Numerical Examination of a Method for Reducing the Temperature of Municipal Solid Waste Landfill Liners

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Abstract: A method to control the increase in landfill liner temperature due to the heat generated by the waste is examined. The design involves installation of an array of cooling pipes beneath the waste. The feasibility of this system for cooling the liner was examined by performing a series of analyses for conditions based on the Tokyo Port Landfill. The results suggest that the introduction of a cooling system can substantially reduce liner temperature and consequently significantly increase the service life of a high-density polyethylene (HDPE) geomembrane liner in an engineered barrier system. The effects of pipe layout, pipe spacing, and coolant flow rate are examined. It is shown that a periodic pipe layout is the most efficient. Liner temperature decreases with increased coolant transfer flow rate

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Introduction

Since the advent of modern regulations, municipal solid waste (MSW) landfill facilities are typically required to have a barrier system that will prevent all but a nominal escape of contaminants to groundwater and surface water for the contaminating lifespan of landfill (expected to be hundreds of years for large modern landfills; Rowe et al. 2004). To provide long-term protection it is necessary to minimize factors that increase leakage through composite liners (Rowe 2005; El-Zein and Rowe 2008; Saidi et al. 2008; Bouazza et al. 2008; Katsumi et al. 2008; Guyonnet et al. 2009; Gassner 2009; Du et al. 2009) and the factors reducing service life of the landfill barrier system such as wrinkles and tensile strains in the geomembrane liner (e.g., Take et al. 2007; Thusyanthan et al. 2007; Brachman and Gudina 2008a,b; Fowmes et al. 2008). The liner temperature is another important factor that affects long-term performance of liner components.

Landfill monitoring has shown that the heat generated by MSW, or from heat of hydration of MSW incinerator ash, can significantly increase the temperature on the underlying landfill liner(s). Liner temperatures of 30–40°C can be expected and in some cases temperatures of up to 60°C have been reported in the literature (Klein et al. 2001; Yoshida and Rowe 2003; Rowe et al. 2004; Rowe 2005; Koerner and Koerner 2006; Koerner et al. 2008; also see Rowe and Hoor 2009 for a comparison of liner time-temperature histories observed in different landfills). The writers are aware that even higher temperatures have occurred at the base of some landfills (at least up to 70°C for MSW and even higher for ash monofills) but these data have yet to be published in the open literature.

Elevated temperatures reduce the service life of geomembranes and potentially that of the clay component of barrier systems (Rowe 2005). Both primary and secondary liners may be affected by elevated temperature (Southen and Rowe 2004; Rowe 2005; Southen and Rowe 2005a,b; Rowe et al. 2008, 2009; Rowe and Hoor 2009). In situations where the service life is not adequate, the barrier system needs to be revised or the liner temperature reduced.

This paper, which is built on earlier work by Rowe et al. (2007) and Hoor et al. (2008), presents one possible method to control the temperature at the base of the landfill. The design involves installation of an array of cooling pipes beneath the waste. The potential effectiveness of the proposed method is examined numerically. First, the model was calibrated for the case with no cooling system against temperature data from the Tokyo Port Landfill. Then the feasibility of controlling liner temperature using the proposed method was examined by hypothetically inserting a heat extraction system into the Tokyo Port landfill at the time of construction under the assumption that all other aspects of waste disposal at the landfill remain the same.

Design Concept

The concept involves a closed system to cool the liner by means of a series of horizontal pipes buried at the base of the landfill. Coolant circulated through the pipes absorbs heat from the surroundings and reduces the temperature of the landfill liner. The heated coolant is pumped to facilities outside the landfill where the thermal energy is recovered for on-site use and the coolant temperature reduced before recirculation back into the landfill. The pipes are installed at the time of barrier system construction. This cooling system would be activated once the temperatures on

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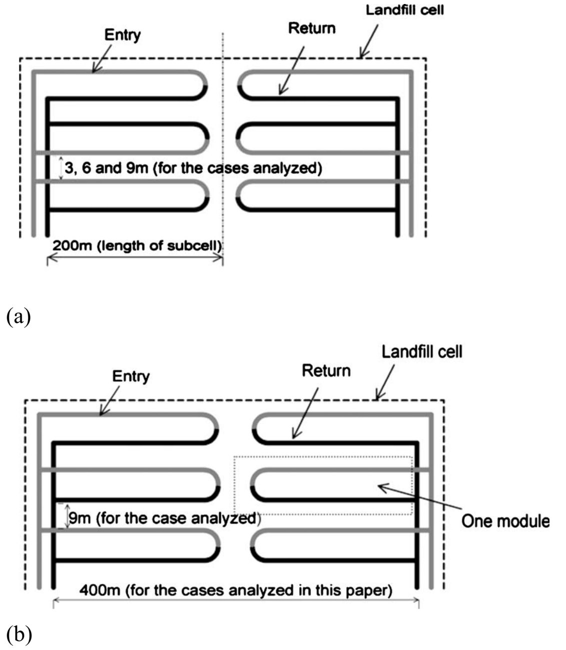

Fig. 1. Schematic layout of cooling pipes (plan view, gray represent "cold" and black represents "warm or hot" coolant): (a) symmetric pipe layout; (b) periodic pipe layout (modified from Hoor et al. 2008)

the liner were found to approach a threshold level (i.e., a temperature approaching that which could adversely affect the long-term performance of the liner). Once activated, it would be run continuously to control the liner temperature to a predetermined acceptable level.

Fig. 1 provides a schematic of two possible alternative patterns for the cooling system. Initially consideration was given to a symmetric pipe arrangement [Fig. 1(a)]. However, as will be discussed later, the results showed that to maintain low temperatures with a reasonable pipe spacing, a more efficient pipe arrangement was required, and therefore, the study was extended to consider a periodic pipe distribution where the entry and return pipes alternate as shown in Fig. 1(b).

Cooling pipes could be installed in the leachate collection system (LCS) or in a sand blanket either above or below LCS. Each design option has advantages and disadvantages. By placing the pipes in sand there is a greater potential to obtain good contact with the cooling pipes (which reduces resistance to heat transfer between the pipe wall and soil) than would be possible in a gravel LCS. Furthermore, due to matric suction and biologically induced clogging (Rowe et al. 2004; Rowe 2005; McIsaac and Rowe 2006; Cooke and Rowe 2008), sand will have a much higher moisture content than gravel, and this will result in higher thermal conductivity than if the pipes are placed in free draining gravel drainage layer.

There are also advantages and disadvantages to placing the sand layer above or below the gravel drainage layer. If placed below the drainage layer, the sand layer will also provide excellent protection of the geomembrane from physical damage (Brachman and Gudina 2008a,b) and will reduce the outward diffusion of antioxidants, which thereby will extend the service life of the geomembrane liner (Rowe and Rimal 2008a; Rimal and Rowe 2009). However, this approach will also potentially increase the leachate head on the liner and may lead to a less effective distribution of cooling. Placing the sand above the gravel eliminates these two problems and may reduce the potential for clogging of the gravel layer (McIsaac and Rowe 2006).

Placing the pipes in the gravel reduces the cost of the installation but as mentioned above, causes some reduced thermal efficiency compared to having them in a sand layer above the LCS. This paper will mainly focus on pipes installed in a sand layer. The effect of installing the pipes in the different locations noted above on the temperature distribution at the top of the liner will also be examined for one case.

Water is selected as the coolant due to its availability, low cost, and low potential risk in the case of leaks. The cooling pipes were assumed to be made of HDPE which is a well-established material in landfill applications both for geomembrane liners and leachate collection pipes and its long-term behavior in a landfill environment is reasonably well-known. Also, HDPE pipes can be installed at reasonable cost (compared to the stainless steel pipes examined by Rowe et al. 2007). However, in spite of a number of advantages, the thermal conductivity of HDPE is relatively low compared to alternative materials such as stainless steel, and therefore, the use of HDPE potentially could reduce the efficiency of heat transfer between coolant and liner compared to the use of stainless steel. To evaluate the effect of pipe material, analyses were performed for the case with HDPE pipes versus the case where the pipe wall was perfectly conductive (or not present). It was found that since the pipe wall is relatively thin compared to the dimensions of the barrier and piping system, the thermal properties of the pipe had negligible effect on heat transfer. The following sections will provide more details on the numerical model and the case studied.

Case Studied

To ensure that the heat generation aspects of the model accorded well with conditions expected in real landfills, the numerical model was calibrated for the case with no cooling system using data for the Tokyo Port Landfill. This landfill was selected because there are considerable data for the temperature at the base of the landfill. In this case there was ample moisture to encourage rapid biodegradation of the readily degradable organic matter with the consequent generation of temperatures in excess of 40°C at the top of the natural clay liner at the bottom of the landfill (Yoshida et al. 1997). The Tokyo Port Landfill accepted 30 m of MSW in 3 years (1976 to 1979). The facility had no LCS and as a consequence a significant leachate mound formed during landfilling and remained after closure (Yoshida and Rowe 2003).

Thermal Behavior of Tokyo Port Landfill

The temperature in the Tokyo Port Landfill was monitored for many years after 1983 (there is no relevant temperature data for the early years). The data recorded since 1983 shows that the temperature in the landfill reached a peak value of more than 60°C in 1985 (Yoshida et al. 1997). Similarly, the temperature at the base of landfill increased to about 45–50°C (Yoshida and Rowe 2003). Subsequently, the temperature at the base of the landfill had reduced to 37–41°C after 20 years.

The heat generated by a landfill depends on waste management practice, the nature of the waste, and the availability of moisture to encourage biodegradation of the waste. For instance, an increased rate of landfilling correlates with an increased rate of temperature rise (Brune et al. 1991). In addition, the ready availability of moisture can accelerate the rate of temperature increase in the landfill (Rowe 2005). The reported data suggests that quick landfilling (around 10 m/year) and the generation of a significant leachate mound were responsible for the observed rapid increase of temperature in the Tokyo Port Landfill. These factors combined with the temperature data led to a heat generation model for the Tokyo Port Landfill that will be discussed in the following section.

Numerical Modeling

The finite volume-based computational fluid dynamics code FLUENT was used to (1) model the original Tokyo Port Landfill and (2) numerically assess the performance of a cooling system which was assumed to have been introduced at the time of landfill construction. The initial analyses used a two-dimensional (2D) model. The model then was extended to three-dimensions (3Ds).

The configuration of the model initially examined is shown in Fig. 1(a). Due to the symmetric distribution of pipes, it was only necessary to model one loop of pipes (i.e., one inlet and one outlet) with a zero heat flux boundary condition at the side boundaries midway between similar pipe loops. The width of the section modeled was twice the pipe spacing.

Subsequent analyses were performed for a periodic distribution of pipes as shown in Fig. 1(b). Given the periodicity, conceptually the case could be represented by one loop of pipes with periodic boundary conditions applied at the side boundaries. However, the computer code does not enable the application of periodic boundary conditions coupled with a heat source and fixed-temperature boundaries that were necessary to model other aspects of the problem. Thus, an alternative approach, which involved modeling a sufficient number of pipe loops so that the middle loop represents periodic conditions, was adopted. The number of modules was varied as will be discussed later.

The effect of pipe location was examined by modeling four different cases in 2D (Fig. 2). In Case 1 (the base case adopted for the rest of paper) the pipes were located in a 1-m-thick sand layer with the pipe invert located 30 cm above the top of liner. Case 2 represents pipes in a 0.5-m sand layer with the pipe invert 15 cm above the top of liner. Case 3 is similar to Case 2 but has a 50 cm gravel LCS underlying the sand. Case 4 was geometrically similar to Case 2 but in this case the pipes were located in an unsaturated gravel LCS. Due to matric suction, the sand was assumed to retain significant amounts of leachate, and have a high degree of saturation from the onset of analysis.

The temperature on the exposed surface of the landfill and deep in soil as well as the coolant temperature were set to 15°C (the annual average temperature in Tokyo). The modeling did not take into account the seasonal variation of incoming waste temperature and, hence, simplifies the real situation. As indicated by Hanson et al. (2006) waste temperature at the time of placement affects heat generation in a landfill and specially landfill temperature near the surface. However, away from the surface (the area of primary interest in this paper) the temperature of the waste is not significantly affected by the seasonal variation in temperature. The thickness of waste in the landfill at closure was 30 m. The distance to the lower boundary beneath the top of the liner was specified to be sufficiently deep so as not to significantly affect the results (30 m from the bottom of landfill). The heat transfer between pipes and soil was assumed to be 100% efficient, which implies that the pipes were in perfect contact with soil. When the cooling pipes are buried in a layer of sand, this assumption is reasonable. Pipes were assumed to be made of HDPE with an average inside diameter of 20 cm. Parametric studies showed that heat extraction increased with increasing the pipe diameter. However, the improvement in extraction efficiency was insignificant compared to the effect of other design features examined herein. Hence, the effect of pipe diameter is not examined in this paper.

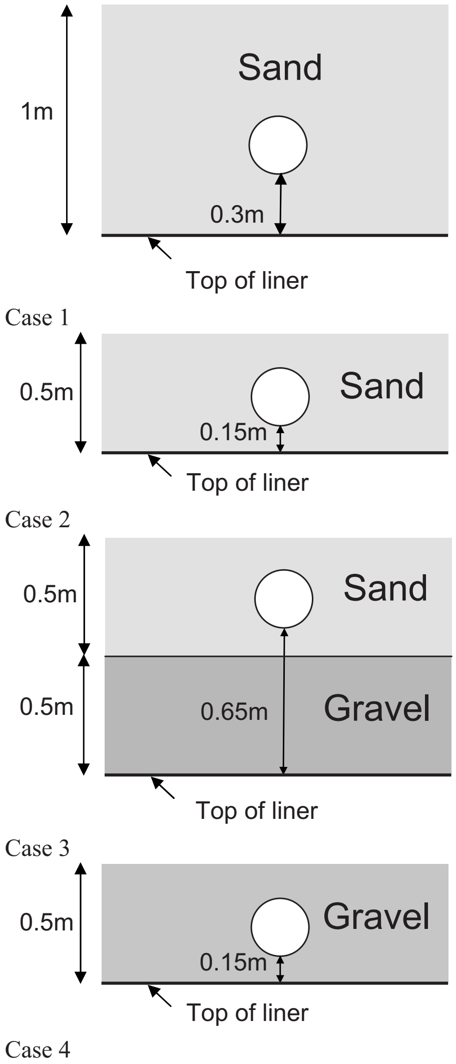

Fig. 2. Location of cooling pipes (cases studied in 2D for symmetric pipe layout)

The landfill was modeled through a series of steps to simulate landfilling and the postclosure stages so as to give a temperature trend similar to that observed in the Tokyo Port Landfill as described earlier. These steps are summarized in Table 1. The effect of the development of a leachate mound over time was considered. Waste placement was modeled in 30 months (similar to the actual case) through five steps. During waste placement, it was assumed that each fresh cell was exposed to air with the upper 1-m waste in the aerobic decomposition stage. The underlying waste was assumed to be in the anaerobic decomposition phase. Step six was the closure step, where the landfill was covered and the entire waste mass underwent anaerobic decomposition. For the cases with a cooling system, the cooling system was activated subsequent to landfill closure and, once initiated, ran continuously. If the cooling system was implemented at a real landfill, it would be activated once the temperature on the liner approaches a predetermined level which might affect long-term performance of liner components. In such a case, constant monitoring of liner temperature is recommended. Temperature monitoring could also

Table 1. Steps Used to Simulate Landfilling and the Postclosure Response

Step	MSW height (m)	Leachate mound (m)	Degradation	Time (from the start of landfilling)
1 Landfilling	6	0	Anaerobic (An):5 m, Aerobic (A):1 m	6 months
2 Landfilling	12	1	An:11 m, A:1 m	12 months
3 Landfilling	18	2	An:18 m, A:1 m	18 months
4 Landfilling	24	3	An:23 m, A:1 m	24 months
5 Landfilling	30	4	An:29m, A:1 m	30 months
6 Closure	30	5	An:30 m	32 months
7 Postclosure	30	6	An:30 m	3 years
8 Postclosure	30	12	An:30 m	5 years
9 Postclosure	30	18	An:30 m	8 years

Note: A=zone in aerobic degradation stage and An=zone in anaerobic degradation stage.

be used to adjust the pumping rate so as to maintain the required cooling. Postclosure, the landfill was in a fully anaerobic stage for almost 8 years after the start of landfilling prior to the temperature reaching the peak observed value. Peak liner temperatures were compared for the cases with and without cooling pipes in an effort to assess the likely effect of the proposed cooling system on liner temperature.

The properties adopted for MSW, sand, LCS gravel, and the underlying foundation soil (estimated based on Yoshida et al. 1997, Yoshida and Rowe 2003, and Rowe and Hoor 2009), and the heat generation rates are summarized in Table 2. The thermal properties were assumed to be constant and do not vary with temperature. The heat generation rates were obtained by fitting the "base case" prediction (case with no cooling system) to the measured temperature profile. Different heat generation rates were adopted for the saturated waste, unsaturated waste, and the waste exposed to air. The heat generation rates estimated in this study are within the range of values reported in the literature (Rees 1980; Yoshida and Rowe 2003; Yeşiller et al. 2005).

The study assumed annual average thermal conditions for ambient and coolant temperatures. A detailed examination of the effect of seasonal variations of temperature on the performance of system would be required if the system was being considered for implementation at a particular location.

2D Model

2D analyses were conducted to study the influence of pipe spacing on temperature as well as to determine the number of modules required to simulate periodic conditions. The analysis was performed using quadrilateral elements with an element size of 0.1 m (36,000 elements for one module with 3-m pipe spacing, 72,000 elements for 6-m pipe spacing and 108,000 elements for 9-m pipe spacing). The cross section modeled represented the cross section at the end of the cell where the pipes enter and leave the landfill since temperatures will generally be lower at other cross sections. The inlet temperature was fixed at 15°C, and the outlet temperature was allowed to be equal to that of the surrounding soil (i.e., the pipes did not provide any cooling at this location). This assumption corresponds to a flow rate in the pipes, where the fluid would reach the temperature of the soil at the point of exit from the landfill, and while it maximized the amount of heat that can be extracted per unit volume of the coolant, it also limits control on temperature. The flow rate cannot be calculated from the 2D model; in order to capture the effect of heat transfer with the flow of fluid in the entire pipe system, a 3D analysis is required as discussed below.

3D Model

The 3D analysis was performed to capture the effect of heat transfer with the flow of fluid along the pipes and to examine the influence of coolant mass flow rate. The landfill cell considered was 400 m long and was divided into two 200 m subcells (Fig. 1). A 200-m-long subcell was modeled for both symmetric and periodic pipe arrangements.

For a symmetric pipe arrangement [Fig. 1(a)], the width of the block analyzed was twice the pipe spacing. For a symmetric pipe arrangement with a 3-m pipe spacing, the analysis was conducted using 1,680,720 hexahedral elements.

For a periodic pipe arrangement [Fig. 1(b)], the inlet and outlet points were 9 m apart. Two loops of pipes were modeled since trial 2D analyses showed that two modules would be sufficient to simulate conditions reasonably close to periodic. The width of the model was four times the pipe spacing (36 m). The analysis was conducted using 8,528,760 hexahedral elements.

For both cases, the inlet temperature was set at 15°C. The outlet temperature was established by the heat uptake and flow rate in the pipe. A sensitivity analysis was performed to define the acceptable mesh refinement. The adopted element size (height and width) ranged from 0.1 m in the pipes and the soil around the pipes to 0.25 m in waste and to 1 m in the subsoil. The length of the elements varied between 0.1 m in the area close to the end of

Table 2. MSW and Soil Properties Adopted

Layer	Layer thickness (m)	Thermal conductivity (W/m°C)	Specific heat (J/kg°C)	Heat generation rate (W/m^3)
MSW—exposed to air	0 to 1	0.35	1,940	4.67
MSW—above leachate level	5 to 26	0.35	1,940	0.436
MSW—below leachate level	0 to 18	0.96	2,360	0.763
Sand	0 to 1	3.15	1,390	—
Gravel	0 to 1	1	910	—
Foundation soil	30	0.86	1,110	—

Table 3. Calculated Temperature on Top of Liner

2D or 3D	Pipe arrangement	Mass flow rate (kg/s)	Pipe spacing (m)	Liner temperature (°C)
2D	Symmetric	—	3	21.9 to 31.3
2D	Symmetric	—	6	23.7 to 39.2
2D	Symmetric	—	9	23.8 to 40.2
3D	Symmetric	0.3	3	19.7 to 24.6
3D	Symmetric	0.4	3	18.4 to 21.7
3D	Periodic	0.3	9	23.6 to 34.7
3D	Periodic	0.4	9	22.8 to 34.4

the cell, where the entry and return pipes are connected to 2 m in the zone where the pipes enter and leave the landfill cell.

Results

Table 3 summarizes the predicted liner temperatures for symmetric and periodic pipe arrangements. A discussion of the results is presented below.

Symmetric Pipe Arrangement

2D Results

The temperature profile in the landfill 8 years after the start of landfilling for the cases without and with a cooling system is provided in Fig. 3. The calculated and measured temperature profiles without a cooling system are compared in Fig. 3 and can be seen to be quite similar. For the case with cooling system, the entry and return pipes initially were assumed to be 3 m apart. The introduction of this cooling system reduced liner temperature by 10.6 to 20°C (from 41.9 to 21.9–31.3°C). For a landfill with a composite liner, this would result in a significant increase in service life of the engineered liner (Rowe 2005). As illustrated in Fig. 4, the temperature on top of the liner ranged between 21.9°C directly below the inlet pipe and 31.3°C between the outlet pipes.

The effect of pipe location was examined by modeling four different cases with a symmetric pipe arrangement. The calculated temperature distribution on top of the liner is shown in Fig. 5 for all four cases. The results obtained for the pipes installed in 0.5-m-thick sand protection layer and 0.5-m gravel LCS with the pipe invert both 0.15 m above the liner (Fig. 2–Cases 2 and 4) were very similar. The temperature below the inlet pipe was lower and the temperature between the outlet pipes was higher than for the other cases examined. The case with the pipes in a sand layer above the gravel LCS (Fig. 2—Case 3) gave the most uniform temperature distribution on the liner and the lowest maximum temperature because the gravel acts as thermal insulation between waste and liner, and hence, the lower thermal conductivity of the gravel both reduces heat transfer to the liner while encouraging a more even distribution of heat in the more thermally conductive sand layer above the gravel. The lowest maximum temperature would correspond to the longest service life (other things being equal) for a geomembrane liner (Rowe 2005).

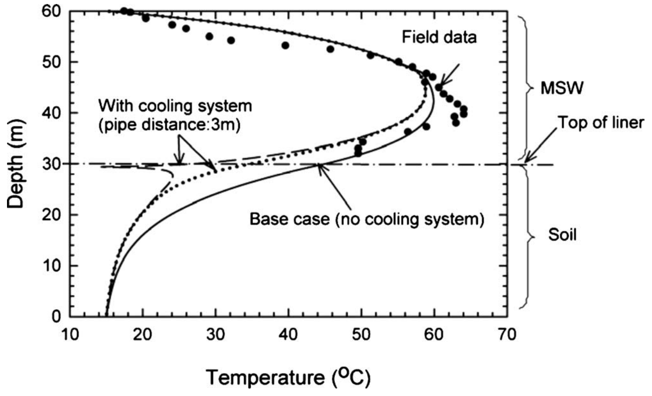

Fig. 3. Temperature profile for 2D analysis (symmetric pipe layout-pipe spacing: 3 m—the dotted and the dashed lines show the minimum and the maximum temperature predicted after the introduction of cooling system) (modified from Hoor et al. 2008)

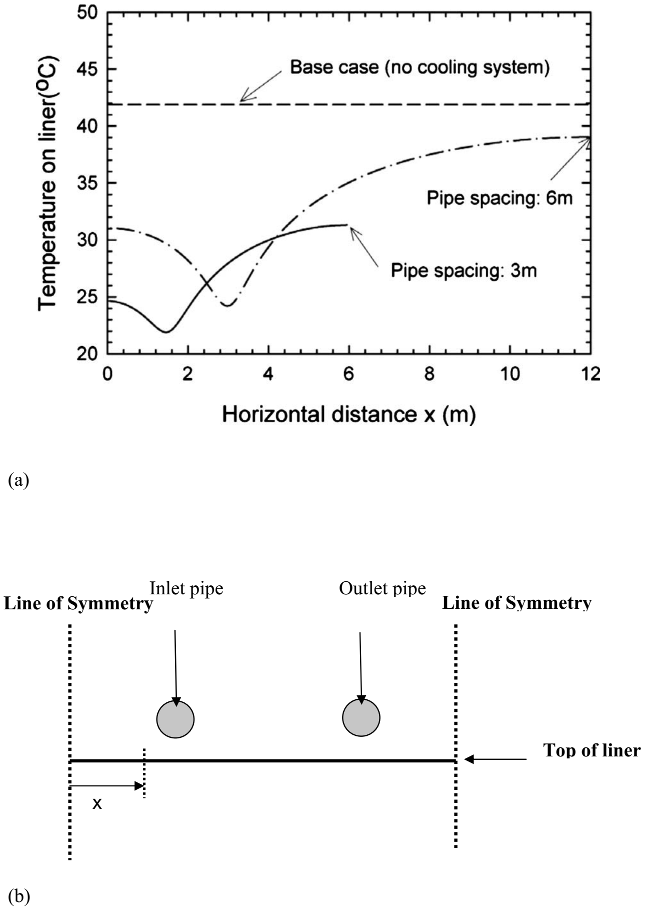

Fig. 4. Symmetric pipe layout: (a) temperature distribution on liner based on 2D analysis with no cooling at the exit; (b) schematic showing position of pipes and defining horizontal distance (*x*) (modified from Hoor et al. 2008)

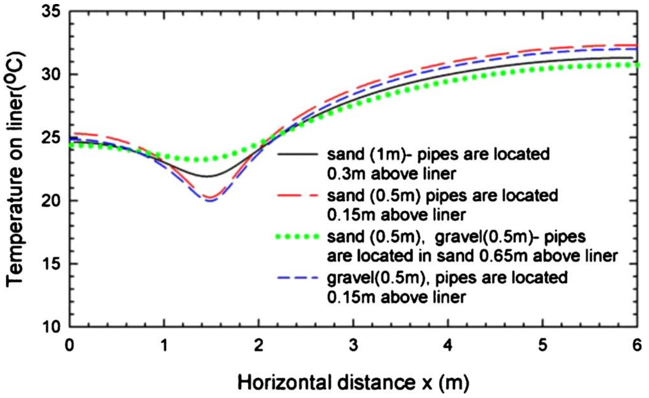

Fig. 5. Symmetric pipe layout: the effect of pipe location on temperature distribution on top of natural liner-2D results for a pipe spacing of 3 m

The pipe spacing is an important factor influencing the efficacy of the proposed system. Also, given that it highly affects the cost of installation, it needs to be as great as possible (ideally within the range of pipe spacing typically chosen for LCS). To illustrate the effect of pipe spacing, the cooling system was examined using a pipe spacing of 3 and 6 m. As shown in Fig. 4, for the 6-m spacing, the analysis gave minimum and maximum temperatures of 23.7°C (below the inlet pipe) and 39.2°C (midway between outlet pipes). Thus, while the temperature below the inlet pipes was reasonably low, in the area between the outlet pipes the cooling system had little effect on reducing temperature and the maximum liner temperature of 39°C was substantially higher than the 31.3°C obtained midway between outlet pipes for a 3-m pipe spacing. A more efficient pipe arrangement [such as the case shown in Fig. 1(a)] or a higher coolant flow rate, which would lower the temperature at the outlet pipe, may be expected to result in lower temperatures on the liner. To explore the effect of coolant flow rate, it is necessary to perform a 3D analysis. As will be demonstrated by the 3D model, an increase in coolant flow rate above the level corresponding to that examined in the 2D model will result in lower liner temperatures for a given pipe spacing, and hence, can be expected to allow control of temperature at a greater pipe spacing than implied by the 2D analysis.

3D Results

A three-dimensional analysis was performed to evaluate the impact of heat convection along the pipe. Fig. 6 shows a contour plot of temperature at the top of the liner for the pipe spacing of 3 m. Minimum and maximum temperatures were encountered around the inlet pipe and between two adjacent outlet pipes, respectively. This is consistent with the 2D results. The temperatures obtained from the 3D model were lower than the temperatures obtained with the 2D model. For example, for mass flow rate of 0.3 kg/s (the case shown in Fig. 6), the liner temperature from the 3D model ranged between 19.7 and 24.6°C, while in the 2D model the temperature varied between 21.9 and 31.3°C. This is mainly due to the inclusion of heat transfer with the flow of fluid along the pipe in the 3D model that could not be captured in the 2D analysis. In addition, in the 2D model, the outlet pipe did not provide any cooling since the outlet temperature was allowed to be equal to that of the surrounding soil. This limitation was addressed in the 3D model as the outlet temperature was established by the heat uptake and water flow in the pipe.

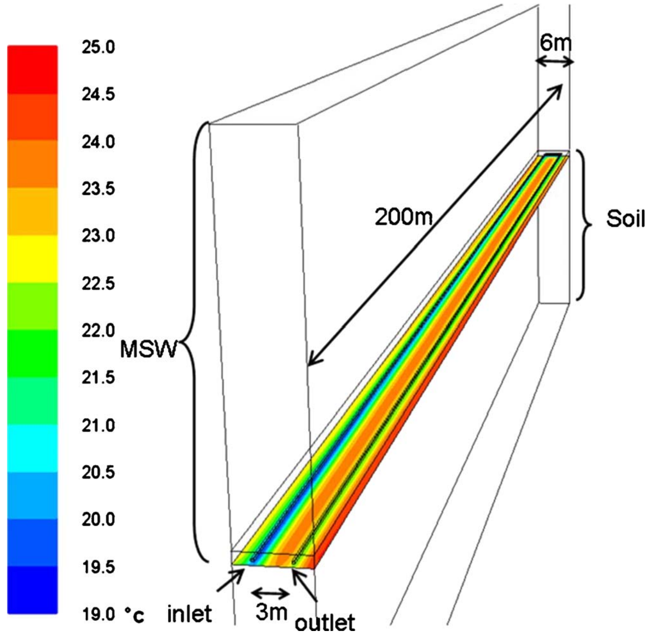

Fig. 6. Symmetric pipe layout: temperature distribution on top of natural liner for a pipe spacing of 3 m and a coolant mass transfer rate of 0.3 kg/s (modified from Hoor et al. 2008)

To illustrate the effect of coolant mass transfer rate, analyses were performed for different mass transfer rates ranging from 0.05 to 0.4 kg/s. As demonstrated in Fig. 7, the higher the mass flow rate, the lower the liner temperature over the range of flow rates examined. However, increasing mass flow rate results in lower outlet temperature, and therefore, the energy extracted is of lower "quality." In this study the upper mass flow rate was limited to 0.4 kg/s (corresponding to Reynolds's number of 2,000) so as to maintain laminar flow in the piping system. For the highest mass flow rate (0.4 kg/s), the liner temperature ranged from 18.4°C directly below the inlet pipe to a maximum of 21.7°C midway between the outlet pipes. These temperatures are substantially below the 41.9°C obtained in the absence of cooling system. Also a comparison with the low (21.9°C) and high (31.3°C) temperatures obtained from the 2D analysis suggests that a full 3D analysis is needed for optimizing the spacing of cooling pipes

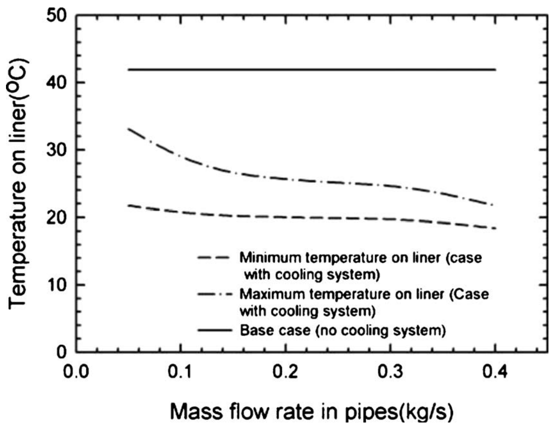

Fig. 7. Symmetric pipe layout: temperature on liner for different coolant mass flow rates (3D model) for a pipe spacing of 3 m (modified from Hoor et al. 2008)

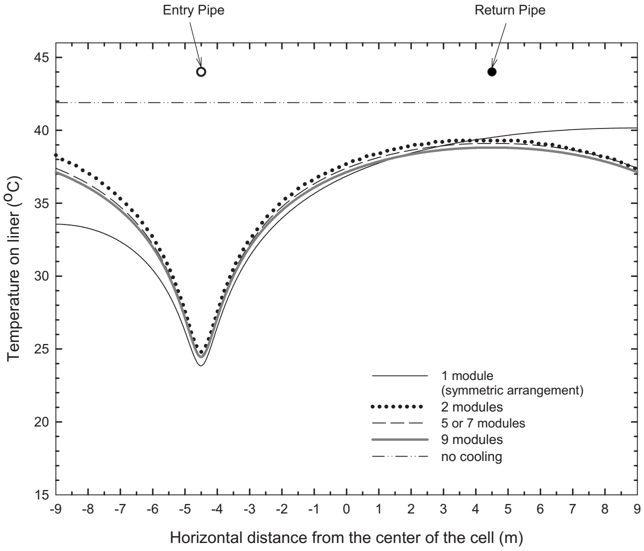

Fig. 8. Periodic pipe layout: liner temperature within the middle 18 m of the pipe arrangement (i.e., from midway between the first pipe pair and midway between the second pipe pair)

and implies that a 3D analysis of the 6-m pipe spacing examined earlier in 2D is likely to result in improved results with respect to cooling the liner.

Periodic Pipe Arrangement

The results presented above indicate that liner temperature may be reasonably controlled by means of a properly designed cooling system (i.e., a cooling system where the main design features, such as pipe layout and spacing, and coolant flow rate are optimized to provide the required cooling). From the 2D study, the pipe spacing using the symmetric arrangement would have to be relatively small (less than 6 m) to obtain a sufficient reduction in liner temperature to meaningfully extend the service life of the geomembrane in the most critical (highest temperature) location. Assuming that the cost of installing pipes will be an important design consideration, a more effective arrangement of cooling pipes is needed. Thus the periodic distribution shown in Fig. 1(b) was examined to evaluate the effect of the pipe layout.

2D Results

The number of modules required to simulate a periodic pipe arrangement for a case with pipe spacing of 9 m was obtained using a 2D model. Cases with 1, 2, 5, 7, and 9 modules were analyzed. Fig. 8 shows temperature distribution on the liner in the middle module (horizontal distance between −9 and +9 m). For the symmetric case (i.e., the case with one module), the analysis gave minimum and maximum temperatures of 23.8°C (below the inlet pipe) and 40.2°C (between the two outlet pipes). The maximum temperature observed in the middle module was reduced to 39.3°C for two modules, 39.1°C for five modules and 38.8°C for nine modules. Thus, to gain sufficient accuracy for present purposes, a periodic pipe arrangement can be simulated by modeling two loops of pipes and focusing the attention on the middle zone. This approach may slightly overestimate the temperature (by less than 20%); however, due to significantly lower computational time (in particular, for the 3D model), this level of approximation was considered acceptable.

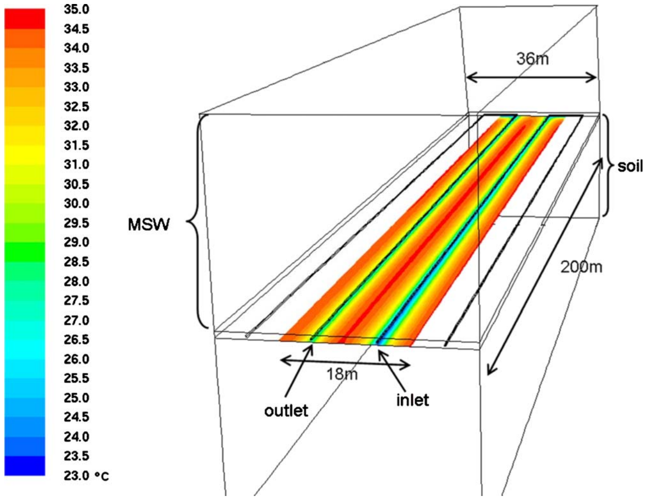

Fig. 9. Periodic pipe layout: temperature distribution on top of the liner for a pipe spacing: 9 m at a coolant mass transfer rate of 0.3 kg/s

3D Results

Fig. 9 shows a contour plot of temperature at the base of the landfill. The simulation was performed using a coolant flow rate of 0.3 kg/s (the case shown in Fig. 9), which gave liner temperatures ranging between 23.6 and 34.7°C. This is up to 4.6°C lower than the similar 2D model. As implied by these lower temperatures, the 3D analysis provides improved results with respect to predicting the cooling of the liner.

For the highest mass flow rate examined (0.4 kg/s), the liner temperature ranged from 22.8 to 34.4°C (Fig. 10). This is 7.5–19.1°C lower than the temperature obtained in the absence of the cooling system. For a landfill with an engineered barrier system, this temperature reduction would result in a substantially increased service life of an HDPE geomembrane liner. To provide an estimate of the magnitude of the effect on geomembrane service life, the cases with and without cooling system were studied and the service lives for a hypothetical geomembrane placed at the base of the landfill were estimated (based on the methodology described by Rowe 2005) for the minimum and maximum temperatures on liner. The predicted service lives considered all three stages of degradation of a geomembrane: (1) time for depletion of

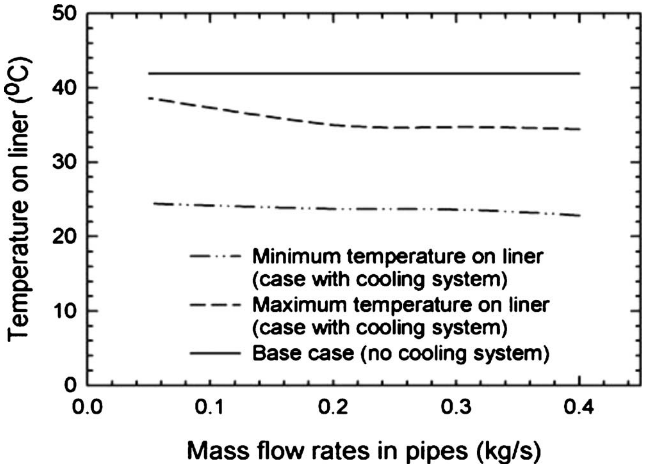

Fig. 10. Periodic pipe layout: temperature on liner for different coolant mass flow rates (3D model) for a pipe spacing of 9 m

antioxidants; (2) induction time to the onset of polymer degradation; and (3) time for degradation of the polymer physical properties to a prescribed level (Viebke et al. 1994; Hsuan and Koerner 1998). The Stage 1 times were calculated based on recent data published by Rowe and Rimal (2008a) for an HDPE geomembrane with standard oxidative induction time (ASTM D3895 2006a) of 135 min, high-pressure oxidative induction time (ASTM D5885 2006c) of 660 min, and single point stress crack resistance (ASTM D5397 2006b, Appendix) greater than 400 h. The data are obtained from the tests for simulated composite liners with leachate above the geomembrane and a geosynthetic clay liner and foundation layer below the geomembrane. Stages 2 and 3 times were estimated based on the data published by Viebke et al. (1994) for a polyethylene gas pipe with minimal antioxidant and with water inside and air circulating around the outside. To take into account the interaction with leachate, the times for Stages 2 and 3 were adjusted based on those data obtained in the tests conducted by Rowe and Rimal (2008b). The service life of geomembrane is taken to be the sum of the time in Stages 1–3 (Rowe 2005).

The service life of geomembrane in this landfill in the absence of a cooling system was estimated to be 85 years using the methodology described above. The introduction of the cooling system with 9-m spacing and coolant flow rate of 0.4 kg/s increased the service life by between 105 and 560% (from 85 years to 175–565 years) at the hottest and coolest locations, respectively. This prediction conservatively assumes that the temperatures within the layers remain constant over time, and therefore, underestimates the service life. Longer service lives are expected if the effect of temperature-time history is considered (Rowe and Islam 2009). The service life can also be increased by decreasing the pipe spacing or introducing fluid at a lower temperature than the annual average ambient temperature (15°C in this case).

The results presented and discussed above highlight the potential effectiveness of a cooling system intended to increase the service life of a geomembrane liner. Although effective, in landfills with high heat generation rates the system may not provide enough cooling unless the pipes are located at a spacing of about 9 m or less, or the fluid is introduced at a temperature well below annual average ambient temperature. In situations where the associated cost of either of these alternatives is unreasonably large, other options including changing the method of landfill operation, revising the type of barrier system, and using other methods of cooling may be considered.

Discussion

Until recently the temperature on landfill liners and the effect that this may have on the service life of composite liners (both the aging of HDPE geomembrane and the potential desiccation of underlying clay liner—see Rowe 2005) used for both MSW and incinerator ash landfills have received relatively little attention. However, there is growing evidence that the temperature on the liner may be sufficient to significantly reduce the service life of the liner. As noted earlier in this paper, liner temperature can be affected by a number of factors including the nature of the waste, waste management practices, the availability of moisture, etc. While these can be controlled to some extent, the question arises as to whether active measures could be taken to control the temperature if the liner temperatures are approaching unacceptable levels in terms of the potential impact on liner service life. Measures such as controlling the influx of water may, in time, reduce temperature and will certainly reduce the potential for leachate buildup and leakage. The insertion of wells to remove heat and introduce coolant may also reduce temperature conceptually. However, these techniques are implemented after the problem arises and must be regarded as experimental at this point in time. The technique suggested in this paper should also be regarded as experimental. Unlike the other techniques, it requires the installation of the piping system at the time of landfill construction but the cooling system would only need to be operated if monitoring indicated that a problem was likely to occur in the absence of active cooling. The use of HDPE pipes, as proposed here, in a sand or gravel layer above the liner would be expected to allow the system to survive typical settlement of the liner in a similar manner to leachate collection pipes—although care would be required in the detailed design to avoid areas of high shear stress on the pipe. The modeling conducted herein suggests that an appropriately designed system could substantially reduce liner temperature. The cost of the use of such a system would need to be evaluated in the context of alternative techniques and the cost of trying to “fix” the problem after it has occurred versus using a contingency measure that is installed at the time of landfill construction. It is suggested that the proposed technique warrants consideration in this context.

Summary and Conclusions

Heat generated by the waste in a landfill can generate liner temperatures sufficiently high to substantially reduce the service life of the liner. This paper has presented one possible method to modify the temperature at the base of the landfill. The service life of liner components can be extended beyond the service life of the case where no heat extraction is used. The design involves installation of an array of cooling pipes beneath the waste. The feasibility of a system for cooling the liner was examined by performing a series of numerical analyses for conditions based on the Tokyo Port Landfill. The results suggest that a cooling system as proposed can substantially reduce liner temperature. In the case of a landfill with an engineered barrier system this would result in a significant increase in the service life of liner components (e.g., geomembrane, compacted clay, and LCS).

Studies were performed to examine the key design features of the cooling system, such as pipe layout, pipe spacing, and coolant flow rate. The results suggest that the pipe layout affects the temperature reduction, with a periodic layout being more efficient than a symmetric arrangement. It was also demonstrated that an increased coolant transfer flow rate resulted in a decrease in liner temperature. However, for high mass flow rates, the outlet temperature of cooling liquid in the pipes would be low, and thus, the extracted heat would be of low quality and of little utility. The cooling effect is improved when pipes are located with lower spacing, although with a relatively close spacing the associated implementation cost may be unreasonably high. The liner temperature could be reduced further by introducing fluid at a lower temperature than the average annual ambient temperature considered herein but the extent of this reduction was not examined in this paper. Thus there is likely a trade-off between (1) minimizing liner temperature; (2) pipe spacing; (3) utilization of the extracted heat; and (4) the cost of installation and long-term maintenance of the system (e.g., issues related to operation of the pumps and the cooling equipment) that need to be examined in future studies.

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