한랭 조건하에서 세가지 매립지복토 시스템에 대한 평가
The Evaluation of Three Landfill Cover Systems in Cold Condition

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Abstract

일반적으로 일반 및 유해 폐기물 매립지에서 진흙층의 기능적 수행목적은 다음과 같다고 할 수 있다: 지표면 유출의 증진을 위하고, 우수의 침투억제 및 폐기물의 표면노출시 완충작용, 따라서 최종복토의 붕괴는 이러한 중요 기능을 마비시키고 있다.

본 연구는 추운 날씨 상태의 폐기물 매립지 최종 복토의 거동을 수행하였으며, 실제로 설계된 세개의 거대한 실험실 Tank에서 복토에 대한 실험이 시행되었다. 이 거대한 실험장비의 제원은 0.75mx2.4m와 2.0m 깊이로 되어 있다. Tank안은 시방서적으로 폐기물 매립지가 요구하는 진흙층과 최종복토를 위한 물질로 채워졌다. 그들의 실험결과는 동결/융해에 따른 진흙과 복토층의 붕괴현상은 물리적.공학적인 측면에 영향을 주는 것으로 나타났다. 본문은 실험에 사용된 복토층의 묘사, 그들의 실험결과들과 실험을 통한 결과분석 및 결론을 설명하고 있다.

실험결과로서는 각 모형들의 우수와 침출수 자료, 온도변화의 배경과 최종복토에서의 Water Balance를 포함하고 있다. 또한 결과로서 시험된 세개의 모형들은 폐기물 매립지에서의 동결깊이(29cm ~32cm)를 나타내주며 그들중 하나의 모형은 배수층을 가지고 있어 침출수억제에 효과적이므로 다른 모형보다 복토층으로서 우위에 있다는 것을 지적하고 있다.

1. Introduction

In 1929, Taber reported that pressure increases are associated with freezing due to the growth of ice crystals and that excessive heaving is to be explained by the segregation of water as it freezes. As water freezes segregation causes shrinkage cracks below the ground surface if the supply of water is limited or if the soil is very impermeable. Also, more water may become concentrated in the surface soil through ice segregation that is followed by thawing.

Many researchers also have developed mathematical models to deal with a comprehensive analysis of heat and moisture movement. Mathematical models simulating heat and moisture movement in freezing soils have been reported by Dirksen and Miller (1966), Harlan (1973), Guymon and Luthin (1974), and Taylor and Luthin (1978). Dirksen and Miller (1966) presented data dealing with the freezing process in a silty soil (highly frost-susceptible to frost heave). Taylor and Luthin (1978) reported the basic elements of the model to be the heat and water flow equations.

Mageau and Morgenstern (1979) presented their observations on moisture migration in frozen soils. Frozen specimens of a clayey silt have been tested under temperature gradients in both closed and open systems. They demonstrated that moisture can be moved through the unfrozen zone (film) under the effect of a temperature gradient. Finally, they concluded the frost heave rate is dominated primarily by the frozen fringe of soil between the warmest ice lens and the frozen/unfrozen interface.

Frost heave is an important consideration for landfill cover liners. When freezing temperatures develop in the soil mass, most of the pore water in the soil is also subject to freezing. There is close correlation between frost heave and ice lenses formation. That is, the amount of total ground surface frost heave has been found to equal the thickness of ice lenses existing in the soil at the heave location (McCarthy, 1977). However, the cover clay liner is protected by a vegetative soil layer, which is not considered in most small-scale laboratory simulations of the problem. In this investigation, the author utilized a large scale laboratory simulation allowing inclusion of the field depth of the cover systems, layered soil profiles, rainfall simulation, a cold climate, and boundary conditions similar to those encountered in the landfill.

This study was performed to evaluate the effect of the cold weather conditions on the landfill cover system. Three designs were simulated in a large tank. The liner materials were obtained from a land waste disposal site in Southeastern Michigan, approximately 30km from Detroit. These soils are used in the construction of the top and bottom liner of the landfill located in the city of Sumpter.

This paper provides the description of testing cover liners, experimental results, and a discussion of the results of the simulation. The experimental results include rainfall and leakage data, the temperature history and water balance for each design.

2. Design of the Simulated Cover Liner

Three different cover liner configurations were investigated. The three designs are shown in Figures 1-3. Design #1 corresponds to the most simplistic cover system, while design #2 includes barrier protection soil between the topsoil and clay. Of the three designs, only design #3 includes a lateral drainage layer above the clay liner to limit fluid pressures above the clay.

3. Experimental Results

3.1 Rainfall and Leakage Simulation

Four rainfall events, separated by freeze/thaw cycles, were simulated for each of the three designs. The rainfall intensity for each event was approximately equivalent to the 100-year 60 minute rainfall of southeastern Michigan. Figures 4 -6 display the time history of rainfall inputs and leakage outputs for each of the designs.
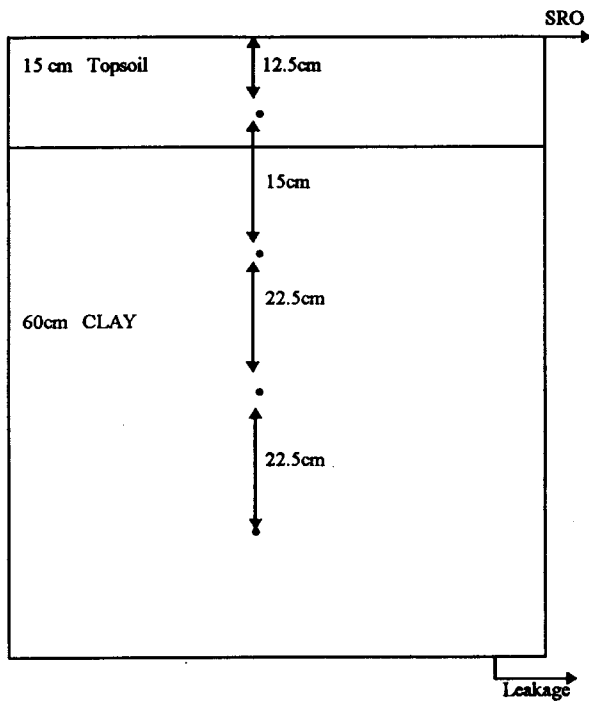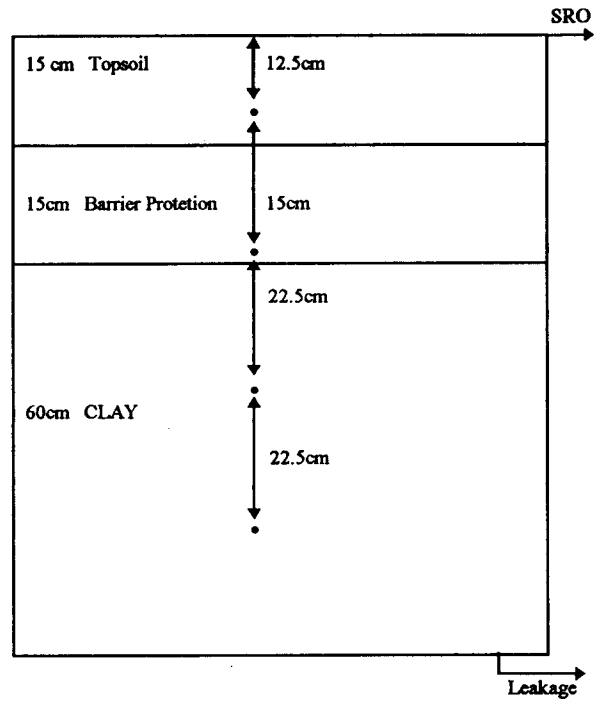
Figure 1

SRO

15 cm Topsoil	12.5cm
	15cm
60cm CLAY	22.5cm
	22.5cm

Leakage

Figure 1 Design #1 for Cover System

Figure 2

SRO

15 cm Topsoil	12.5cm
15cm Barrier Protetion	15cm
60cm CLAY	22.5cm
	22.5cm

Leakage

Figure 2 Design #2 for Cover System

Figure 3

SRO

15cm Topsoil	12.5cm
30cm Barrier Protection	15cm
	10cm
30cm Drainge	12.5cm
	22.5cm

Drainge

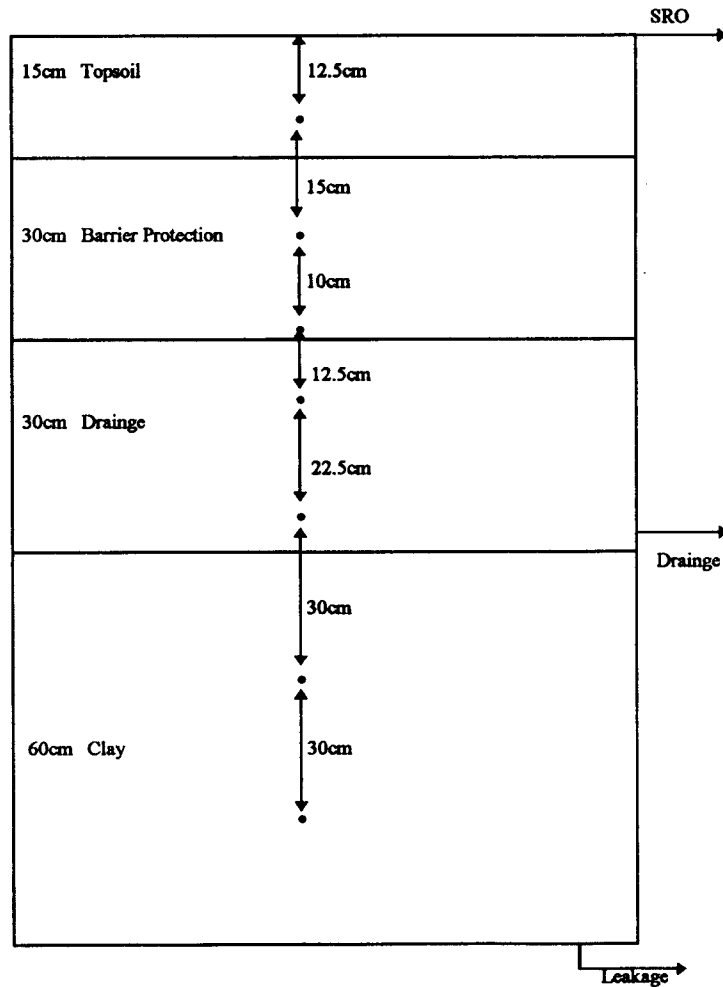|	
60cm Clay	30cm
	30cm

Leakage

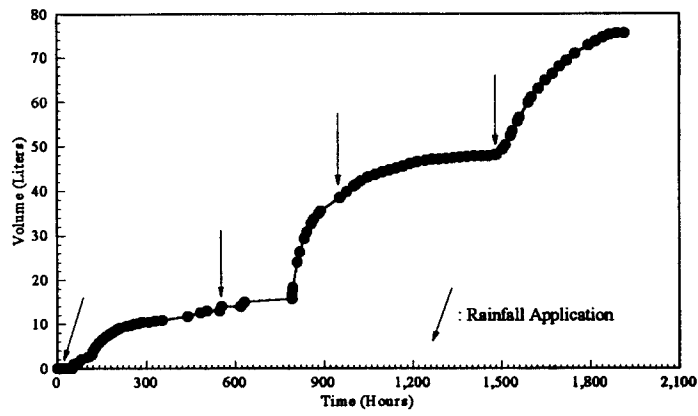Figure 3 Design #3 for Cover System

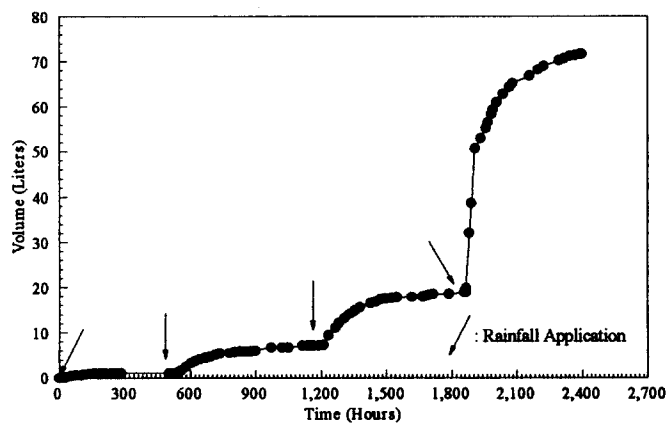Figure 4 Leakage for Design #1
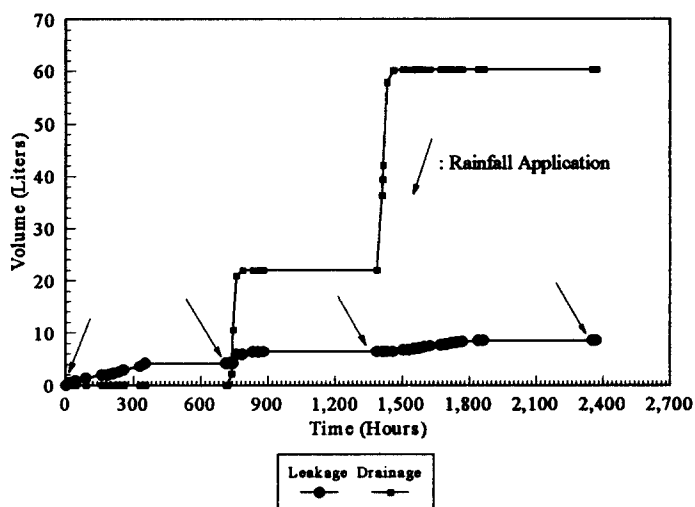

Figure 5 Leakage for Design #2

Figure 6 Leakage and Drainage for Design #3

3.2 Temperature History of Each Design

A primary focus of this project was the evaluation of temperature profiles resulting from continuous freezing periods. Thermocouples were located above the simulated cover liner and at several depths within the cover as illustrated earlier in Figures 1 - 3. Figures 7 - 9 display the temperature history for each of the three designs.

The temperature profile is nearly linear. However, the top-most soils were influenced by the cold air temperature, and so the temperature of top-most soils changed frequently and dramatically, resulting in an unstable top-most soil. A stage before the first freezing in design #1 performed as a test of the refrigeration unit in the tank.
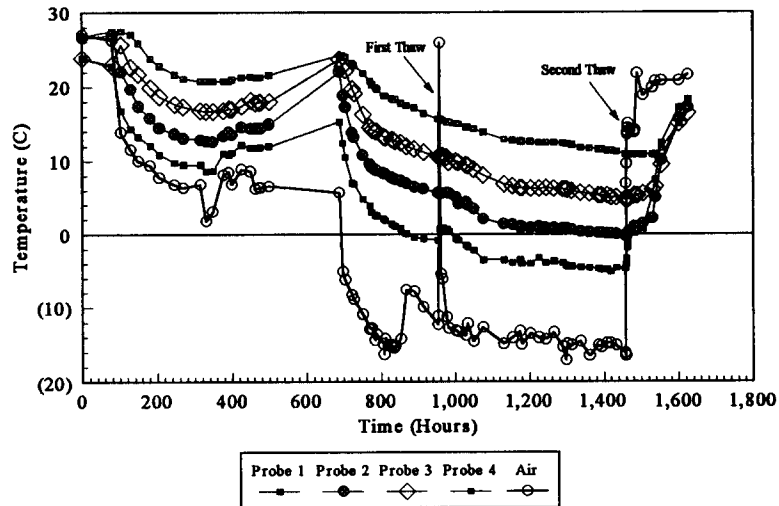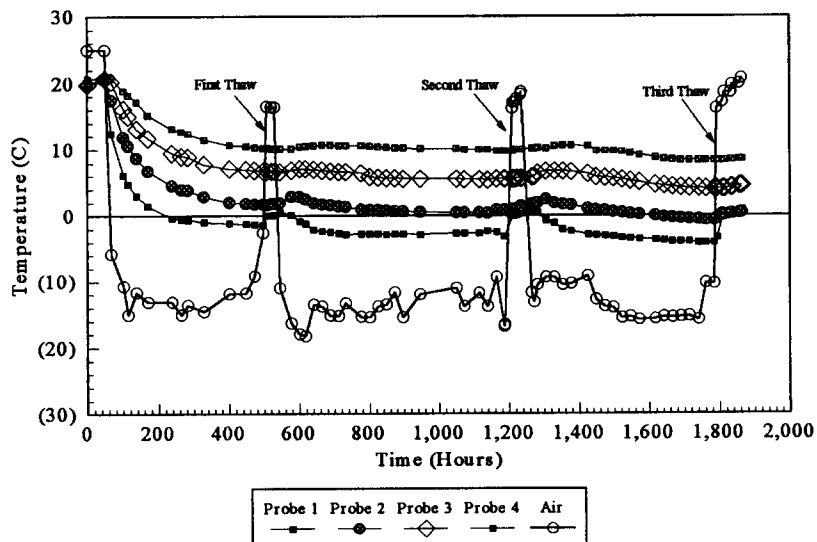
Figure 7 Temperature History for Design #1

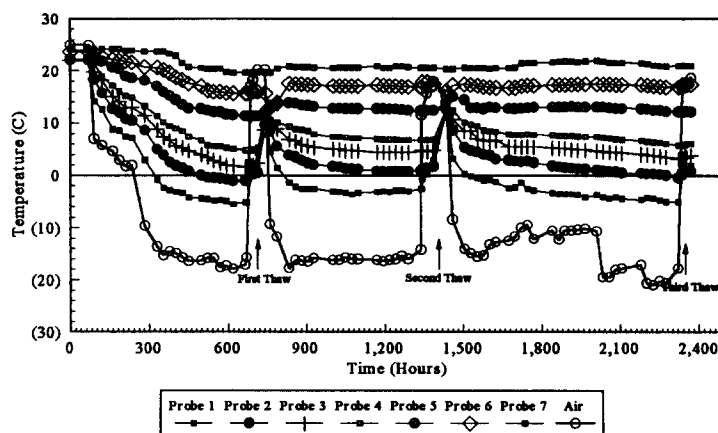Figure 8 Temperature History for Design #2

Figure 9 Temperature History for Design #3

3.3 Moisture Contents

The moisture contents in the compacted clay liner were measured in two places for each lift placed in the tank. Moisture contents were measured before the simulation was started. Moisture contents were evaluated as the clay liner was disassembled after the completion of a simulation. Table 1 shows the moisture content measurements for each design.

Table 1 Comparison between Initial and Final Moisture Contents in the Clay of Each Design

	Design #1	Design #2	Design #3
* Initial Measurement (%)	14.2	14.4	15.2
* Final Measurement (%)	15.8	16.2	15.5

* Values shown represent an average of all measurements for each design.

4. Discussions and Conclusions

The purpose of this investigation was to provide a comparative analysis of three different landfill cover liner designs under freeze/thaw conditions. The primary basis for the comparison was the frost penetration characteristics of the liners. Therefore, the average air temperature maintained for each design was similar.

Table 2 provides a performance-based comparison of the three liner designs. Although the depth of frost penetration was similar for all designs tested, the freezing zone never propagated into the clay of Design #3 because of the additional depth of cover materials used in Design #3. A maximum depth of frost penetration in Design #3 was measured at 32cm. One explanation for this that Design #3 was run at the coolest average freezing period temperature, -13° c. It appeared that even had the test been performed for a much greater period of time, the clay would have remained unfrozen, with a steady state condition having been achieved. Certainly the low boundary condition is acting to limit depth of frost penetration.

Several locations of frost heave appeared with surface disruption. The frost heave was measured for each design and found to vary between 3.8cm - 4.4cm.

Designs #1 and #2 were very similar in regards to the leakage performance (% of infiltration that exits system as leakage). However, design #3 had much less leakage. This was clearly attributed to the presence of the 30cm drainage layer employed in Design #3. The drainage layer appeared to be very effective in removing potential leakage from the system before it had an opportunity to migrate through the clay. It may also be true that the clay liner of Design #3 was more effective at "holding up" the leakage because the frost had not propagated to the clay in this design.

As shown in Table 1, moisture contents increased from 0.3% to 1.8% at three designs. Design #3 indicated much less moisture content than designs #1 and #2. It may also prove that the drainage layer appeared to be effective in removing potential leakage from the system.

Hence, Design #3 had clearly superior performance to each of the earlier designs. The performance was measured in terms of leakage through the clay barrier, frost penetration of the clay, and frost heaving. However, the depth of frost penetration in Design #2 was very minimal. Considering that the air temperatures simulated were much more severe than those typically encountered in a Michigan winter, it appears that Design #2 would be adequate for frost penetration concerns. Design #3 had superior performance for leakage. Again, however, Design #1 and #2 have only minimal percentages of the incipient rainfall exiting as leakage.

As shown in Table 4.2, the moisture increase of 223.3 liters in design #3 represents the change in moisture throughout the various layers of soil. The excessmoisture, 30.0 liters, represents the quantity: (rainfall - surface runoff - leakage - evaporation - moisture increase). It is the moisture that is unaccounted for in the various components of water balance. It is a measure of the error of the experimental techniques. Therefore, the indication is that there is a water balance error in design #3 of 2.4% (30.0/1234.9).

Table 2 Performance Comparison of Three Cover Liner Designs

Characteristic	Design #1	Design #2	Design #3
Avg. air temperature ($^{\circ}$c) during the freezing cycle	-11.6	-12.6	-13.0
Depth of frost penetration - Total (cm)	29.0	31.0	32.0
Depth of frost penetration - In Clay (cm)	13.9	1.2	None
Frost Heave after first freeze/thaw cycle (cm)	4.4	3.8	3.8
Water Balance (liter)			
Rainfall	1490.0	1131.7	1234.9
Surface Runoff	1107.5	760.5	904.0
Leakage	75.5	71.4	8.5
Evaporation	26.3	38.5	36.9
Drainage	-	-	62.2
Moisture Increase (liter)	280.7	261.3	223.3
Excess Moisture (liter)	18.7	5.5	30.0
Leakage as % of Infiltration (Rainfall - SRO)	19.7	19.2	2.6

The experimental approach was adopted for investigating the cover liner performance, as analytical models are generally unavailable. For example, the Stefan equation is often referred to for calculation of frost penetration in single- and multi-layer soil systems. However, because it is an analytical technique, it requires significant assumptions be made, that render it much less applicable for the cover liner problem. One such assumption is the absence of a lower boundary condition of forced temperature. Therefore, the only thermodynamic control that enters the problem is air temperature at the surface. For the landfill problem, the temperature at the interface between the cover soils and the waste may be vastly different (typically warmer) than the temperature in the atmosphere. Therefore, one would expect the Stefan formula to overpredict the depth of frost penetration. Stefan's formula predicts a frost penetration of 53cm as opposed to the 29cm observed experimentally.

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