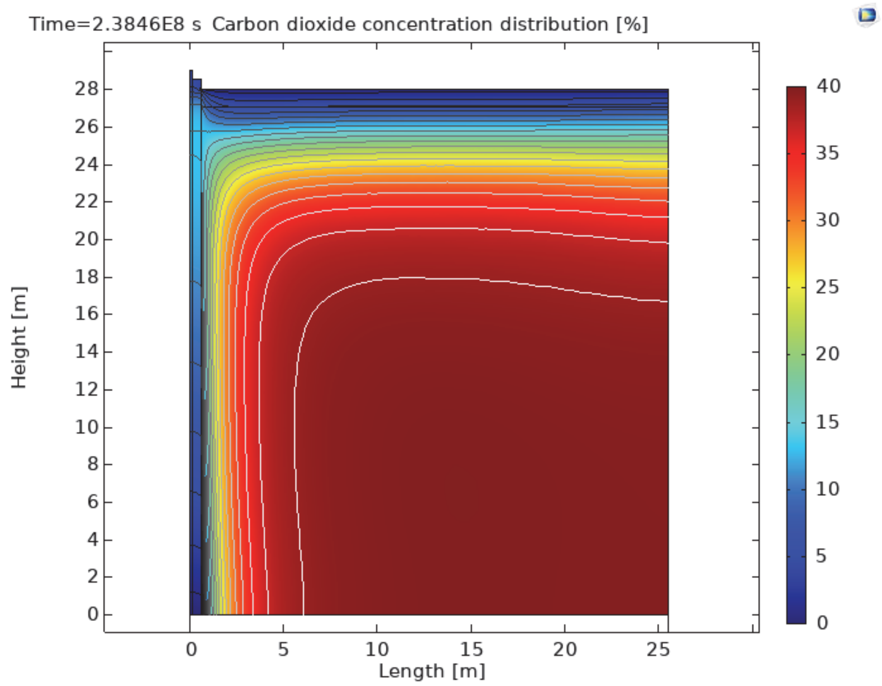

**Figure 35** Comparing the simulated LFG concentration and the observed LFG concentration at the exit of the LFG venting pipe M2 (from 2006 to August 2014)

The calculated methane gas and carbon dioxide concentration are less than 10%. The calculated methane gas looks fit with observed data.

*4.2.1.4. The distribution of gas component around the LFG venting pipe*





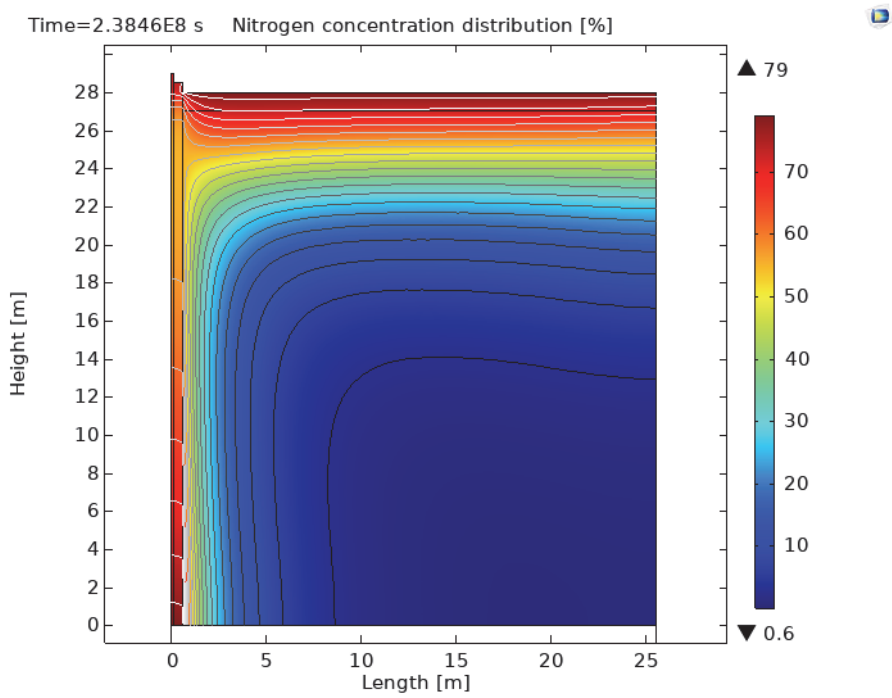




**Figure 36** The distribution of gas component (a) $CH_4$ concentration, (b) $O_2$ concentration, (c) $CO_2$ concentration, (d) $N_2$ concentration in in August 2014 (t=7 years after starting the operation)

High oxygen concentration only distributes along the venting pipe, the vertical gravel and near the surface. Other areas far away from the gravel layer, the oxygen concentration is 0. It means that the aerobisation only happens in the limited areas.

Methane gas and carbon dioxide concentration still maintain more than 30% from about 3-meters far from the vertical gravel layer and from 5-meters far from the surface. It can be concluded that anaerobic condition is dominant.

From these above results, the usage of numerical simulation to predict the behaviors of landfill such as LFG temperature and LFG concentration is applicable. This helps operators and designers be able to calculate the appropriate distance between the LFG venting pipes to improve the stabilization of the landfill, for example, in landfill aeration projects.

# CHAPTER 5: CONCLUSION

The dissertation attempted to survey the elevated temperature and gas components inside an operating semi-aerobic landfill during 6 years from 2010 until 2018. Based on this work it is concluded that:

- High landfill temperature can be observed in the landfill. The maximum temperature is over 60°C.
- Aerobic biodegradation happens effectively in semi-aerobic landfill.
- The temperature increase of one LFG extraction well will affect on the other if the distance between 2 well is not so large.
- Clogging phenomenon causes the high increase in methane concentration.
- If clogging happens in many wells, a semi-aerobic landfill will be changed into anaerobic landfill.
- Need to prevent the clogging phenomena.

In addition, a basic simulation was implemented in order to model the movement of LFG flow from waste layers through gravel layer, venting pipe discharging into atmosphere, the heat transport and the mass transfer within the landfill body.

- Simulation results showed the distribution of LFG pressure, the temperature distribution, and the gas concentration at the exit of the gas venting pipe M2.
- The simulated gas concentration looks fit with the observation gas concentration at the exit of the gas venting pipe M2.
- Gas well contributes to aerobisation from the top to the bottom surrounding the vertical gas well.
- The visualized maximum temperature is 41.5˚C. The aerobic biodegradation happen effectively near surrounding the gas venting pipe.

  Numerical simulation can helps us predict (1) the biodegradation process happening within the landfill which cannot be seen in reality; (2) the influence of factors on the stabilization of the landfill. This will help improve the design goals.

In the near future, the author will try to make a simulation of temperature distribution and movement and transport of concentration of gas component within a landfill. In the simulation, we will consider the effects of surrounding environmental conditions, oxygen consumption, and water vapour transport on the heat generation and gas transport and how to accelerate the high temperature inside a landfill. Further research will consider the effects of temperature on the material of liner at the bottom of an operating semi-aerobic landfill.

---------------------------------------------------*The end* ------------------------------------------------