

A Method for Reducing the Temperature of Landfill Liners in MSW Landfills

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ABSTRACT: Modern landfills typically included a composite liner (a geomembrane over a clay liner) to control contaminant migration to the groundwater. These liners have been proven to be very effective so long as they remain intact. However heat generated in landfill can have undesirable impacts on both contaminant migration and the long-term performance of barrier system. High temperatures increase the advective and diffusive migration through a liner. Elevated temperature also accelerates the ageing of high density polyethylene and therefore reduces the service life of the geomembrane. Furthermore, the temperature gradient between the base of landfill and aquifer may result in desiccation of the clay liner. Recognizing the desirability of controlling the temperature increase on the landfill liner, a method of reducing the temperature at the base of landfill is examined.

The proposed technique involves application of heat exchanger technology. The system is comprised of a horizontal pipe array buried at the base of landfill. Coolant circulated through the pipes absorbs the heat and reduces temperature in landfill liners. The hot coolant is pumped to facilities outside the landfill, where the excess heat is extracted and the coolant temperature is reduced and the coolant recirculated through the system.

A preliminary numerical examination of the feasibility of the proposed system for controlling liner temperature is reported. The results show that introduction of cooling pipes can substantially reduce liner temperature. For instance, in Tokyo Port Landfill, the hypothetical introduction of cooling system could reduce liner temperature by at least 9°C for the base case examined. The influence of key design variables such as coolant flow rate and pipe spacing are also discussed. For the case studied, it is shown that an increase in coolant mass flow rate from 0.05 to 0.4 kg/s would reduce the maximum liner temperature by about 11°C. It is shown that an increase in pipe spacing could reduce the efficacy of system. It is also suggested that the layout of cooling system may affect the temperature reduction. The study shows that detailed examination of these design features is required and that full three-dimensional analyses are required since two-dimensional analyses overestimate liner temperature.

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INTRODUCTION

Modern landfill facilities are expected to limit the environmental impact of waste disposal to a negligible level. To achieve this objective, landfills are typically required to have a barrier system that will prevent all but a nominal escape of contaminant 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 reducing service life of the landfill barrier system.

Landfill monitoring has shown that the heat generated by municipal solid waste 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 (Rowe et al., 2004 and Rowe 2005). The authors are aware that even higher temperatures have occurred at the base of some landfills (at least up to 70°C) but these data have yet to be published in the open literature. Elevated temperatures reduce the service life of geomembranes and potentially also that of clay component of barrier systems (Rowe 2005). In situations where the service life is not adequate, the barrier system needs to be revised or the liner temperature reduced.

This paper builds on earlier work by Rowe et al. (2007) in examining a proposed means to control the increase in liner temperature, and hence the impact on the service life of the liner, through the extraction of heat from the landfill. The model is 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 is examined numerically by hypothetically inserting a heat extraction system into the Tokyo Port landfill at the time of construction assuming all other aspects of waste disposal at the landfill remained the same.

DESIGN CONCEPT

The concept involves cooling the liner by means of a series of horizontal pipes buried at the base of landfill. Coolant circulated through the pipes absorbs heat from the surroundings and reduces the temperature of the landfill liner. The heated coolant is then pumped to facilities outside the landfill where excess heat is extracted and the coolant temperature is reduced. The recovered energy is used for onsite purposes and the coolant is recirculated through the system. 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 high density polyethylene (HDPE) with the inside diameter of 200mm. The pipes are installed at the outset in a sand layer under the landfill. Cooling system may be activated at any time during or after landfilling and it continuously runs to maintain the liner temperature low.

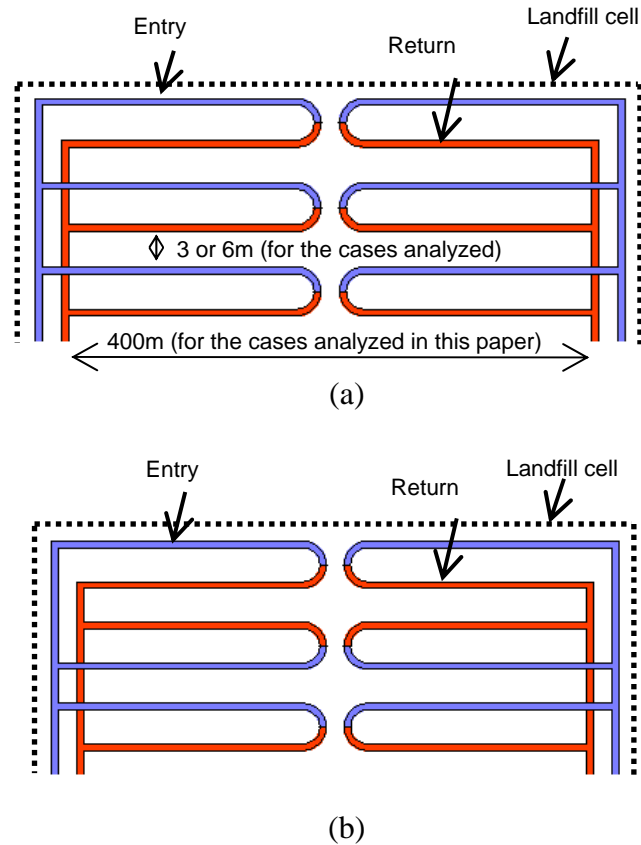


Fig. 1. Schematic layout of cooling pipes (plan view). Blue colour represent “cold” and red colour represents “warm or hot” coolant.

Fig. 1 provides a schematic of two possible alternative patterns for the cooling system. According to heat exchanger principles, the most efficient arrangement is achieved when the entry and return pipes are alternated as shown in Fig. 1a. However, due to the difficulty of modeling the boundary condition for the case shown in Fig. 1a together with heat generation and fixed-temperature boundaries in the program FLUENT, this study has been limited to a simpler, albeit less efficient, case shown in Fig. 1b.

CASE STUDIED

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 for the case where there is 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 30m of municipal solid waste (MSW) in 3 years (1976 to 1979).

The facility has no leachate collection system and therefore possesses a significant leachate mound formed during landfilling and after closure (Yoshida and Rowe 2003).

Thermal Behaviour of Tokyo Port Landfill

The temperature in Tokyo Port Landfill has been monitored in detail over many years. Data collected indicate that temperatures in the landfill reached a peak value of more than 60°C in 1985 (Yoshida et al. 1997). Similarly, temperatures at the base of landfill increased to about 45-50°C (Yoshida and Rowe 2003). Subsequently, at the base of the landfill, it reduced to 37-41°C after 20 years.

The heat generated by a landfill depends on the waste management practice and the nature of the waste and degradation process occurring in the landfill. For instance, as reported by Brune et al. (1991), increased rate of landfilling correlates very well with increased rate of temperature rise. 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 10m/a) and the generation of a significant leachate mound were responsible for the observed rapid increase of temperature in Tokyo Port Landfill.

NUMERICAL MODELING

The finite volume-based commercial computational fluid dynamics code FLUENT, was used to (a) model the original Tokyo Port Landfill and (b) assess the performance of a hypothetical cooling system introduced into the landfill (assumed to have been introduced at the outset). The initial analyses used a two-dimensional (2D) model. However, to capture more details, the model was extended to three-dimensions (3D) for one case. The pipes were arranged as shown in Figure 1b. Because of symmetry, only one loop of pipes (i.e. one inlet and one outlet) was simulated and zero heat flux was prescribed at the side boundaries midway between similar pipe loops. The width of the section modeled was twice the pipe spacing (e. g. 6m for a pipe spacing of 3m) and the height of landfill was 30m. The temperature on the exposed surface of the landfill and deep in soil as well as the coolant temperature were set to be 15°C (the annual average temperature in Tokyo). The distance to the lower boundary was specified to be sufficiently deep so as not to significantly affect the results (30m 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 close contact with soil. Given that the cooling pipes are buried in a layer of sand, this assumption can be readily achieved in the field.

The landfill was modeled through series of steps to simulate landfilling and the post-closure stages. These steps are summarized in Table 1. The effect of the development of leachate mound over time was considered. Waste placement was modeled in 30 months (similar to the actual practice) through 5 steps. During waste placement, it was assumed that each fresh cell was exposed to air with the upper 1m waste in aerobic

decomposition stage. The underlying waste was assumed to be in anaerobic phase. Step six was the closure step, where the landfill was covered and the entire waste mass undergoes anaerobic decomposition. For the case with cooling system, the cooling system was activated subsequent to landfill closure and, once initiated, ran continuously. Post-closure, the landfill was left in anaerobic stage for almost 8 years after the start of landfilling until the temperature reached the peak observed value. Peak liner temperatures have been compared for the cases with and without cooling pipes in an effort to assess the performance of the cooling system.

The properties adopted for MSW, the underlying soil and heat generation rates are summarized in Table 2. Additional details regarding the waste and soil parameters are given by Yoshida et al. (1999) and Yoshida and Rowe (2003). 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. The heat generation rates estimated in this study are within the range of values reported in the literature (Rees 1980; Yoshida and Rowe 2003; Yesiller et al. 2005). The heat generation rate is the most important factor affecting the temperature in the waste and at the liner. The heat generation rate of waste is affected by many factors and there is a high level of uncertainty regarding the actual values. The values used in this modelling did, however, provide a reasonable simulation of what was observed at the Tokyo Port Landfill.

Table 1. Steps used to simulate landfilling and the post-closure response.

Step	MSW Height (m)	Leachate Mound (m)	Degradation	Time (from the Start of Landfilling)
1 Landfilling	6	0	Anaerobic(An):5m Aerobic(A): 1m	6 months
2 Landfilling	12	1	An: 11m, A:1m	12 months
3 Landfilling	18	2	An:18m, A:1m	18 months
4 Landfilling	24	3	An:23m, A:1m	24 months
5 Landfilling	30	4	An:29m, A:1m	30 months
6 Closure	30	5	An: 30m	32 months
7 Post-closure	30	6	An: 30m	3 years
8 Post-closure	30	12	An: 30m	5 years
9 Post-closure	30	18	An: 30m	8 years

2D Model

Two-dimensional analyses were conducted to study the influence of pipe spacing on temperature level. The analysis was performed using quadrilateral elements with element size of 0.1m (36000 elements for 3m pipe spacing, 72000 elements for 6m pipe spacing). Dimensions of the model are shown in Fig. 2. The inlet temperature was

held at 15°C and the outlet temperature was allowed to be equal to the surrounding soil. This assumption maximizes the amount of heat that can be extracted per unit volume of the coolant. It represents the severe situation at the end of the cell where the pipes enter and leave the landfill (conditions will generally be better at other cross-sections). As will be demonstrated by the 3D model, an increase in coolant flow rate above this minimal level 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 Model

The 3D analysis was performed to capture the effect of heat convection along the pipe and to examine the influence of coolant mass flow rate. A 200m-long cell was examined. The pipe length from the entry point to the exit was 403m and the inlet and outlet points were 3m apart. The width of the block analyzed was twice the pipe spacing (i. e. 6m). 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 0.1m in the pipes and the soil around the pipes to 0.25m in waste and to 1m in subsoil. The length of the elements varies between 0.1m in the area close to the end of the cell, where the entry and return pipes are connected, to 2m in the zone where the pipes enter and leave the landfill cell. The analysis was conducted using 1,680,720 hexahedral elements.

Table 2. MSW and soil properties.

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	1939	4.67
MSW- above Leachate Level	5 to 26	0.35	1939	0.436
MSW- below Leachate Level	0 to 18	0.96	2363	0.763
Soil	30	0.86	1109	-

RESULTS

2D Results

Fig. 2 displays contour plots of the 2D temperature distribution in landfill 8 years after the start of landfilling for the cases with and without a cooling system. The predicted and measured temperature profiles without a cooling system are compared in Fig. 3. It

can be seen that introduction of cooling system reduced liner temperature by 10.6 to 20°C (from 41.9°C to 21.9~31.3°C). In case of a landfill with 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 clay liner ranged between 21.9°C directly below the inlet pipe to 31.3°C between the outlet pipes.

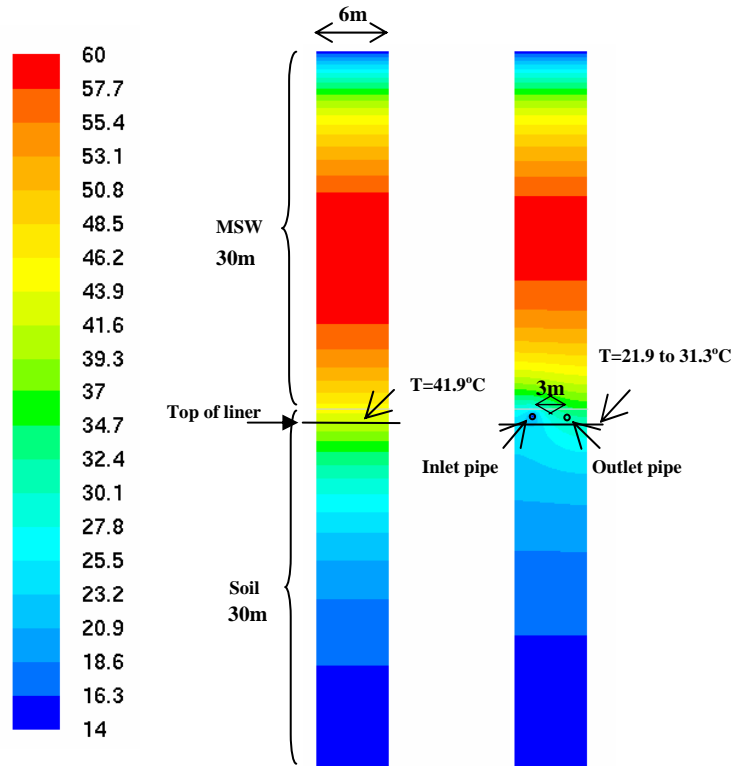


Fig. 2. Contour plot of temperature for 2D analysis (a) no pipes and (b) Pipe spacing: 3m (the plot shows the elevation view at the location where the pipes enter and leave the landfill).

The pipe spacing is an important factor influencing the efficacy of the proposed system. To illustrate this effect, the landfill was examined using pipe spacing of 3m and 6m. As shown in Fig. 4, for the 6m spacing, the analysis gave minimum and maximum temperatures of 24.2°C (below the inlet pipe) and 39°C (midway between outlet pipes). The temperature around inlet pipes was reasonably low. However, in the area between outlet pipes the cooling system had little effect on reducing temperature. A more efficient pipe arrangement (such as the case shown in Fig.1a) 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.

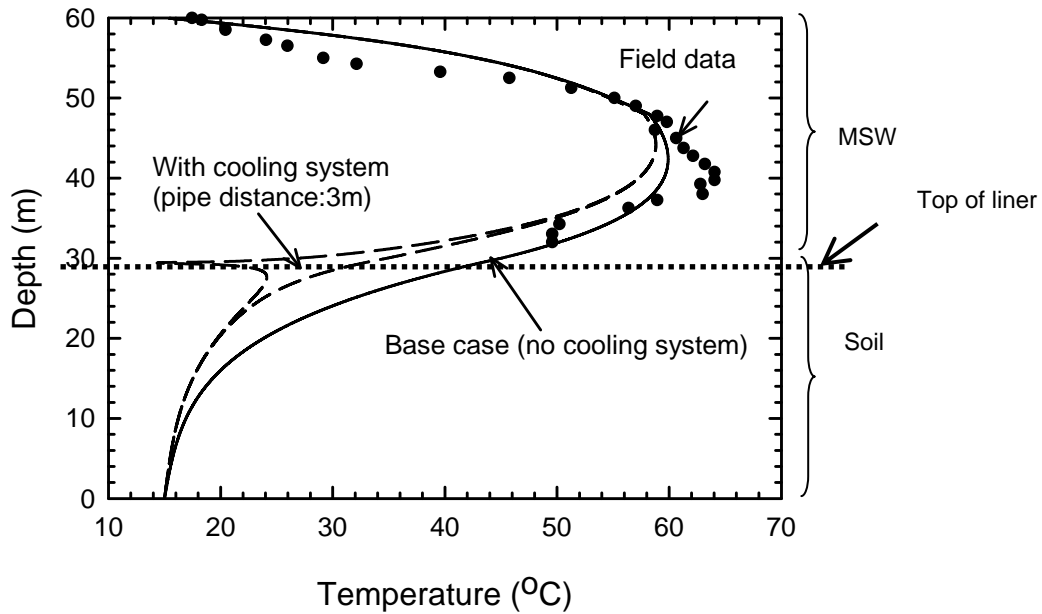


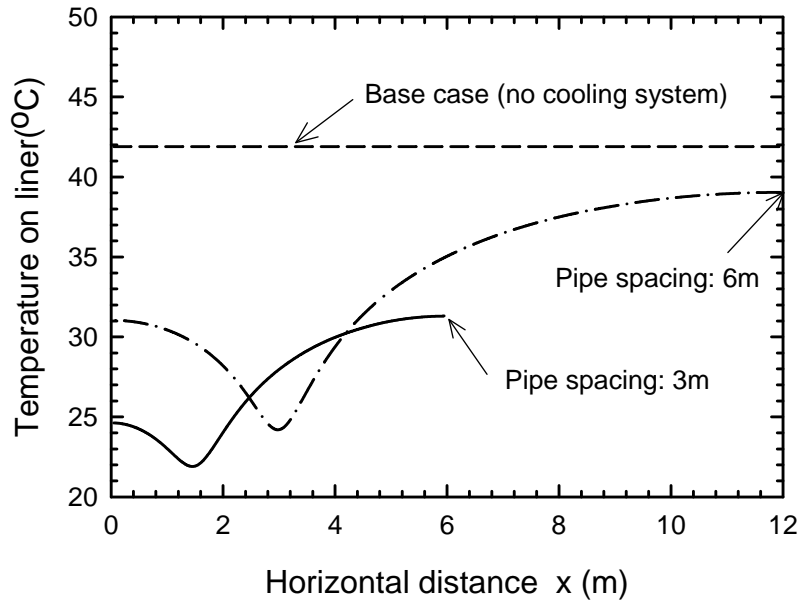
Fig. 3. Temperature profile for 2D analysis

3D Results

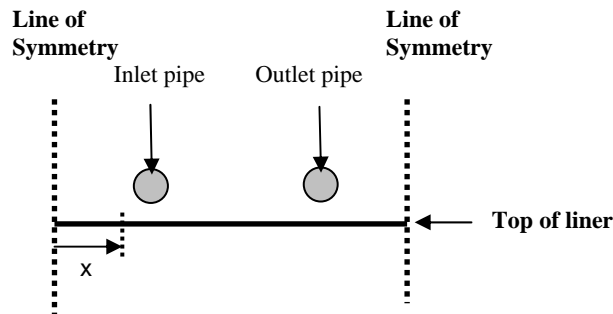
A three-dimensional analysis was performed to evaluate the impact of heat convection along the pipe. Fig. 5 shows a contour plot of temperature at the base of landfill. Minimum and maximum temperatures were encountered around the inlet pipe and between two adjacent outlet pipes, respectively. This is consistent with 2D results. In addition, temperatures obtained from the 3D model were lower than obtained with the 2D model. For example, for mass flow rate of 0.3 kg/s (the case shown in Fig. 5), liner temperature from the 3D model ranged between 19.7°C to 24.6°C, while in 2D model the temperature varied between 21.9°C to 31.3°C.

To illustrate the effect of coolant mass transfer rate, analyses were performed for different mass transfer rates ranging from 0.05 kg/s to 0.4kg/s. As demonstrated in Fig. 6, 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 upper mass flow rate was limited to 0.4kg/s (corresponding to Reynolds’s number of 2000) to avoid turbulence in the piping system. For the highest mass flow rate (0.4kg/s), the liner temperature ranged from 18.4°C directly below the inlet pipe to a maximum of 21.7°C between the outlet pipes. These can be compared to 41.9°C observed in the absence of cooling system. Also comparison with the low (21.9°C) and high (31.3°C) temperature obtained for the 2D analysis suggest that a full 3D analysis is needed for future research directed at optimizing the spacing of cooling

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



(a)



(b)

Fig. 4. (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)

SUMMARY AND CONCLUSION

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 presented one possible method of modifying the temperature at the base of the landfill. The service life of liner components is therefore extended beyond that if no heat extraction is used. The design involves installation of an array of cooling pipes beneath the waste. The

feasibility of 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. In the case of a landfill with an engineered barrier system this would result in a significant increase in service life of the HDPE components of the liner.

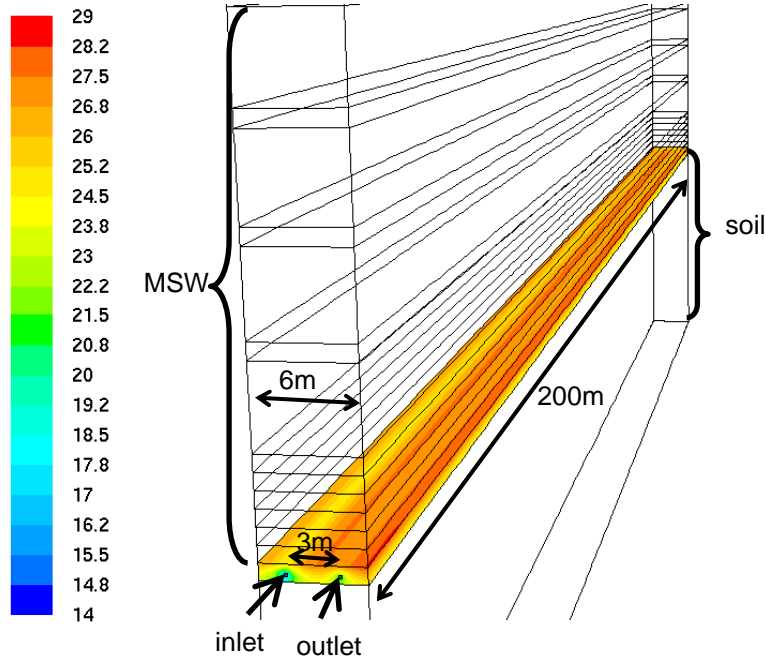


Fig. 5. Temperature distribution around cooling pipes- pipe spacing: 3m (for one module) at a coolant mass transfer rate of 0.3kg/s.

Preliminary studies were performed to examine the key design features of the cooling system such as pipe spacing using the layout shown in Figure 1b. The results suggest that to maintain low temperatures, a more efficient pipe arrangement may be required as shown in Figure 1a. It was also demonstrated that the 2D analysis considerably overestimated the liner temperature and underestimated the efficiency of the cooling system highlighting the need for full 3D analyses in future studies. Increased coolant transfer flow rate resulted in a decrease in liner temperature. However, for high mass transfer rates the extracted heat would be of low quality and is unlikely to be useful. Thus there maybe a trade off between (a) minimizing liner temperature, (b) pipe spacing, and (c) utilization of the extracted heat that needs to be examined in future studies.

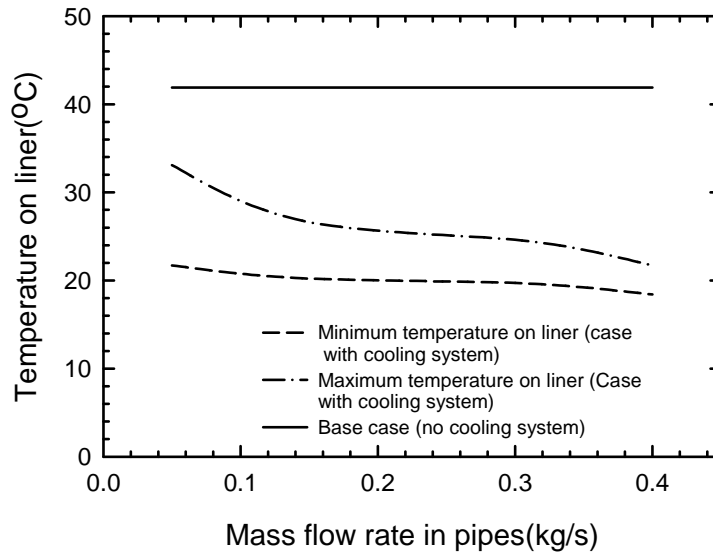


Fig. 6. Temperature at the base of landfill for different coolant mass flow rates (3D model) - Pipe spacing: 3m.

This study was performed for a landfill where the rate of heat generation was relatively high. Also, the landfill studied does not have leachate collection system and is built on natural clay. Further work will examine landfills with engineered barrier system, landfills with a lower heat generation rate, and bioreactor landfills. 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 is required. It is expected that future studies will provide additional insight into the feasibility of system and the use of recovered energy.

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REFERENCES

- Brune, M., Ramke, H. G., Collins, H., and H. H. Hanert (1991). Incrustation process in drainage systems of sanitary landfills, *Proc. 3rd. Int. Landfill Sym.*, Cagliari, Italy.
- Rees, J. F. (1980). Optimization of methane production and refuse decomposition in landfills by temperature control, *J. Chem. Technol. Biotechnol.*, 30(8), 458-465.
- Rowe, R.K. (2005). Long-Term Performance of Contaminant Barrier Systems, 45th Rankine Lecture, *Geotechnique*, 55 (9), 631-678.
- Rowe, R. K., Quigley, R. M., Brachman, R. W. I. and J. R. Booker (2004). *Barrier systems for waste disposal facilities*, Taylor and Francis (E and FN Spon), London.
- Rowe, R.K., Pollard, A. Chong, Chisholm, E., Toda, R. and C. Tomson (2007). Sustainable landfills – a technique for extracting heat to prolong service-life of geomembrane liners, *60th Canadian Geotechnical Conference*, Ottawa, Canada.
- Yesiller, N., Hanson, J. L., and W. L. Liu (2005). Heat Generation in Municipal Solid Waste Landfills, *Jl Geotech. and Geoenvironmental Enng.*, 131(11), 1330-1344.
- Yoshida, H., Tanaka, N., and H. Hozumi (1997). Theoretical study on heat transport phenomena in a sanitary landfill, *Proc. 6th. Int. Landfill Sym.*, Cagliari, Italy.
- Yoshida, H., Tanaka, N. and H. Hozumi (1999). Theoretical study on temperature distribution in landfills by three-dimensional heat transport model, *Second International Congress on Environmental Geotechnics*, Osaka, Japan.
- Yoshida, H., and R. K. Rowe (2003). Consideration of landfill liner temperature, *Proc. 9th. Int. Landfill Sym.*, Cagliari, Italy (CD-ROM).