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**LEACHATE RECIRCULATION IN BIOREACTOR
LANDFILLS: FIELD-SCALE TESTING AND MODELING**

By

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ABSTRACT

LEACHATE RECIRCULATION IN BIOREACTOR LANDFILLS: FIELD-SCALE TESTING AND MODELING

By

Mazen Mohamad Haydar

Leachate recirculation (LR) in municipal solid waste (MSW) landfills operated as bioreactors offers significant economical and environmental benefits. Leachate recirculation systems (LRSs) consisting of horizontal trenches and vertical wells are conventional methods. However, need for excavation, relatively high installation costs and non-uniform distribution of recirculated leachate are the key disadvantages of these conventional methods. In this dissertation, a new design concept called permeable blankets (PBs) was evaluated numerically and tested in the field using instrumented test sections. This design concept consists of placing a relatively thin and high hydraulic conductivity material on a relatively flat or inclined waste surface in a landfill. A perforated pipe is embedded in the PB in the direction parallel to the shorter or longer plan view dimension of the PB where leachate is injected under a positive pressure. PBs require no excavation, can substitute multiple horizontal trenches or vertical wells and achieve a relatively uniform wetting of waste. PBs made up of granular materials can also provide an ideal platform to embed sensors for monitoring the pressure, temperature, and migration of injected leachate. Field-scale testing of PBs was conducted at an active MSW landfill located in Jackson Michigan where three 60-m-wide by 10-m-long PBs made up of crushed recycled glass, shredded tires and a geocomposite drainage layer (GDL) were constructed. Total about 50 sensors were embedded in these blankets to measure moisture content, pore-

water pressure, temperature, and vertical stress. Leachate was injected at flow rates ranging from 0.9 m³/hr to 3.6 m³/hr per unit meter length of the injection pipe. The data collected from the sensors during the period from September 2003 to May 2005 indicated that the injected leachate traveled across the entire width of the blankets in time periods ranging from a few minutes to a few hours depending upon the injection rate. The key conclusion of this study is that permeable blankets can be used as a new LRS in MSW landfills operated as bioreactors. The key parameters that influence pore water pressure in the blanket are: leachate injection rate; and (2) the hydraulic properties and water contents of the PB and waste. The pore water pressure in PBs does not exceed the leachate injection pressure head as long as perched water tables do not exist in the landfill.

DEDICATION

I thank God and my family for the completion of this work.

I owe everything to the continuous love and prayer of my father (Mohamad), my mother (Rasmie), my sister (Abir) and my brother (Rabih).

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TABLE OF CONTENTS

LIST OF TABLES	x
LIST OF FIGURES.....	xi
KEY TO ABBREVIATIONS.....	xvi
KEY TO SYMBOLS.....	xvii
INTRODUCTION.....	1
BACKGROUND.....	1
CONVENTIONAL LEACHATE RECIRCULATION METHODS.....	2
NEW LEACHATE RECIRCULATION METHOD.....	3
OBJECTIVES AND METHODOLOGY	7
DISSERTATION ORGANIZATION	8
 PAPER NO. 1: LEACHATE RECIRCULATION USING HORIZONTAL TRENCHES IN BIOREACTOR LANDFILLS	 10
ABSTRACT.....	10
INTRODUCTION.....	11
NUMERICAL MODELING.....	13
HYDRUS-2D Computer Model.....	13
Conceptual Model and Assumptions	14
Boundary Conditions and Mass Balance	16
Hydraulic Properties	17
Dimensions.....	20
Modeling Results.....	21
Effect of Leachate Injection Pressure Head.....	22
Effect of Hydraulic Conductivity of Trench Backfill.....	25
Effect of Horizontal Trench Geometry and Size.....	26
Effect of Horizontal Trench Spacing.....	26
Effect of Vertical Spacing.....	33
Effect of Geometric Formation of HTs.....	36
MODEL VALIDATION	40
McCreanor (1998)	40
Bachus et al. (2002).....	41
Doran (1999)	43
SUMMARY AND PRACTICAL IMPLICATIONS	44
ACKNOWLEDGEMENT	45
REFERENCES.....	47
 PAPER NO. 2: EVALUATION OF HETEROGENEITY AND ANISOTROPY OF WASTE PROPERTIES ON LEACHATE RECIRCULATION IN BIOREACTOR LANDFILLS.....	 50
ABSTRACT.....	50
INTRODUCTION.....	50

HYDRAULIC PROPERTIES OF MSW	52
HORIZONTAL TRENCH LEACHATE RECIRCULATION SYSTEM	54
METHODOLOGY	55
Conceptual Model.....	56
Numerical Model.....	56
Monte Carlo Analysis	60
RESULTS	64
Homogeneous and Isotropic Properties	64
Heterogeneous and Anisotropic Properties.....	66
Leachate Flow Patterns	68
SUMMARY AND CONCLUSIONS.....	72
ACKNOWLEDGEMENTS	73
REFERENCES.....	74

PAPER NO. 3: NUMERICAL EVALUATION OF PERMEABLE BLANKETS FOR LEACHATE RECIRCULATION IN MSW LANDFILLS	77
--	----

ABSTRACT	77
INTRODUCTION	77
NUMERICAL MODELING.....	79
HYDRUS-2D Computer Model.....	79
Conceptual Model and HYDRUS-2D Input	82
Boundary Conditions and Mass Balance	82
Hydraulic Properties	83
Geometry and Dimensions.....	83
SIMULATION RESULTS	84
Horizontal Trench.....	84
Permeable Blanket.....	84
Effect of Injection Head	86
Effect of Width of Permeable Blanket.....	86
Effect of Hydraulic Conductivity of Permeable Blanket.....	88
Permeable Blanket and Horizontal Trench Equivalency	88
Effect of Settlement of Permeable Blanket.....	90
SUMMARY AND CONCLUSIONS.....	90
ACKNOWLEDGEMENTS	93
REFERENCES.....	94

PAPER NO. 4: Leachate Recirculation Using Horizontal Permeable Blankets in BIOREACTOR Landfills	95
--	----

ABSTRACT	95
BACKGROUND.....	95
LEACHATE RECIRCULATION USING PERMEABLE BLANKETS	97
Design and Construction Aspects.....	97
Advantages of Permeable Blankets	99
LEACHATE FLOW IN WASTE.....	100
NUMERICAL MODELING OF PERMEABLE BLANKETS	101
HYDRUS-2D Computer Model.....	101
Conceptual Model.....	102
Boundary Conditions	104

MODELING RESULTS.....	106
Hydraulic Properties of Waste	109
<i>Saturated Hydraulic Conductivity of MSW</i>	110
<i>Unsaturated Hydraulic Properties of Waste</i>	112
<i>Saturated Hydraulic Conductivity of Permeable Blanket</i>	112
<i>Hysteresis in Hydraulic Conductivity of Permeable Blanket</i>	115
Geometry of Permeable Blanket	115
<i>Permeable Blanket Depth</i>	115
<i>Permeable Blanket Width and Vertical Spacing</i>	117
<i>Settlement of Permeable Blanket</i>	118
Leachate Dosing Frequency.....	118
Degrees of Saturation of Waste and Permeable Blanket	122
<i>Initial Degree of Saturation of Waste</i>	124
<i>Initial Degree of Saturation of Permeable Blanket</i>	124
FIELD-SCALE TESTING OF PERMEABLE BLANKET	127
Field Installation of PB	127
Automated Monitoring System	128
Field Data versus Simulated Results	128
SUMMARY AND PRACTICAL IMPLICATIONS	132
ACKNOWLEDGEMENTS	134
REFERENCES.....	135

PAPER NO. 5: GEOTECHNICAL SENSING SYSTEM TO MONITOR INJECTED LIQUIDS IN LANDFILLS

138

INTRODUCTION.....	138
Leachate Recirculation Using Permeable Blankets.....	140
Common Sensors Used in Landfills	140
<i>Moisture Content Sensors</i>	142
AUTOMATED SENSING SYSTEM	143
Electrical Impedance Moisture Content Sensors.....	145
FIELD INSTRUMENTATION	149
Monitoring System	150
Laboratory Testing and Calibration.....	153
RESULTS	155
Detection of Leachate Migration in Permeable Blankets	155
Response of Pressure Transducers and Thermistors	158
Limitations of Sensor System to Detect Leachate Migration	160
Drainage of Permeable Blanket.....	162
Effect of Diurnal Air Temperature on Measurements.....	163
SUMMARY AND CONCLUSIONS.....	165
ACKNOWLEDGMENTS	166
REFERENCES.....	167

PAPER NO. 6: LEACHATE RECIRCULATION IN BIOREACTOR LANDFILLS USING GEOCOMPOSITE DRAINAGE MATERIAL

169

ABSTRACT.....	169
BACKGROUND.....	170
Leachate Recirculation Using Permeable Blankets.....	171

OBJECTIVES	172
GEOCOMPOSITE DRAINAGE LAYER	173
NUMERICAL MODELING OF PERMEABLE BLANKETS.....	174
FIELD TEST SECTION AND METHODOLOGY.....	177
Test Section Layout	177
Embedded Sensors.....	179
Monitoring System	182
RESULTS	183
Leachate Recirculation Trials.....	183
Verification of Response of Moisture Content Sensors.....	183
Verification of Response of Temperature and Pressure Transducer Sensors ...	185
Flow of Leachate through the GDL Blanket.....	187
Effect of Injection Rate on Leachate Travel	189
Correlation of Modeling and Field Results.....	191
Monitoring of Pressure Head and Temperature in the GDL Blanket.....	195
SUMMARY AND CONCLUSIONS	199
ACKNOWLEDGEMENTS.....	200
REFERENCES.....	202
 SUMMARY AND PRACTICAL IMPLICATIONS	 204
HORIZONTAL TRENCHES	204
PERMEABLE BLANKETS.....	205

LIST OF TABLES

PAPER NO. 1: LEACHATE RECIRCULATION USING HORIZONTAL TRENCHES IN BIOREACTOR LANDFILLS

Table 1. Saturated and unsaturated hydraulic parameters input to HYDRUS-2D to simulate leachate recirculation system consisting of horizontal trenches.	18
Table 2. Effect of vertical spacing between HTs on the hydraulic efficiency of LRS.	35
Table 3. Comparison of simulation results from SUTRA-2D and HYDRUS-2D.	42

PAPER NO. 2: EVALUATION OF HETEROGENEITY AND ANISOTROPY OF WASTE PROPERTIES ON LEACHATE RECIRCULATION IN BIOREACTOR LANDFILLS

Table 1. Hydraulic properties of simulated landfill components.	58
Table 2. Summary of recursive Q_s and standard deviation in Q_s for realizations using heterogeneous and anisotropic waste properties.	63

PAPER NO. 4: Leachate Recirculation Using Horizontal Permeable Blankets in BIOREACTOR Landfills

Table 1. Saturated and unsaturated hydraulic properties used in HYDRUS-2D simulations.	105
---	-----

PAPER NO. 5: GEOTECHNICAL SENSING SYSTEM TO MONITOR INJECTED LIQUIDS IN LANDFILLS

Table 1. Hydraulic conductivity of loose and dense crushed glass.	151
--	-----

PAPER NO. 6: LEACHATE RECIRCULATION IN BIOREACTOR LANDFILLS USING GEOCOMPOSITE DRAINAGE MATERIAL

Table 1. Physical Properties of the Geocomposite Drainage Material.	180
--	-----

LIST OF FIGURES

INTRODUCTION

- Figure 1. Simulated wetted patterns of leachate recirculation using an LRS consisting of: (a) 3 HTs spaced 20 m; (b) 5 HTs spaced 15 m; and (c) a 60-m-wide PB for a total leachate injection rate of 5.4 m³/hr/m. 4
- Figure 2. Simulated wetted areas for LRS consisting of: (a) 3 HTs spaced 20 m; (b) 5 HTs spaced 15 m; and (c) a 60-m-wide PB for a total leachate injection rate equal to 2.7 m³/hr/m. 6

PAPER NO. 1: LEACHATE RECIRCULATION USING HORIZONTAL TRENCHES IN BIOREACTOR LANDFILLS

- Figure 1. Conceptual model for HYDRUS-2D simulation of leachate recirculation in MSW landfill using horizontal trench system (a); and detail of a horizontal trench (b). 15
- Figure 2. Simulated leachate flux at steady-state versus leachate injection pressure head for a 0.6-m-wide by 1-m-deep single HT for $k_w = 10^{-7}$, 10^{-6} , and 10^{-5} m/s. 23
- Figure 3. Simulated wetted areas at steady-state for 0.6-m-wide by 1.0-m-deep single HT for $k_w = 10^{-6}$ m/s for (a) $H_i = 5$ m (degree of saturation $\geq 45\%$ to $\geq 90\%$); and (b) H_i ranging from 0 to 5 m (degree of saturation $\geq 90\%$). 24
- Figure 4. Simulated leachate flux at steady state versus leachate injection pressure head as a function of width and depth of HT for $k_w = 10^{-6}$ m/s. 27
- Figure 5. Distribution of wetted area corresponding to degree of saturation $\geq 90\%$ at steady-state for LRS consisting of seven HTs at 10-m-horizontal spacing (a); and five HTs at 15 m spacing (b) for $k_w = 10^{-6}$ m/s and $H_i = 1.5$ m. 29
- Figure 6. Effect of horizontal spacing between HTs and leachate injection pressure head on the hydraulic efficiency for LRS consisting of two HTs in a row for $H_i = 1.5, 3$, and 5 m and $k_w = 10^{-6}$ m/s. 31
- Figure 7. (a) Simulated total leachate flux at steady-state versus leachate injection pressure head for LRS consisting of four, five, and seven HTs spaced horizontally at $s = 10, 7.5$, and 5 m for $k_w = 10^{-6}$ m/s; and (b) hydraulic efficiency. 32
- Figure 8. Hydraulic efficiency as a function of vertical spacing for LRS consisting of two vertically positioned HTs for $H_i = 1.5$ and 5 m and $k_w = 10^{-6}$ m/s. 34

Figure 9. Hydraulic efficiency as a function of number of HTs positioned vertically at a fixed spacing of 5 m and for $k_w = 10^{-6}$ m/s.	37
Figure 10. Pattern of wetted area at degree of saturation $\geq 90\%$ at steady-state for geometric formations A, B, C and D for $H_i = 3$ m, $k_w = 10^{-6}$ m/s, $s = 20$ m, and $D = 15$ m.	38
Figure 11. Hydraulic efficiency for formations A, B, and C presented in Figure 10.	39
 PAPER NO. 2: EVALUATION OF HETEROGENEITY AND ANISOTROPY OF WASTE PROPERTIES ON LEACHATE RECIRCULATION IN BIOREACTOR LANDFILLS	
Figure 1. Conceptual model for HYDRUS-2D simulation of leachate recirculation in MSW landfill using horizontal trench system (a); and detail of a horizontal trench (b).	57
Figure 2. Conceptual model for generation of a random hydraulic conductivity realization using correlation lengths λ_x and λ_z , where $\lambda_x > \lambda_z$, and hydraulic conductivity variance (σ^2) is lognormally distributed.	61
Figure 3. Distribution of wetted area corresponding to degree of saturation $\geq 90\%$ at steady-state using homogeneous and isotropic properties of waste having $k_w = 10^{-4}$ cm/s and $H_i = 2$ m.	65
Figure 4. Simulated recursive average leachate flux versus number of realizations for geostatistical realizations corresponding to Sets 1 and 2.	67
Figure 5. Distribution of wetted area corresponding to degree of saturation $\geq 90\%$ for geostatistical realizations corresponding to Set 1 ($\lambda_x = 10$ m, $\lambda_z = 0.5$ m, and $\sigma^2 = 0.42$) (a); and Set 2 ($\lambda_x = 2$ m, $\lambda_z = 0.5$ m, and $\sigma^2 = 0.42$) (b) for lognormal average $k_w = 10^{-4}$ cm/s and $H_i = 2$ m.	69
Figure 6. Schematic of leachate breakout distance (a); and simulated leachate breakout distance for simulations using Sets 1 and 2 for $k_w = 10^{-4}$ cm/s and $H_i = 2$ m (b).	71
 PAPER NO. 3: NUMERICAL EVALUATION OF PERMEABLE BLANKETS FOR LEACHATE RECIRCULATION IN MSW LANDFILLS	
Figure 1. (a) Conceptual model for simulation of leachate recirculation in MSW landfill using a conventional horizontal trench and permeable blanket alternative using HUDRUS-2D; (b) detail for permeable blanket, (c) detail for horizontal trench.	80

Figure 2. Moisture distribution for leachate recirculation system containing (a) 3 horizontal trenches; and (b) a permeable blanket.	81
Figure 3. Simulated steady state recirculated leachate flux versus leachate injection pressure head for single horizontal trench for $k_w = 10^{-6}$, 5×10^{-6} , and 10^{-5} m/s.	85
Figure 4. Simulated steady-state recirculated leachate flux versus leachate injection pressure head for single horizontal trench and for 30-m-wide and 60-m-wide permeable blankets for $k_w = 10^{-6}$ m/s and k_{HT} & $k_B = 10^{-2}$ m/s.	87
Figure 5. Simulated steady-state recirculated leachate flux versus leachate injection pressure head for 60-m-wide permeable blankets having $k_B = 10^{-3}$, 5×10^{-3} , and 10^{-2} m/s.	89
Figure 6. Simulated steady-state recirculated leachate flux versus leachate injection pressure head for single horizontal trench, seven horizontal trenches spaced at 10m c/c, and a 60-m-wide permeable blanket having k_B and $k_{HT} = 10^{-2}$ m/s.	91
 PAPER NO. 4: Leachate Recirculation Using Horizontal Permeable Blankets in BIOREACTOR Landfills	
Figure 1. (a) Conceptual model used for numerical simulation of leachate recirculation in MSW landfill using a horizontal permeable blanket; and (b) detail of a permeable blanket.	103
Figure 2. Schematic of wetting front of injected leachate in permeable blanket.	107
Figure 3. Effect of k_w on simulated wetted width and pressure head of injected leachate for a 60-m-wide PB for $Q = 1.1 \text{ m}^3/\text{hr/m}$ (a); and $Q = 3.6 \text{ m}^3/\text{hr/m}$ (b).	111
Figure 4. Simulated wetted width of waste and simulated pressure head in the PB as a function of the soil waster characteristic curve used in simulating the waste.	113
Figure 5. Effect of k_B on simulated wetted width and pressure head of injected leachate for a 60-m-wide PB for: (a) $Q = 1.1 \text{ m}^3/\text{hr/m}$; and (b) $Q = 3.6 \text{ m}^3/\text{hr/m}$	114
Figure 6. Effect of PB depth on simulated wetted width and pressure head of injected leachate for a 60-m-wide PB.	116
Figure 7. Simulated wetted width of waste as a function of leachate dosing frequency for a 150-m-wide PB (a); and corresponding simulated pressure head in the PB (b).	120

Figure 8. Contours of Simulated maximum wetted width of waste at steady-state as a function of k_B and k_W for continuous leachate injection rates: (a) $Q = 1.1 \text{ m}^3/\text{hr/m}$; and (b) $Q = 3.6 \text{ m}^3/\text{hr/m}$.	121
Figure 9. Simulated wetted width of waste as a function of the initial degrees of saturation of the waste and permeable blanket for a 150-m-wide PB.	123
Figure 10. Simulated wetted width and pressure head of injected leachate as a function of the degree of saturation of waste (S_W) for a 60-m-wide PB.	125
Figure 11. Simulated wetted width and pressure head of injected leachate versus leachate injection period as a function of the initial degree of saturation of blanket (S_B) for a 60-m-wide PB.	126
Figure 12. Correlation between the wetted width of waste measured in the field and the simulated wetted width of waste for a 60-m-wide PB for k_W ranging from 10^{-7} m/s to 10^{-5} m/s , $S_B = 30\%$, $Q = 1.1 \text{ m}^3/\text{hr/m}$, $S_W = 45\%$ (a); and $S_W = 65\%$ (b).	130
Figure 13. Measured and simulated pressure head of injected leachate in the glass permeable blanket for three leachate injection events corresponding to $Q = 1.1 \text{ m}^3/\text{hr/m}$.	131
 PAPER NO. 5: GEOTECHNICAL SENSING SYSTEM TO MONITOR INJECTED LIQUIDS IN LANDFILLS	
Figure 1. Schematic of a permeable blanket (a) perspective view; and (b) cross section AA'.	1411
Figure 2. Geotechnical sensors used in this study.	1466
Figure 3. Lab evaluation of electrical conductivity of liquid on the measurements by TDR and impedance moisture content sensors.	154
Figure 4. Field response of TDR and impedance moisture content sensors to a leachate injection event.	157
Figure 5. Field response of pressure transducers and thermistors to a leachate injection event.	159
Figure 6. Field response of pressure transducers and impedance moisture content sensors to a leachate injection event.	161
Figure 7. Effect of diurnal air temperature on the field measurements of thermistors and thermocouples.	164
 PAPER NO. 6: LEACHATE RECIRCULATION IN BIOREACTOR LANDFILLS USING GEOCOMPOSITE DRAINAGE MATERIAL	

Figure 1. Schematic of wetted area at steady-state simulated by HYDRUS-2D for leachate recirculation system consisting of: (a) four horizontal trenches; (b) a horizontal permeable blanket; and (c) a sloped permeable blanket.	175
Figure 2. Schematic of an instrumented GDL leachate recirculation blanket: (a) plan view; and (b) cross section AA' through the blanket in west – east direction.	178
Figure 3. Verification of response of impedance moisture content sensor using TDR moisture content sensor at location E 9 m.	184
Figure 4. Migration of leachate in the GDL blanket evaluated by change in temperature and increase in pressure head measured by embedded sensor at location E 4.5 m.	186
Figure 5. Response of impedance moisture content sensors located in the (a) eastern; and (b) western portions of the blanket to a leachate injection event at leachate injection rate equal to $0.9 \text{ m}^3/\text{hr/m}$	188
Figure 6. Effect of leachate injection rate on the rate of travel of leachate in the blanket for leachate injection events corresponding to injection rates equal to 0.9 and $2.6 \text{ m}^3/\text{hr/m}$	190
Figure 7. Correlation between simulated and measured rate of travel of injected leachate for leachate injection events corresponding to injection rates equal to $0.9 \text{ m}^3/\text{hr/m}$	193
Figure 8. Measured and simulated pressure head of injected leachate in the GDL blanket for two leachate injection events corresponding to $Q = 0.9 \text{ m}^3/\text{hr/m}$	194
Figure 9. Leachate injection pressure and leachate injection rate measured at the site.	197
Figure 10. Leachate pressure heads and temperatures within the blanket and waste temperature outside the blanket measured at the site.	198

KEY TO ABBREVIATIONS

ID	= internal diameter
DI	= deionized water
FG	= leachate flow gauge
GDL	= geocomposite drainage layer
GDLs	= more than a single geocomposite drainage layer
GN	= geonet
GT	= geotextile
HDPE	= high density polyethylene
HT	= horizontal trench
HTs	= horizontal trenches
KCl	= potassium chloride
LCS	= leachate collection system
LR	= leachate recirculation
LRS	= leachate recirculation system
MSW	= Municipal solid waste
PB	= permeable blanket
PBs	= permeable blankets
SWCC	= soil water characteristic curve
SWCCs	= soil water characteristic curves
TDR	= time domain reflectometry
TDRs	= more than a single time domain reflectometry
TSS	= total suspended solids

KEY TO SYMBOLS

C_c	= coefficient of curvature
C_u	= coefficient of uniformity
D	= vertical spacing between horizontal trenches in a leachate recirculation system or the vertical spacing between a horizontal trench and leachate collection system
D_{50}	= average particle size diameter
E 4.5 m	= sensor location at 4.5 m east of the injection pipe
G_s	= specific gravity
H_i	= leachate injection pressure head
M	= electrical impedance moisture sensor
N	= total number of horizontal trenches in a leachate recirculation system or number of realizations used to estimate recursive leachate flux, Q_s
NE 9 m	= sensor location at 9 m northeast of the injection pipe
NW 4.5 m	= sensor location at 4.5 m northwest of the injection pipe
P	= piezometer
Q_a	= recursive average of Q_s
Q_{s_i}	= simulated leachate flux at steady-state condition corresponding to the i^{th} realization
Q_s	= simulated leachate recirculated flux at steady-state condition for a single HT
$Q_{s(L)}$	= simulated recirculated leachate flux at steady-state condition for the lower HT in an LRS consisting of 2 HTs positioned vertically
$Q_{s(T)}$	= simulated total recirculated leachate flux at steady-state condition for an LRS consisting of more than one HT
$Q_{s(U)}$	= simulated recirculated leachate flux at steady-state condition for the upper HT in an LRS consisting of 2 HTs positioned vertically
R	= impedance measured by moisture content sensor
S	= sink term in Richards equation
S_e	= effective degree of saturation
SE 9 m	= sensor location at 9m southeast of the injection pipe
SW 4.5 m	= sensor location at 4.5 m southwest of the injection pipe
T	= thermocouple
W 9 m	= sensor location at 9 m west of the injection pipe
W_w	= wetted width of underlying waste
W_B	= saturated wetted width of the permeable blanket
d	= spacing between leachate collection system pipes
h_i	= leachate injection pressure head
h_p	= leachate pressure head
i	= iteration number or realization count
k_B	= saturated hydraulic conductivity of the permeable blanket material
k_{HT}	= saturated hydraulic conductivity of HT backfill
k_{LCS}	= saturated hydraulic conductivity of the drainage material in leachate collection system
k_w	= saturated hydraulic conductivity of MSW
k_{WH}	= saturated hydraulic conductivity of MSW in horizontal direction

k_{wv}	= saturated hydraulic conductivity of MSW in vertical direction
k_s	= saturated hydraulic conductivity
m	= dimensionless fitting parameter for van Genuchten (1980) fitting function for soil-water characteristic curve
n	= dimensionless fitting parameter for van Genuchten (1980) fitting function for soil-water characteristic curve or porosity
s	= lateral spacing between horizontal trenches in a leachate recirculation system
t	= time
t_{LCS}	= thickness of leachate collection system
z	= vertical spatial dimension through the landfill model domain
α	= fitting parameter for van Genuchten (1980) fitting function for soil-water characteristic curve
β	= slope angle of leachate collection system with respect to horizontal
$k(\psi)$	= unsaturated hydraulic conductivity as a function of matric suction head
θ	= volumetric water content
θ_r	= residual volumetric water content
θ_s	= saturated volumetric water content
η_h	= hydraulic efficiency of leachate recirculation system
ψ	= matric suction head
λ_x	= correlation length of waste hydraulic conductivity in the horizontal direction
λ_z	= correlation length of waste hydraulic conductivity in the vertical direction
ρ_d	= dry density
σ^2	= variance in k_w for lognormal distribution

INTRODUCTION

BACKGROUND

In the United States, Resource Conservation and Recovery Act (RCRA) Subtitle D regulations require containment, collection, and treatment of leachate before it is released into the environment. Leachate recirculation (LR) is a leachate management alternative that is commonly practiced in municipal solid waste (MSW) landfills. LR operation consists of injecting leachate into MSW and collecting it using leachate collection system (LCS) located above the lining system at the bottom of the landfill. LR offers significant economical and environmental benefits for MSW landfills. These benefits include: (1) added flexibility in leachate storage; (2) reduction in the leachate disposal and treatment costs; (3) reduction in the discharge of leachate constituents to the environment due to reduction in the volume of leachate treated and discharged by waste water treatment plants; (4) accelerated decomposition and settlement of waste resulting in an airspace gain and an increase in the rate of gas production; (5) faster improvement in the leachate quality; and (6) potential reduction in the post-closure care period and associated maintenance costs.

Currently, there are no specific design guidelines available for designing leachate recirculation systems for MSW landfills. Due to the absence of such design guidelines, these risks and drawbacks cannot be appropriately evaluated: (1) potential decrease in the factor of safety for slope stability of landfills; (2) potential increase in the leachate head on the liner if the leachate collection system is not designed to efficiently drain injected leachate; (3) potential flooding of the gas collection system; and (4) leachate seeps from

the sides of the landfill if an appropriate buffer distance is not provided. Hence, before implementation, landfill operators should weigh the advantages and risks associated with leachate recirculation on a site-specific basis.

CONVENTIONAL LEACHATE RECIRCULATION METHODS

Conventional leachate recirculation techniques can be divided into surface and subsurface application. Surface application consists of: (1) direct application of leachate or spray irrigation of leachate on the landfill surface; or (2) surface ponding of leachate. Surface application is climate dependant, labor intensive, and requires surface availability. Advantages of surface application include potentially uniform infiltration of leachate into the waste and reduction in leachate volume due to a greater evaporation. Disadvantages of surface application include odor problems, poor aesthetics, and potential runoff of applied leachate into storm water management system.

Most commonly used conventional subsurface leachate recirculation systems (LRSs) consist of horizontal trenches (HTs) and vertical wells. HTs are more commonly used in relatively modern landfills, while vertical wells are relatively common in retrofit landfills where it is not cost-effective or possible to install HTs. Unlike surface application, subsurface application is not labor intensive and do not cause odors and direct leachate exposure unless leachate seeps out from the sides of the landfill. Disadvantages of using conventional subsurface LRSs include: (1) higher capital cost for the installation compared to surface application; and (2) need for an excavation during construction resulting in odor problems.

Due to the lack of specific design guidelines, design of the conventional systems is done on an ad hoc basis with no clear understanding of the effect of design parameters on

the long-term performance of the LRS. Lack of specific design guidelines for subsurface LR has resulted in non-uniform wetting of the waste causing: (1) leachate seeps resulting in discharge concerns; (2) differential settlement resulting in increased cap maintenance costs; (3) under-generation of landfill gas affecting gas-to-energy revenues; and (4) lack of understanding to design and implement a monitoring system. Hence, in this dissertation, one of the tasks consisted of performing a numerical parametric study to provide specific design guidelines for subsurface LRSs

NEW LEACHATE RECIRCULATION METHOD

This dissertation evaluates a new subsurface LRS called “permeable blanket” as an alternative LRS for MSW landfills. The permeable blanket (PB) design concept consists of placing a relatively thin and high hydraulic conductivity material on a relatively flat or inclined waste surface in a landfill. A perforated pipe is embedded in the PB in the direction parallel to the shorter or longer plan view dimension of the PB where leachate is injected under a positive pressure. The relatively high permeability of PB results in preferential travel of injected leachate within the blanket before the leachate infiltrates through the underlying waste.

The key advantages of PBs over conventional systems are: (1) excavation of waste is not needed during the construction of the blanket resulting in less odor problems; (2) a PB acts as an engineered heterogeneity and reduces the effect of spatial variation of waste properties when wetting the waste resulting in a relatively uniform distribution of leachate in the landfill; and (3) a PB can substitute multiple horizontal trenches (Figure 1) or vertical wells requiring very little pipe work. PBs made up of granular materials can also

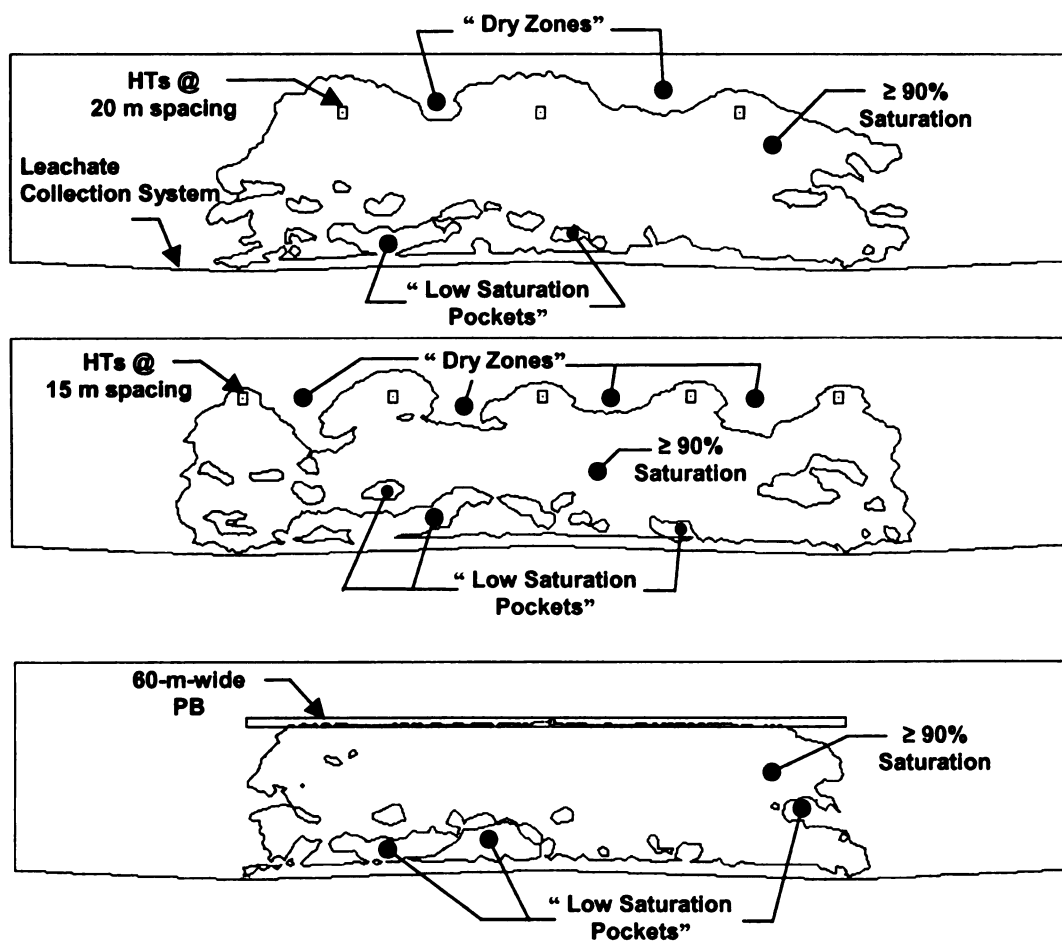


Figure 1. Simulated wetted patterns of leachate recirculation using an LRS consisting of: (a) 3 HTs spaced 20 m; (b) 5 HTs spaced 15 m; and (c) a 60-m-wide PB for a total leachate injection rate of 5.4 m³/hr/m.

provide an ideal platform to embed sensors for monitoring the pressure, temperature, and migration of injected leachate.

Figure 1 presents numerically simulated wetting patterns resulting from LR using HTs (Figures 1a and 1b) versus that for a PB (Figure 1c). Heterogeneity and anisotropy in the hydraulic conductivity of waste was simulated for the waste matrix in this evaluation. The distribution of k_w used for the waste matrix was maintained the same for all scenarios presented in Figure 1 in order to allow comparison under equivalent conditions.

Total leachate injection rate equal to $5.7 \text{ m}^3/\text{hr}/\text{m}$ (cubic meter per hour per meter length of the injection pipe) was simulated for each of the LRS presented in Figure 1. The wetted areas shown in Figure 1 correspond to a degree of saturation $\geq 90\%$ at steady-state condition. Figures 1a and 1b show that an LRS made of HTs can result in the formation of “dry zones”. Dry zones are the zones where injected leachate cannot reach and hence cannot wet the waste. Reducing the lateral spacing and increasing the density of HTs can reduce the formation of dry zones. However, it is relatively expensive. Figures 1a and 1b also present the presence of low saturation pockets. These pockets result from high k_w pockets that do not retain moisture. Figure 1c shows that an LRS made of a PB resulted in a relatively more uniform distribution of injected leachate with less dry zones. However, low saturation pockets similar to those observed for HTs were observed.

Leachate injection rate used for a PB should be chosen such that injected leachate can fill up the entire or required width of the PB without causing excessive pressure buildup in the PB. If injected leachate cannot fill up the design width of a PB, it is not economical to use this PB due to costs associated with the excess material used for constructing the PB. Figure 2 presents the wetting patterns resulting from LR using HTs

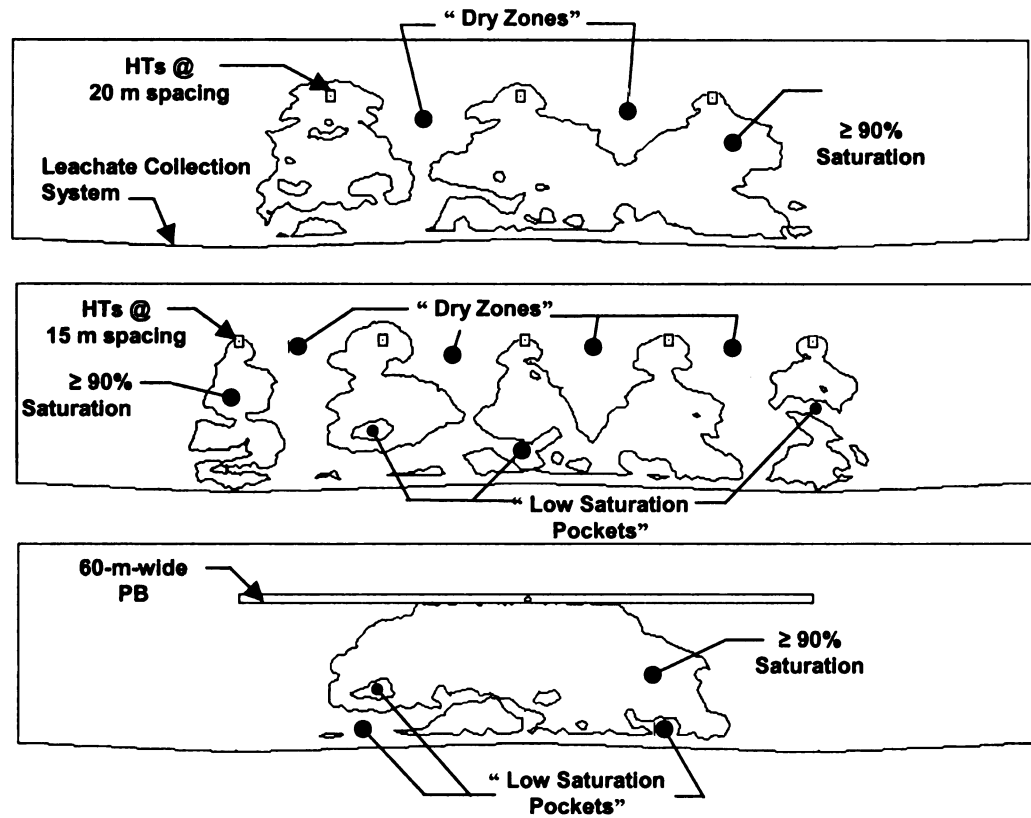


Figure 2. Simulated wetted areas for LRS consisting of: (a) 3 HTs spaced 20 m; (b) 5 HTs spaced 15 m; and (c) a 60-m-wide PB for a total leachate injection rate equal to $2.7 \text{ m}^3/\text{hr}/\text{m}$.

and a PB. The wetted areas shown in Figure 2 correspond to a degree of saturation $\geq 90\%$ at steady-state condition. The leachate injection rate simulated in Figure 2 was equal to $2.7 \text{ m}^3/\text{hr}/\text{m}$, which is half of the injection rate used for the wetted areas presented in Figure 1. The distribution of k_w used for the set of simulations presented in Figure 2 is same as that for simulations presented in Figure 1. Figure 2c when compared to Figure 1c shows that the wetted area for the PB was greatly reduced when the leachate injection rate was reduced to half the value.

There are other concerns that need to be considered when designing an LRS using PBs. Biological activities that occur in landfills may partially or fully clog the PB and decrease its hydraulic conductivity and hence may jeopardize the hydraulic efficiency of the LRS. When a PB settles or sags, to compensate for the elevation head loss, the pump needs to have the adequate head. If PBs are subjected to excessive non-uniform vertical loads, differential settlement may jeopardize the physical integrity and the hydraulic continuity of the blanket and cause disruption in the flow. In addition, liquid pressure heads generated in the blanket during leachate injection periods need to be closely monitored to keep the factor of safety for slope stability of the landfill in an acceptable range.

OBJECTIVES AND METHODOLOGY

The key objectives of this dissertation are to: (1) prepare design guidelines by performing parametric studies for leachate recirculation or liquid addition using HTs and PBs; and (2) evaluate the use of a PB to recirculate leachate for MSW landfills. To achieve the first objective, numerical modeling of HTs and PBs was carried out. To achieve the second

objective, numerical modeling followed by field-scale testing of three instrumented PBs was carried out at an active MSW landfill located in Jackson, Michigan.

The saturated/unsaturated flow model HYDRUS-2D was used to perform the parametric study. The key design parameters simulated in the study were: leachate injection rate or pressure, leachate dosing frequency, geometry of LRS, and hydraulic properties of the waste and LRS.

For the field-scale testing, three 60-m-long and 10-m-wide PBs made up of crushed recycled glass, shredded tires, and a geocomposite drainage material were constructed. Total about 50 sensors were embedded in these blankets to measure moisture content, pore-water pressure, temperature, and vertical stress. Leachate was injected at flow rates ranging from 0.9 m³/hr to 3.6 m³/hr per unit meter length of the injection pipe.

DISSERTATION ORGANIZATION

This dissertation has been organized into six sections. Each section is written in the form of a technical paper. The first paper presents a parametric study, using numerical modeling, for the design of HTs used for leachate recirculation. The second paper addresses the effect of heterogeneity and anisotropy of waste hydraulic properties on the performance of LRSs consisting of HTs. The third paper compares the use of HTs to PBs for recirculating leachate in MSW landfills using a steady-state modeling approach. The fourth paper presents a parametric study for designing LRSs consisting of PBs including field data from the instrumented PB constructed using crushed glass. The fifth paper presents the design of an automated sensing system used in the field to monitor pressure, temperature, and travel of injected leachate in the PBs. The sixth paper presents the

results from field-scale testing of the instrumented PB constructed using a geocomposite drainage material.

PAPER NO. 1: LEACHATE RECIRCULATION USING HORIZONTAL TRENCHES IN BIOREACTOR LANDFILLS

ABSTRACT

Leachate recirculation in municipal solid waste (MSW) landfills operated as bioreactors offers significant economical and environmental benefits. Subsurface leachate recirculation in MSW landfills is commonly achieved by using horizontal trenches or vertical wells. Currently, there are no design guidelines available for leachate recirculation using subsurface leachate recirculation system (LRS). The key objective of this study is to prepare design guidelines for LRS consisting of horizontal trenches. This paper presents a numerical study of LRS consisting of horizontal trenches. The design parameters evaluated in this study include: (1) leachate injection pressure head; (2) hydraulic conductivity of trench backfill and MSW; (3) dimensions of trench; and (4) spacing and geometric formation of trenches. The finite-element saturated/unsaturated flow model HYDRUS-2D was used for the numerical study. The hydraulic performance of the LRS was evaluated primarily using the simulated recirculated leachate flux and distribution of flow under steady-state flow condition. The key findings of this numerical study are: (1) logarithm of leachate flux and leachate injection pressure head have a curvilinear relationship and leachate flux is directly proportional to the hydraulic conductivity of MSW; (2) if hydraulic conductivity of trench backfill is equal to or greater than that of MSW, any further increase in the hydraulic conductivity of the trench backfill has negligible impact on leachate flux; (3) for a given cross sectional area, horizontal trenches having width greater than depth can recirculate greater leachate flux and can wet more area of the waste; and (4) reduction in the horizontal spacing between trenches and vertically

staggering the trenches reduces “dry zones” between trenches where otherwise recirculated leachate may not reach.

INTRODUCTION

Leachate recirculation (LR) is a leachate management alternative that is commonly used for municipal solid waste (MSW) landfills. In the United States, Subtitle D regulations (Resource Conservation and Recovery Act) require containment, collection, and treatment of leachate before it is released into the environment. LR operation consists of injecting leachate into MSW and collecting it using leachate collection system (LCS) located above the lining system at the bottom of the landfill. LR offers many environmental and economical benefits (Doran 1999; Mehta et al. 2002) to MSW landfills including: (1) reduction in leachate treatment and disposal costs; (2) greater flexibility in leachate management and treatment; (3) relatively faster biodegradation of waste resulting in increased gas production and quicker waste stabilization and settlement; (4) reduction in the risk associated with contamination from spills during off-site transportation, treatment, and disposal of leachate; and (5) potential reduction in the post-closure care period of the landfill. Trucking and leachate treatment costs in the U.S. range from approximately \$5 to \$25/m³ (Leachator 2004). Depending upon the site-specific leachate quantities generated, LR can save hundreds of thousands of dollars for a typical medium size landfill over its design life.

Leachate recirculation also has a few disadvantages. These disadvantages include: (1) reduction in the shear strength of MSW potentially reducing the factor of safety against slope stability of the landfill; (2) potential leachate breakouts from the sides of the landfill; and (3) increase in the leachate head build up on the liner

potentially increasing the risk for ground water contamination. Hence, designers and landfills owners are expected to weigh the advantages and disadvantages on a site-specific basis before a leachate recirculation system (LRS) is implemented.

Leachate recirculation can be performed using multiple techniques. These techniques are divided into surface and subsurface application. Surface application consists of: (1) direct application of leachate or spray irrigation of leachate on the landfill surface; or (2) surface ponding of leachate. Odor problems, poor aesthetics, and potential runoff of applied leachate into storm water management system are key the drawbacks of these surface application techniques.

Conventional subsurface application techniques are (Khire and Haydar 2003; Qian et al. 2002): (1) vertical wells; and (2) horizontal trenches (HTs). Unlike surface application of leachate, subsurface LRS do not cause odors and direct leachate exposure unless leachate seeps out from the sides of the landfill. HTs are more commonly used in modern lined landfills. Vertical wells are relatively common in retrofit landfills where it is not cost effective or not possible to install HTs. Currently, there are no specific design guidelines available for designing subsurface LRS. The key objective of this study is to prepare design guidelines for LRS consisting of HTs.

Various cross-sectional dimensions of HTs have been reported in the literature including 0.6-m-wide by 1-m-deep (Maier and Vasuki 1996), 1.0-m-wide by 1.0-m-deep (Miller and Emge 1997), and 0.9 to 1.2-m-wide by 1.2 to 1.8-m-deep (Reinhart and Carson 1993). HTs are backfilled with relatively high conductivity drainage material (e.g. gravel, coarse sand, crushed glass, shredded tires) with a 50 to 150 mm diameter perforated pipe installed at the center of the trench. Leachate is recirculated by injecting leachate into the perforated pipe at positive pressures ranging from 0 to 5 m (SWANA 2002). Townsend and Miller (1998) have presented a field study on

leachate recirculation using horizontal trenches backfilled with shredded tires. Typical horizontal spacing of HTs varies from 3 to 30 m (SWANA 2002). In this paper, in order to meet the key objective, we have evaluated these parameters: (1) leachate injection pressure head; (2) hydraulic conductivity of HT backfill; (3) dimensions of HT; and (4) horizontal spacing and the geometric formation of HTs. We have evaluated the effect of these parameters on the leachate flux that can be recirculated at steady-state (Q_s) using the saturated/unsaturated flow model HYDRUS-2D developed by Simunek et al. (1999).

NUMERICAL MODELING

HYDRUS-2D Computer Model

HYDRUS-2D is a computer model that can simulate water, heat, and solute transport in unsaturated, partially saturated, or fully saturated porous media (Simunek et al. 1999). The program numerically solves the Richards' Equation for saturated/unsaturated water flow. A 2-D form of Richards' equation can be expressed as follows:

$$\frac{\partial \theta}{\partial t} = -\frac{\partial}{\partial x}\left[k(\psi)\frac{\partial \psi}{\partial x}\right] - \frac{\partial}{\partial z}\left[k(\psi)\frac{\partial \psi}{\partial z}\right] + \frac{\partial k(\psi)}{\partial z} - S \quad (1)$$

where θ = volumetric water content; ψ = matric suction head; k = hydraulic conductivity of the porous material which is strongly dependant on the soil suction or water content; z = vertical dimension; S = volume of water removed per unit time per unit volume of soil by plant water uptake (sink term); and t = time.

HYDRUS-2D was selected for this study due to its diverse capabilities. HYDRUS-2D can be used to simulate flow regions delineated by irregular boundaries. The boundaries can be selected as constant or time-variable prescribed head, flux, or controlled by atmospheric conditions. The flow region can be simulated

with an arbitrary degree of local anisotropy and heterogeneity. The model also has a built-in database for hydraulic properties of soils and can incorporate hysteresis in the soil-water characteristic curves. The model can present the output in a graphical format as plots or contours of water content, pressure head, and velocity. This model has been used for saturated/unsaturated liquid and solute transport through porous media in several studies (Scanlon et al. 2002; Henry et al. 2002; Pang et al. 2000; Rassam et al. 2002).

Conceptual Model and Assumptions

A schematic of the conceptual model used to simulate the LRS is presented in Figure 1. We simulated leachate as pure water in this study. Henceforth, any reference to leachate flow corresponds to water flow. Nevertheless, the results of this study can be applied to any liquids as long as the liquid has physical and hydraulic properties that are relatively close to water. The effects of gas flow, temperature, and biochemical reactions occurring within a landfill were ignored. The maximum leachate injection head simulated was 5 m to cover the maximum injection head that has been used in the field (SWANA 2002). Most existing landfills where leachate is recirculated use less than 5 m injection head to reduce leachate breakouts and to keep the factor of safety against slope stability failure of the landfill in an acceptable range (SWANA 2002).

Korfiatis et al. (1984) have demonstrated success when the authors applied Richards's equation for saturated and unsaturated flow to a lab-scale MSW sample having 0.5 m diameter and 1.5 m height. A wide variety (size and composition) of organic and inorganic MSW deposited in landfills results in MSW that exhibits heterogeneity and anisotropy in its hydraulic properties. Hence, the soil-water

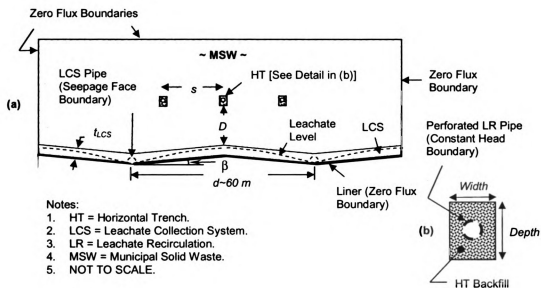


Figure 1. Conceptual model for HYDRUS-2D simulation of leachate recirculation in MSW landfill using horizontal trench system (a); and detail of a horizontal trench (b).

characteristic curves for waste can vary significantly. McCreanor (1998) simulated the effect of daily cover on the spread of recirculated leachate and found that daily cover having lower hydraulic conductivity than waste can enhance lateral spreading but restrict vertical spreading of leachate. The flow pattern of leachate is also affected by channeling (Zeiss and Ugguccioni 1995). In this numerical study, we assumed MSW as a homogeneous and isotropic porous medium. Effect of channeling was not considered in this study. Even though this assumption may not be completely in line with field conditions, the results from this numerical study can be useful in comparing designs or to investigate alternatives during an iterative design phase of an LRS (Straub and Lynch 1982). The effect of heterogeneity and anisotropy of MSW on the hydraulic performance of LRS consisting of HTs is presented in detail by Haydar and Khire (2005). Haydar and Khire (2005) found that the introduction of heterogeneity and anisotropy resulted in a greater leachate flux compared to that when waste was assumed homogenous and isotropic for an equivalent average hydraulic conductivity of the waste.

Boundary Conditions and Mass Balance

All external boundaries were simulated as zero-flux boundaries (Figure 1). Leachate flow as a result of percolation from the cap or waste above the model domain was assumed zero. We believe that this assumption is reasonable because our key objective in this study was to evaluate the subsurface hydraulics of recirculated leachate. The perforated pipe used for leachate injection was simulated as a constant head boundary (Figure 1b). The diameter of the leachate injection pipe was assumed equal to 0.1 m based on what is commonly used in the field. The leachate injection pressure heads ranged from zero (gravity drainage) to 5 m. The leachate injection

pressure head assigned as constant head was exclusive of head loss in pipes, joints, manifolds, and pumps used in a typical LRS.

We also conducted a limited number of simulations by assigning the perforated leachate injection pipe as a constant flux boundary. These simulations yielded the same constant head at the injection pipe for the corresponding flux at steady-state. Thus, assigning the leachate injection pipe as a constant head or constant flux boundary yields the same result for steady-state flow condition.

Leachate collection pipes embedded in the LCS were simulated as seepage face boundaries. The diameter of such LCS pipes was assumed equal to 0.15 m. The minimum size of the finite-elements used for discretization of the problem domain, the time step, and the error tolerances for pressure head and water content were selected such that cumulative water balance error did not exceed 0.1%. In order to achieve such a low mass balance error, the problem domain was divided into triangular finite elements having maximum dimensions ranging from 1 mm to 25 mm. We used an error tolerance of 0.1% for the volumetric water content and 10^{-4} m for the matric suction. We used a minimum time step of 8×10^{-6} second and a maximum time step of 8 hours. HYDRUS-2D gradually increases the time step automatically if mass balance and error tolerance criteria are met. Typically it took about 1 to 2 days for completing a simulation on a Pentium 2.5 MHz processor.

Hydraulic Properties

Three material types were selected for simulating the key components of the LRS. These three components included MSW, HT backfill, and the LCS. The three materials for these components were simulated as homogeneous and isotropic porous materials. The materials and the saturated hydraulic conductivities of these materials are presented in Table 1.

Table 1. Saturated and unsaturated hydraulic parameters input to HYDRUS-2D to simulate leachate recirculation system consisting of horizontal trenches.

Landfill Unit	Material	θ_r	θ_s	α (1/m)	n	k_s (m/s)
MSW	Silt loam	0.067	0.45	2	1.41	10^{-5} , 10^{-6} , & 10^{-7}
HT Backfill	Pea gravel	0.01	0.3	57.44	2.44	10^{-2}
	Sand	0.045	0.43	14.5	2.68	10^{-4}
LCS	Pea gravel	0.01	0.3	57.44	2.44	10^{-2}

Notes: MSW = municipal solid waste; HT = horizontal trench; LCS = leachate collection system.

The hydraulic conductivities of MSW, k_w , were selected based on the typical values published by Hughes et al. (1971), Fungaroli and Steiner (1979), Korfiatis et al. (1984), Oweis et al. (1990), and Bleiker et al. (1993). The hydraulic conductivities of the HT backfill, k_{HT} , were selected based on the values for pea gravel, shredded tires, or coarse sand which are commonly used as the HT backfill material (Doran 1999). The hydraulic conductivity of the LCS drainage material, k_{LCS} , was selected based on the values for pea gravel which is commonly used for constructing LCS of MSW landfills. The unsaturated hydraulic properties for the materials listed above consisted of the van Genuchten (van Genuchten 1980) fitting parameters for the soil-water characteristic curves and unsaturated hydraulic conductivity function (Table 1). The soil-water characteristic curves for the materials simulated are represented by the van-Genuchten model (van Genuchten 1980) as follows.

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{\left(1 + |\alpha\psi|^n\right)^m} \quad (2)$$

where ψ = matric suction head; θ = water content; θ_s = saturated water content; θ_r = residual water content; and α , n , and m ($m = 1 - n^{-1}$) are fitting parameters. HYDRUS-2D model uses the van Genuchten-Mualem (Mualem 1976) function to predict the unsaturated hydraulic conductivities using the van Genuchten fitting parameters and the saturated hydraulic conductivities. The unsaturated hydraulic conductivities are estimated by using the van Genuchten-Mualem model (Mualem 1976) presented in Equation 3.

$$k(\psi) = k_s S_e^{0.5} \left[1 - \left(1 - S_e^{\frac{1}{m}} \right)^m \right]^2 \quad (3)$$

where S_e is effective degree of saturation; k_s is saturated hydraulic conductivity; $k(\psi)$ is unsaturated hydraulic conductivity function; ψ is the matric suction; and m is the fitting parameter for the soil-water characteristic curve.

The unsaturated hydraulic properties for the materials were selected from the database built into HYDRUS-2D for soils having saturated hydraulic conductivities closest to the assumed saturated hydraulic conductivities. Except for the saturated hydraulic conductivity, rest of the parameters presented in Table 1 do not have any influence on the leachate flux predicted by the model at steady-state flow condition. However, transient leachate flux before the steady-state is reached is a function of the initial conditions and all saturated and unsaturated hydraulic parameters presented in Table 1. The time to reach steady-state is primarily a function of the initial moisture content, the injection pressure head, and the unsaturated hydraulic properties of the waste. The unsaturated hydraulic properties also influence the water content profile in the capillary zone of the LRS where degree of saturation is less than 100%. In this paper we have presented the leachate flux after the steady-state flow condition was reached. Transient analysis of leachate recirculation is beyond the scope of this study.

Dimensions

The dimensions of the simulated rectangular HT ranged from 0.6- to 2-m-wide by 1- to 2-m-deep. These dimensions were selected based on the most common designs used at existing landfills (Miller and Emge 1997; Doran 1999). The thickness of the LCS layer, t_{LCS} , was assumed equal to 0.3 m. The U.S. EPA Subtitle D regulations require that the leachate head on the liner not exceed 0.3 m. The hydraulic conductivity of the LCS drainage material, k_{LCS} , was assumed equal to 10^{-2} m/s. The spacing between the adjacent leachate collection pipes, d , was assumed equal to 60 m (Figure 1a). The slope ($\tan\beta$) of the LCS was assumed equal to 3.5%. These LCS

design parameters (t_{LCS} , k_{LCS} , d , and $\tan\beta$) resulted in less than 0.3 m leachate head on the liner for all simulations conducted in this study. The leachate head on the liner was continuously monitored using observation points distributed along the liner. The vertical distance, D , between the row of HTs and the top of the LCS was assumed equal to 15 m. When this distance was varied in the model, we found that leachate flux at steady-state was not affected for distances greater than or equal to 3 m. Distance from the top of the horizontal trench to the upper zero flux boundary was assumed equal to 8 m to contain all leachate flow and to prevent artesian conditions under the simulated leachate injection heads of up to 5 m.

MODELING RESULTS

In this study, over 100 simulations using HYDRUS-2D were conducted to evaluate the effect of the design parameters on the steady-state leachate flux, Q_s . We assumed the leachate flux reached steady-state when the injected leachate flux equated the total leachate flux seeping from the LCS pipes located within the LCS (Figure 1a). Note that Q_s in $\text{m}^3/\text{d}/\text{m}$ represents the leachate flux that can be recirculated at steady-state in cubic meters per day per linear meter length of the HT perpendicular to the plane of the paper.

Leachate recirculation in the field is often carried out in on/off dosing cycles. Hence, steady-state flow condition can be rarely achieved in the field. In the field, when the LRS is turned off, gravity drainage of leachate creates storage space in the voids of MSW. Until steady-state is reached, leachate flux greater than Q_s can be recirculated in the landfill for a given injection head.

Q_s represents the lower limit of leachate flux that can be recirculated in a landfill for the given set of design parameters. Hence, a LRS designed using the Q_s values presented in this manuscript would be conservative.

Effect of Leachate Injection Pressure Head

The simulated leachate injection pressure head, H_i , ranged from 0 to 5 m. The HT simulated to evaluate the effect of injection pressure head was 0.6-m-wide by 1-m-deep. Figure 2 shows a curvilinear relationship between H_i and $\log Q_s$. The shape and approximate dimensions of the wetted area correspond to degree of saturation ranging from 45% to 90% at steady-state for $H_i = 5$ m and $k_w = 10^{-6}$ m/s are presented in Figure 3a. Figure 3a shows that the wetted area corresponding to a lower degree of saturation is larger. Figure 3b presents the shape and approximate dimensions of the wetted area at steady-state for degree of saturation $\geq 90\%$ and for H_i ranging from 0 to 5m. Figure 3b shows that as injection head increases the wetted area corresponding to degree of saturation $\geq 90\%$ at steady-state expands and hence Q_s increases.

To illustrate the wetted area at steady-state, we have selected degree of saturation $\geq 90\%$. However, we are not endorsing the idea of saturating waste to 90% during leachate recirculation. Target degree of saturation to achieve optimum bioreactor performance is beyond the scope of this study. We believe that the degree of saturation to achieve optimum bioreactor performance will vary based on composition, density, organic fraction, waste temperature, and meteorological factors. We recommend design engineers and landfill operators to select a target degree of saturation based on site-specific factors. Our modeling results show that the shape and size of the wetted area corresponding to degree of saturation $\geq 90\%$ are independent of k_w . This finding is similar to saturated flow through homogeneous and isotropic

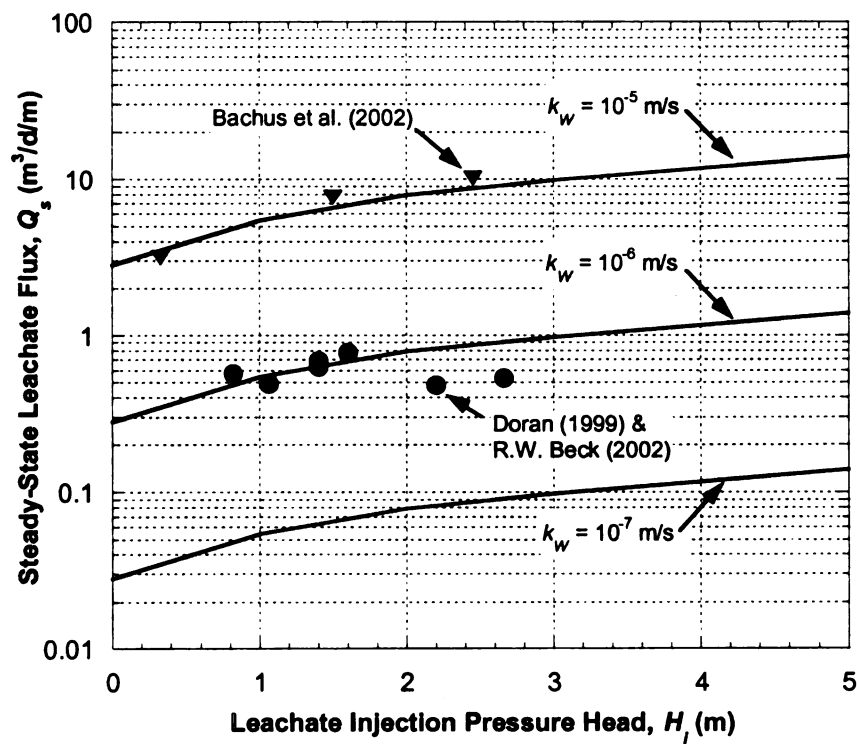


Figure 2. Simulated leachate flux at steady-state versus leachate injection pressure head for a 0.6-m-wide by 1-m-deep single HT for $k_w = 10^{-7}$, 10^{-6} , and 10^{-5} m/s.

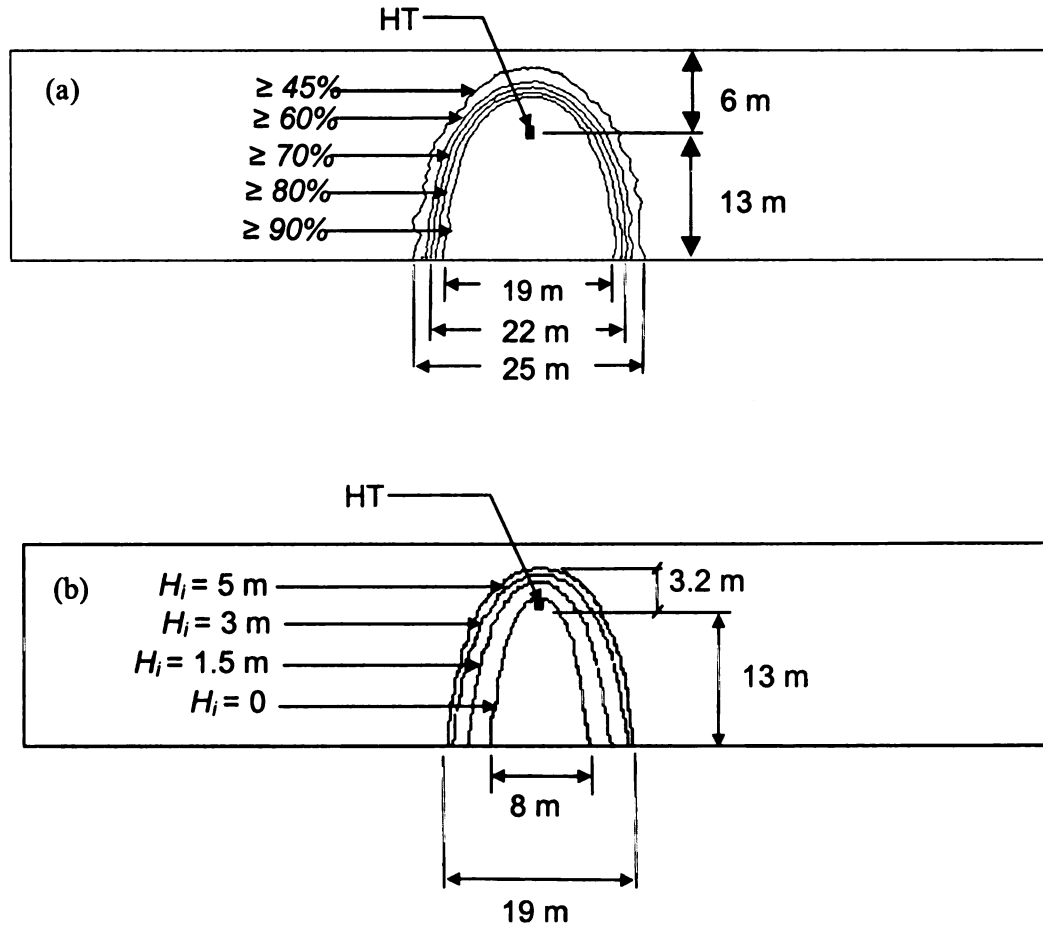


Figure 3. Simulated wetted areas at steady-state for 0.6-m-wide by 1.0-m-deep single HT for $k_w = 10^{-6}$ m/s for (a) $H_i = 5$ m (degree of saturation $\geq 45\%$ to $\geq 90\%$); and (b) H_i ranging from 0 to 5 m (degree of saturation $\geq 90\%$).

porous materials analyzed using a flow net. The shape of the flow net is independent of the hydraulic conductivity of the homogeneous and isotropic soil

For a given H_i , Q_s is directly proportional to k_w . Thus, if k_w is increased or decreased by an order of magnitude, assuming all other parameters remain constant, Q_s would also increase or decrease by an order of magnitude, respectively. McCreanor and Reinhart (1999) have reported leachate recirculation rates of 2 to 8 m³/d per linear meter of HT. These values correspond to Q_s that we simulated for k_w ranging from 5×10^{-6} to 10^{-6} m/s and H_i ranging from 0 to 5 m. In order to validate the modeling results presented in Figure 2, we compared the simulated Q_s to the values for HTs measured in the field by Doran (1999) and to that simulated by Bachus et al. (2002). We have discussed the validation of our modeling results in detail in a section entitled “Model Validation” in this manuscript.

Effect of Hydraulic Conductivity of Trench Backfill

HTs are typically backfilled with granular material such as gravel, crushed recycled glass, shredded tires, or coarse sand. The backfill is used to enhance the distribution of leachate, to protect the perforated leachate injection pipe by providing a bedding layer for a relatively uniform support, and to prevent clogging of the pipe from fines in the surrounding MSW. For a 0.6-m-wide by 1.0-m-deep HT, we varied k_{HT} from 10^{-4} to 10^{-2} m/s, k_w was varied from 10^{-6} to 10^{-5} m/s and H_i was varied from zero to 5 m. The simulations indicated no significant impact on the magnitude of Q_s and on the shape of the wetted area when k_{HT} was equal to or greater than k_w . For example, when k_w was 10^{-6} m/s and k_{HT} was equal to 10^{-6} , 10^{-5} , 10^{-4} m/s or more, it resulted in about the same Q_s . However, when k_{HT} was reduced below 10^{-6} m/s, Q_s decreased. Because the cross sectional area of an HT represents a relatively small area fraction and MSW represents a much larger area fraction of the model domain (Figure 1), until k_{HT} drops

below k_w , the equivalent hydraulic conductivity of the model domain does not alter significantly to impact Q_s . Henceforth, for all simulations, we used $k_{HT} = 10^{-2}$ m/s.

Effect of Horizontal Trench Geometry and Size

We evaluated the effect of HT size (width and depth) by maintaining k_w constant at 10^{-6} m/s and varying the width and depth from 0.6 to 2 m. Four combinations of HT sizes were simulated. The results are presented in Figure 4. Figure 4 shows that Q_s increases with increase in the cross-sectional area of the HT. The increased cross sectional area of HT results in a wider wetted area and hence a greater leachate wetting volume. Greater leachate wetting volume results in greater Q_s . However, for a given area of an HT, width greater than depth results in greater Q_s . This finding is also confirmed by Khire and Haydar (2003) where the authors have demonstrated that relatively thin but laterally extensive blankets can recirculate relatively large leachate flux. The difference in Q_s for the four combinations of trench sizes presented in Figure 4 is relatively small. This is because the cross sectional area of HT represents a relatively small area fraction of the model domain (Figure 1). Henceforth, for all simulations we used 0.6-m-wide by 1.0-m-deep HTs.

Effect of Horizontal Trench Spacing

The horizontal spacing, s , between adjacent HTs is one of the key parameters in LRS design. It affects the volume, duration, and frequency of leachate dosing cycle for the LRS. If the HT spacing is reduced, it translates into additional number of trenches for a given coverage area, which increases the capital cost. For a given injection pressure head, the spacing required to achieve degree of saturation $\geq 90\%$ to virtually eliminate dry zones between adjacent trenches can be estimated by comparing the wetted area corresponding to degree of saturation $\geq 90\%$ at steady-state. A dry zone is that region

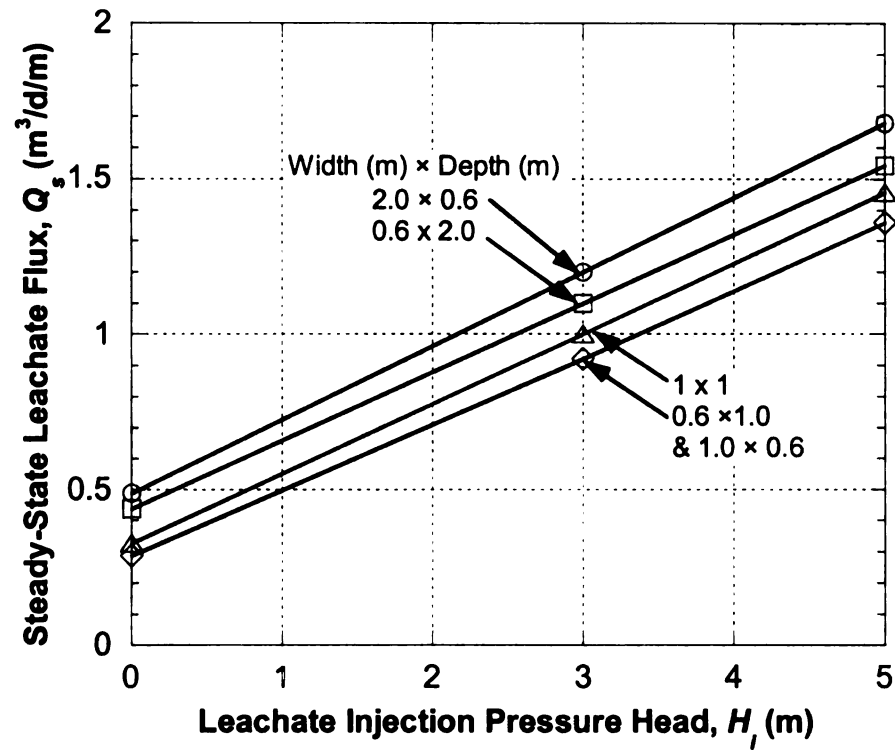


Figure 4. Simulated leachate flux at steady state versus leachate injection pressure head as a function of width and depth of HT for $k_w = 10^{-6}$ m/s.

of MSW where recirculated leachate may not reach. Figure 5a presents the wetted area corresponding to degree of saturation $\geq 90\%$ for $H_i = 1.5$ m at steady-state for $s = 10$ m.

Figure 5b presents the wetted area corresponding to greater than 90% saturation for $H_i = 1.5$ m at steady-state for $s = 15$ m. At 10-m-spacing, the wetted areas corresponding to degree of saturation $\geq 90\%$ do overlap. Hence, at spacing equal to or less than 10 m, dry zones would not result or would be relatively small. However, at 15 m or greater spacing, the wetted areas corresponding to degree of saturation $\geq 90\%$ do not overlap. Hence, relatively large area of dry zones would result for spacing equal to or greater than 15 m for $H_i = 1.5$ m. If H_i is increased, the area of dry zones would shrink.

For LRS consisting of two or more HTs, we have used the indicator parameter hydraulic efficiency (η_h) to quantify the hydraulic efficiency of the LRS and the relative area of dry zones. This parameter can be used to optimize the LRS design. We have computed η_h by dividing the total flux of LRS achieved at steady-state [$Q_{s(T)}$] by the product of number of HTs in the LRS, N , and the leachate flux achieved at steady-state for LRS consisting of a single HT, Q_s , as presented in Equation 4.

$$\eta_h = \frac{Q_{s(T)}}{N \times Q_s} \quad (4)$$

Hydraulic efficiency, as defined by equation 4, can never exceed 100%. If η_h is equal to 1 or 100%, it means that the HT spacing is such that wetted areas corresponding to degree of saturation $\geq 90\%$ do not overlap for a given H_i . Thus, there is a good likelihood that dry zones would result. If η_h is less than 100%, wetted areas corresponding to degree of saturation $\geq 90\%$ will overlap for a given H_i . Hence, there would be less likelihood for dry zones to result. As η_h further decreases, the wetted

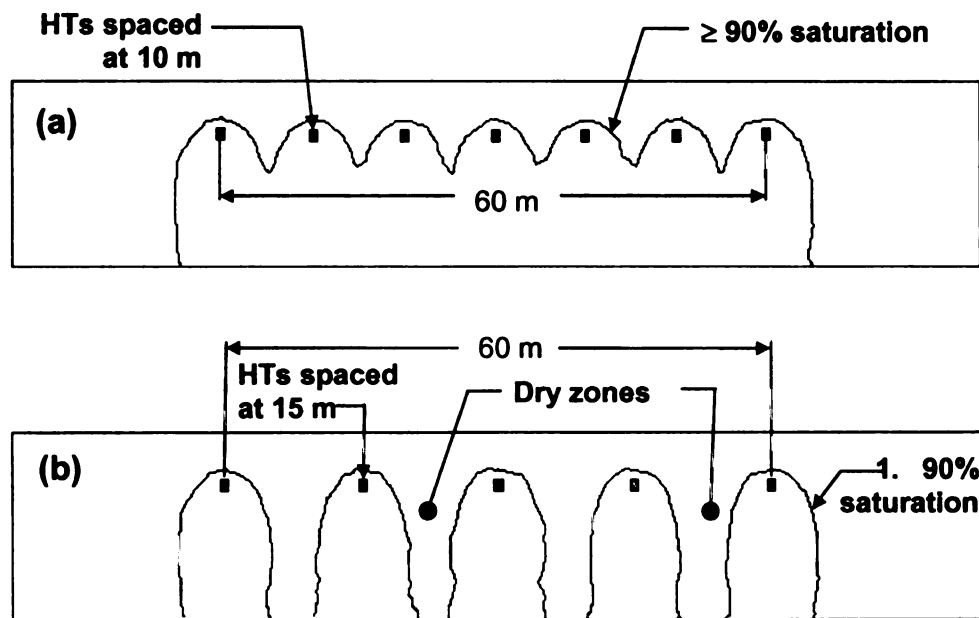


Figure 5. Distribution of wetted area corresponding to degree of saturation $\geq 90\%$ at steady-state for LRS consisting of seven HTs at 10-m-horizontal spacing (a); and five HTs at 15 m spacing (b) for $k_w = 10^{-6}$ m/s and $H_i = 1.5$ m.

areas would further overlap and this will result in a more uniform wetting. However, it will decrease the hydraulic efficiency of the LRS (Eq. 4) and will increase the capital cost associated with greater number of HTs required for the LRS. If the key objective of the LRS is to minimize dry zones, the spacing shall be selected such that η_h is slightly less than 100%.

For a given k_w and for $k_{HT} > k_w$, η_h is a function of s and H_i . Figure 6 shows that reducing s beyond a certain spacing for a given H_i reduces η_h . If H_i is increased, s can be increased without increasing the area of dry zones. Hence, for a given s , a greater H_i can result in a lower value of η_h because the overlap of the wetted areas corresponding to degree of saturation $\geq 90\%$ increases (Figure 6).

We simulated $s = 5, 7.5$ and 10 m over a 30 m width resulting in $7, 5$, and 4 total HTs respectively. We maintained k_w constant at 10^{-6} m/s. Figure 7a shows a relatively small increase in total Q_s [or $Q_{s(T)}$] as s is reduced and N is increased. Figure 7b shows a decrease in η_h as s is decreased. As s is reduced, wetted area corresponding to degree of saturation $\geq 90\%$ for adjacent HTs begins to overlap. This reduces the dry zones and reduces η_h for the LRS. Data presented in Figure 7 combined with the shape and size of the wetted area presented in Figure 3b for an individual HT can be used to optimize the horizontal spatial distribution of HTs to achieve a relatively uniform wetting of the MSW.

Al-Yousfi et al. (1992) presented an analytical approach to estimate the maximum spacing for horizontal perforated leachate injection pipes of an LRS consisting of HTs under the final cap of a sanitary landfill. The authors proposed Equation 5 for the maximum distance between consecutive perforated injection pipes:

$$s = 2H_i \left(\frac{k_w H}{k_{wV}} \right)^{0.5} \quad (5)$$

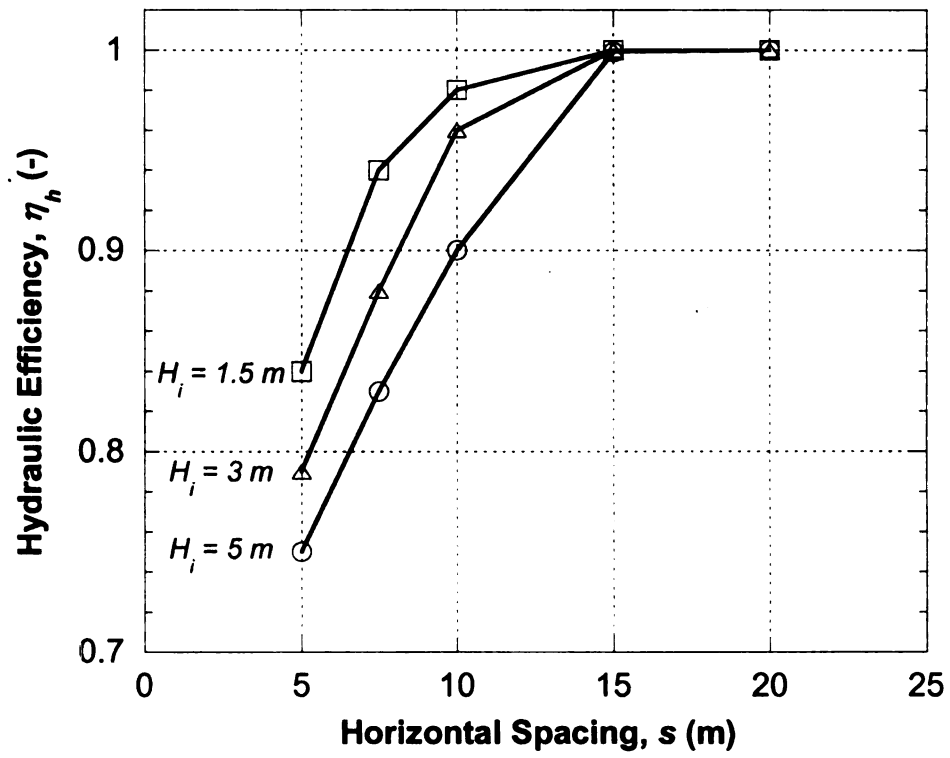


Figure 6. Effect of horizontal spacing between HTs and leachate injection pressure head on the hydraulic efficiency for LRS consisting of two HTs in a row for $H_i = 1.5$, 3, and 5 m and $k_w = 10^{-6} \text{ m/s}$.

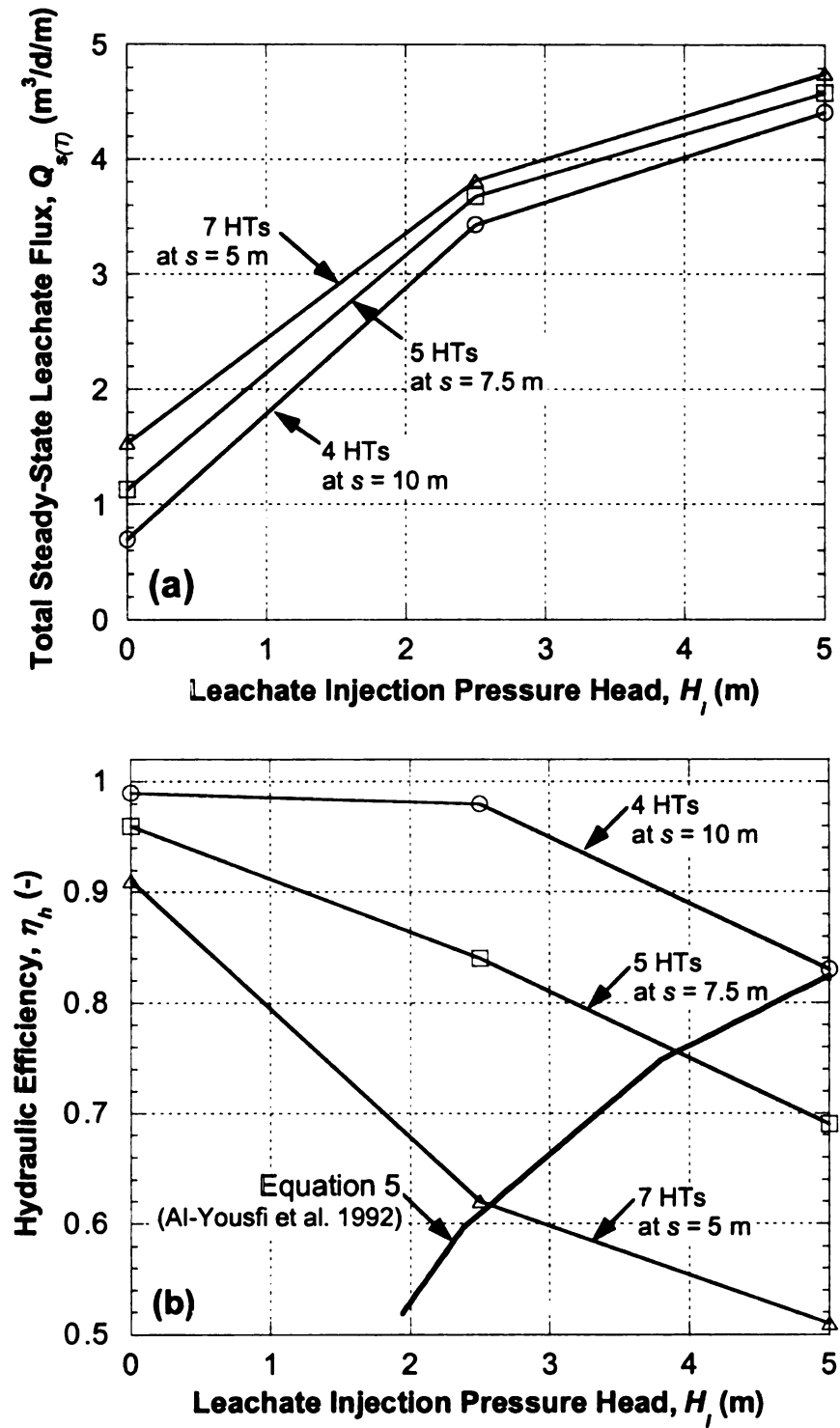


Figure 7. (a) Simulated total leachate flux at steady-state versus leachate injection pressure head for LRS consisting of four, five, and seven HTs spaced horizontally at $s = 10, 7.5$, and 5 m for $k_w = 10^{-6}$ m/s; and (b) hydraulic efficiency.

where s is the distance between horizontal injection pipes; H_i is the leachate injection head; and k_{wH} and k_{wV} are the horizontal and vertical hydraulic conductivities of waste, respectively.

For homogeneous and isotropic MSW, hydraulic conductivity is equal in all directions ($k_{wH} = k_{wV}$). Hence, Equation 5 converts to: $s = 2 \times H_i$. Equation 5 is plotted in Figure 7(b) for $s = 5, 7.5$, and 10 m. The plot of Equation 5 in Figure 7b indicates that η_h is about 60%, 75%, and 84% when HTs are spaced at 5, 7.5, and 10 m and operated at $H_i = 2.5, 3.8$, and 5 m, respectively. These values of η_h are far below 100%. Hence, if HTs are spaced based on Equation 5, wetted areas of the adjacent HTs would overlap significantly when $H_i \leq 5$ m. Hence, design based on Eq. 5 would be extremely conservative.

Effect of Vertical Spacing

We evaluated the effect of vertical spacing, D , between HTs by simulating two HTs separated vertically by a distance, $D = 1, 5, 10, 15$ and 30 m for $k_w = 10^{-6}$ m/s and $H_i = 1.5$ and 5 m. Figure 8 presents η_h as a function of D for $H_i = 1.5$ and 5 m. Figure 8 shows that as D is reduced, η_h decreases. For a given value of D , η_h increases as H_i increases (Figure 8). We also observed that simulated leachate flux at steady-state for the upper HT [$Q_{s(U)}$] is greater than that for the lower HT [$Q_{s(L)}$]. Table 2 presents these ratios: $Q_{s(U)} / [Q_{s(U)} + Q_{s(L)}]$ and $Q_{s(L)} / [Q_{s(U)} + Q_{s(L)}]$ for $H_i = 5$ m and for D ranging from 1 to 30 m. Note that $Q_{s(U)} + Q_{s(L)} = Q_{s(T)}$. As D is reduced, the overlap of the wetting front of the HTs increases. This leads to decrease in $Q_{s(T)}$. Table 2 and Figure 8 show that once the vertical spacing is 15 m or more, η_h of the LRS reaches a constant value of about 85% for $H_i = 5$ m. At lower values of H_i , D corresponding to $\eta_h = 85\%$ is greater than 15 m (Figure 8).

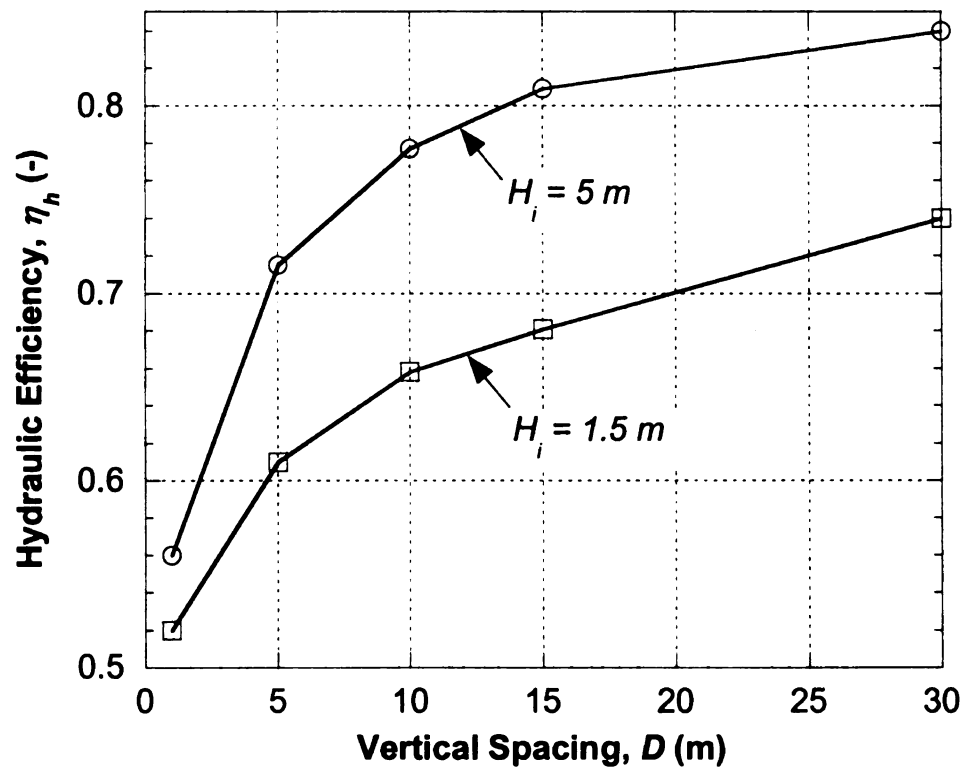


Figure 8. Hydraulic efficiency as a function of vertical spacing for LRS consisting of two vertically positioned HTs for $H_i = 1.5$ and 5 m and $k_W = 10^{-6}$ m/s.

Table 2. Effect of vertical spacing between HTs on the hydraulic efficiency of LRS.

Vertical Spacing, <i>D</i> (m)	$\frac{Q_{S(U)}}{Q_{S(T)}}$	$\frac{Q_{S(L)}}{Q_{S(T)}}$	$\frac{Q_{S(T)}}{2 \times Q_S}$
1	0.65	0.42	0.53
5	0.83	0.57	0.70
10	0.91	0.61	0.76
15	0.97	0.62	0.80
30	0.99	0.64	0.82

Figure 9 presents η_h as a function of H_i for LRS consisting of two and three HTs spaced vertically at $D = 5$ m. Figure 9 shows that, for a given value of H_i , η_h decreases as total number of HTs increases. This occurs because there is a greater overlap of wetted areas of adjacent HTs.

Effect of Geometric Formation of HTs

It is common practice to install HTs in individual cells of a landfill at various elevations depending upon the permitted height of the cell and filling schedule. We simulated four possible geometric formations of HTs that are or could be used in LRS to evaluate the shape and size of wetted areas and the effect on η_h . These formations are presented in Figure 10. The vertical distance, D , between two consecutive rows (R1, R2, or R3) of HTs, was fixed at 15 m. H_i was varied from zero to 5 m and k_w was fixed at 10^{-6} m/s. Horizontal spacing, s , was set at 20 m for all rows of HTs presented in Figure 10. Figure 10 shows the wetted area at steady-state for degree of saturation $\geq 90\%$ for $H_i = 3$ m. Figure 11 shows η_h for formations A, B, and C.

Figure 10 indicates that vertically staggered HTs (Formations A and C) resulted in the least area of dry zones. Figures 5 and 6 show that if horizontal spacing between HTs is less than or equal to 10 m, the wetted areas of individual HTs corresponding to $\geq 90\%$ degree of saturation overlap and hence minimize dry zones. Formation D in Figure 10 shows that at 20 m horizontal spacing, there would be significant area of dry zones for $H_i = 3$ m. However, Formations A and C in Figure 10 show that if HTs can be installed at various elevations, it allows us to double the horizontal spacing between HTs for a given row to about 20 m as long as the HTs are staggered. Figure 11 shows that η_h for Formations A and C is greater than that for Formation B. Figure 11 shows that if Formations A or C are to be implemented, a horizontal spacing of 20

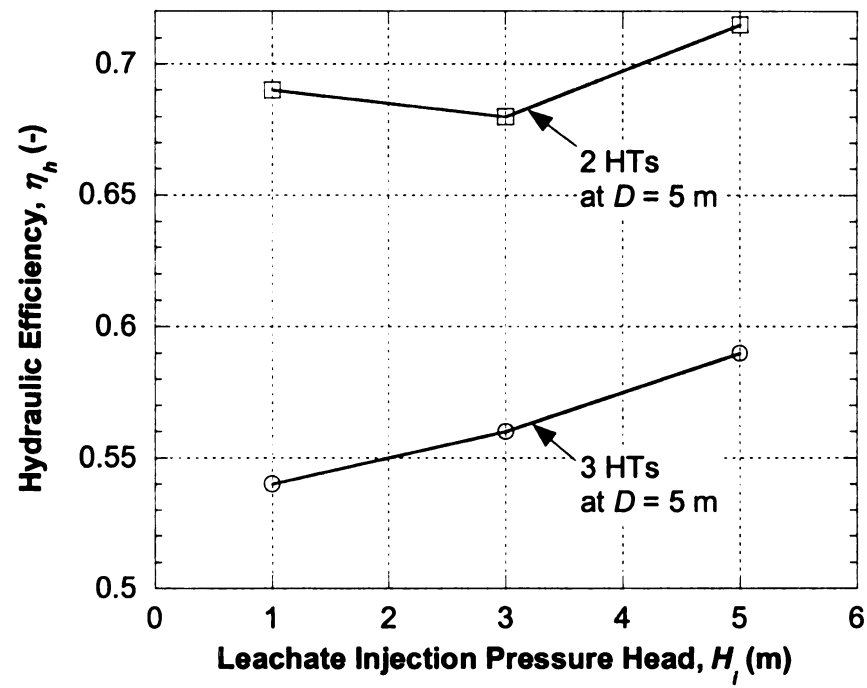
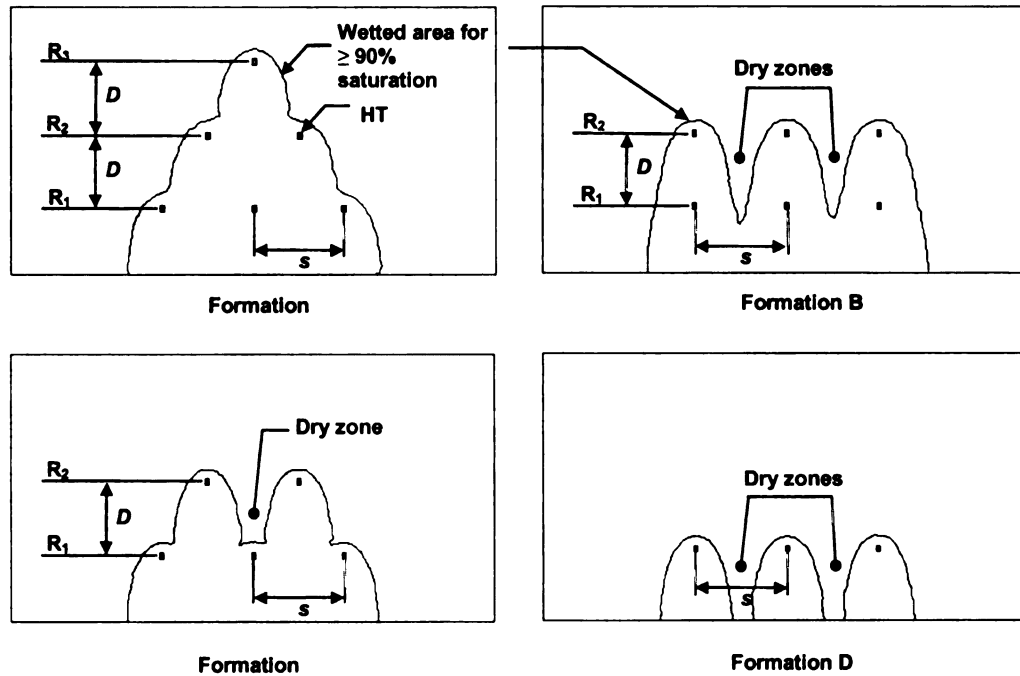


Figure 9. Hydraulic efficiency as a function of number of HTs positioned vertically at a fixed spacing of 5 m and for $k_w = 10^{-6}$ m/s.



Notes:
 R_1 = Row 1, R_2 = Row 2, and R_3 = Row 3
 D = Vertical distance between two successive rows of HTs
 s = center to center spacing between HTs

Figure 10. Pattern of wetted area at degree of saturation $\geq 90\%$ at steady-state for geometric formations A, B, C and D for $H_i = 3$ m, $k_w = 10^{-6}$ m/s, $s = 20$ m, and $D = 15$ m.

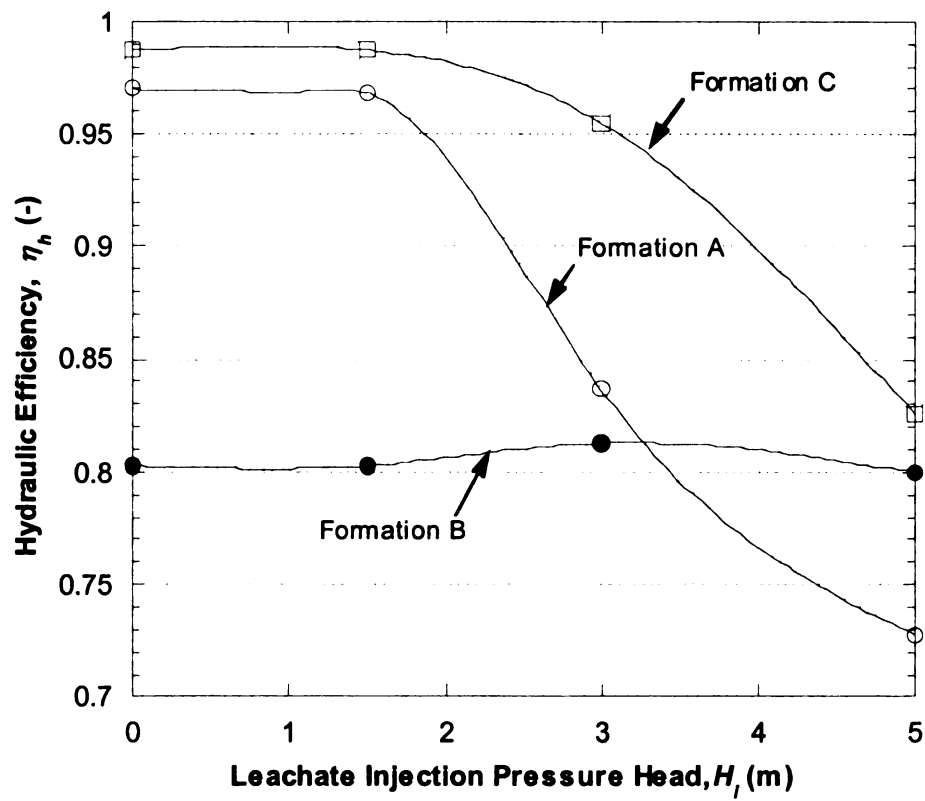


Figure 11. Hydraulic efficiency for formations A, B, and C presented in Figure 10.

m at an injection head of 2 to 3 m would be sufficient to significantly reduce dry zones. Thus, vertical staggering of HTs allows to increase the horizontal spacing between HTs for a given row.

MODEL VALIDATION

The numerical study presented in this paper is primarily based on numerical modeling conducted using HYDRUS-2D. MSW is a highly heterogeneous and anisotropic material consisting of pore fluid (leachate) having complex geochemical properties. Heterogeneity and anisotropy of MSW may not ever be fully characterized or the cost of characterization using conventional field methods would exceed the benefits of such characterization in design or operation of a MSW landfill. Hence, it may not be possible to measure the representative values of water content and hydraulic properties of MSW (Oweis et al. 1990). Due to these reasons, majority of the modeling results presented in this paper have not or cannot be accurately validated in the field for MSW landfills. There have been two modeling studies related to the design of LRS consisting of HTs conducted by McCreanor (1998) and Bachus et al. (2002). Doran (1999) has presented findings from a field study of an LRS consisting of HTs. In this section we have presented the results from these studies as a validation of our modeling work.

McCreanor (1998)

McCreanor (1998) used the United States Geological Survey's (USGS) Saturated-Unsaturated Flow and Transport (SUTRA-2D) model to simulate leachate hydrodynamics using LRS consisting of a single HT. The author simulated a 2-m-wide by 1-m-deep HT. The trench backfill had a porosity of 0.3 and hydraulic conductivity equal to 10^{-3} m/s. The initial degree of saturation of MSW was assumed

equal to 40%. MSW was simulated as a homogeneous and isotropic medium using $k_w = 10^{-5}$, 10^{-6} and 10^{-7} m/s. McCreanor (1998) studied the effect of k_w on wetted leachate area by modeling the lateral and vertical spread of the wetted area corresponding to degree of saturation $\geq 45\%$ a week after the leachate injection began.

McCreanor (1998) modeled the lateral and vertical movement of leachate by simulating both, continuous and intermittent (8hr on/16hr off) application of leachate. The modeling results showed that the lateral and vertical spread of wetted area is almost similar for continuous or intermittent applications. The lateral and vertical spread of the wetted area was measured along horizontal and vertical lines passing through the centre of the perforated leachate injection pipe installed inside the HT. We conducted similar modeling using HYDRUS-2D and compared our modeling results to the results presented by McCreanor (1998) for continuous application of leachate at 2, 4, and 8 m³/d/m for one week. The wetted area dimensions corresponding to degree of saturation of 45% or more simulated by HYDRUS-2D and SUTRA-2D at the end of one week are presented in Table 3. The wetted area dimensions simulated by both models are relatively close. We believe that the slight difference is because McCreanor (1998) used power function to fit the soil-water characteristic curves for the materials including MSW and we used van Genuchten fitting parameters in HYDRUS-2D.

Bachus et al. (2002)

Bachus et al. (2002) used VS2DI (Hsieh et al. 2000) to simulate the liquid flow in a LRS consisting of HTs. VS2DI is a finite-difference model that simulates liquid flow and solute or energy transport in variably saturated porous media. The authors simulated 0.9-m-wide by 0.9-m-deep HT and assumed homogenous and isotropic material properties. The authors assumed $k_w = 10^{-5}$ m/s and $H_i = 2.4$ m and presented

Table 3. Comparison of simulation results from SUTRA-2D and HYDRUS-2D.

Flow Model	Application and Rate of Leachate Injection	Lateral Spread of Wetted Area ¹ (m)	Vertical Spread of Wetted Area ¹ (m)
SUTRA-2D by McCreanor (1998)	Continuous Application at 2, 4 and 8 m ³ /d/m (Time period = 1 week)	2.1, 2.8 and 3.5	0.2, 0.3 and 1.5
HYDRUS-2D (this study)		2.0, 3.4 and 5.3	0.4, 0.5 and 1.3

Note: 1. Corresponds to degree of saturation $\geq 45\%$.

the lateral and vertical spread of wetting front corresponding to various degrees of saturation for intermittent (8 hrs on and 16 hours off) leachate recirculation.

Bachus et al. (2002) also simulated steady-state leachate flux for $k_w = 10^{-5}$ m/s at various values of H_i . We have plotted Q_s values presented by Bachus et al. (2002) in Figure 2. The VS2DI results are relatively close to what we simulated using HYDRUS-2D.

Doran (1999)

Doran (1999) recirculated leachate using an LRS consisting of HTs at the Crow Wing County MSW landfill (CWCL). The size of the horizontal trenches installed ranged between 0.65-m-wide by 0.65-m-deep to 1.4-m-wide by 1.4-m-deep. The trenches were backfilled with shredded tires. A system of seven laterals was used to recirculate leachate under gravity drainage ($H_i = 0$). However, these HTs had positive elevation head ranging from about 1 m to 5 m. One lateral was run at a time and the recirculated leachate flux was recorded using flow meters. Laterals 3 and 7 had a diameter of 0.1 m, were 150-m-long and embedded in 0.65-m-wide by 0.65-m-deep HTs. The leachate flux estimated by HYDRUS-2D was compared to that obtained from monitoring laterals 3 and 7. This field leachate flux measured at CWCL (R.W. Beck 2002) is plotted against the elevation head ($\sim$ injection pressure) in Figure 2. Note that we ignored the head loss due to friction in the Doran (1999) and R.W. Beck (2002) data in Figure 2. However, as per our estimates using Moody diagram (Moody 1944), the head loss due to friction in the laterals is less than 0.5 m. Figure 2 shows that the recirculated leachate flux at CWCL mostly fell within the range estimated by HYDRUS-2D for $k_w = 10^{-6}$ m/s. Doran (1999) has not measured the field k_w , however, the interpreted k_w is in the range reported in the literature for k_w (Korfiatis et al. 1984; Fungaroli and Steiner 1979; Hughes et al. 1971).

SUMMARY AND PRACTICAL IMPLICATIONS

This paper presents a numerical study of key design variables used for the design of an LRS consisting of HTs. The design of the leachate pipe network including the head loss in the pipes, joints, manifolds, and pump has not been considered in this study. The design parameters evaluated included: (1) H_i ; (2) k_{HT} and k_w ; (3) geometry and size of HT; and (4) spacing and formation of trenches. The saturated-unsaturated flow model HYDRUS-2D was used to simulate the hydraulics of leachate recirculation in MSW landfills operated as bioreactors. The key findings of this study are as follows.

- $\log Q_s$ and H_i have a curvilinear relationship;
- When k_{HT} is equal to or greater than k_w , any further increase in k_{HT} has negligible impact on Q_s ;
- Q_s is directly proportional to k_w for a given H_i ;
- If the width of HT is increased, it results in greater wetted area for a given degree of saturation. Depth of HT has a smaller impact on wetted area compared to the width of HT;
- In order to optimize number of HTs in LRS and reduce dry zones between adjacent trenches, η_h defined in this paper can be used to establish maximum spacing between 2 or more HTs. For HTs spaced horizontally, hydraulic efficiency slightly less than 1 (100%) is an indicator of relatively uniform wetting of MSW and hence relatively fewer dry zones.
- When two or more rows of HTs are designed, HTs in these rows should be vertically staggered to reduce dry zones.
- Because the lateral and vertical spreading of leachate under steady-state conditions is not a function of k_w , the shape and dimensions of the wetted area

presented in Figure 3b can be used to design formations of HTs to optimize and to achieve relatively uniform wetting of MSW.

- Based on the data presented in Figures 3b, 5, and 10, HTs should be placed at about 10 m horizontal spacing for formations consisting of HTs in a single row and operated at $H_i \leq 5$ m. HTs should be placed at about 20 m horizontal spacing for formations consisting of HTs in multiple rows where HTs are staggered (e.g., Formations A or C in Figure 10) and operated at $H_i \leq 5$ m.
- The simulated Q_i values presented in Figure 2 can be used to estimate the total number of HTs, the rate of leachate recirculation, duration, and frequency of leachate dosing. The leachate flux values presented in Figure 2 depend on k_w . Because it is almost impossible to measure representative values of field k_w and k_w may vary significantly in a landfill, the designer needs to assume a range of possible values for k_w and incorporate redundancy in the design.

Although not explored in this study, we recommend that LRS designers consider the effect of these issues when designing LRS: (1) potential increase in the leachate head on the liner; (2) potential decrease in the shear strength of MSW affecting the slope stability of the landfill; (3) potential leachate breakouts from the side slopes of the landfill; and (4) effect on the efficiency of gas collection system. We also recommend that designers consider the effect of hydraulic properties of daily cover, potential of clogging of LRS and the effect of waste settlement on the long-term performance of the LRS.

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PAPER NO. 2: EVALUATION OF HETEROGENEITY AND ANISOTROPY OF WASTE PROPERTIES ON LEACHATE RECIRCULATION IN BIOREACTOR LANDFILLS

ABSTRACT

Leachate recirculation in municipal solid waste (MSW) landfills was modeled using HYDRUS-2D, a saturated/unsaturated flow model. The recirculation system consisted of three horizontal trenches spaced laterally at 20 m. The model was used to simulate the effect of heterogeneity and anisotropy in the hydraulic conductivity of MSW on the leachate flux that can be recirculated at steady-state flow condition. Monte Carlo analysis (MCA) was used for two sets of correlation lengths and variance using a lognormal hydraulic conductivity distribution for MSW. MCA estimated the mean leachate flux and its standard deviation. MCA quantified the variability and the uncertainty in the magnitude of leachate flux. The key finding is that increasing the correlation length ratio of hydraulic conductivity of MSW (greater stratification) results in relatively lower leachate flux that can be recirculated at steady-state. Heterogeneity and anisotropy in hydraulic conductivity of MSW also results in relatively non-uniform wetting of MSW. Hence, greater than 15 m buffer distance between the landfill side slopes and the leachate injection system is needed to minimize the potential of leachate breakouts from the side slopes of the landfill.

INTRODUCTION

Leachate recirculation is commonly used in MSW landfills because it offers these economical and environmental benefits (Khire and Haydar 2005; Miller and Emge 1997; Mehta et al. 2002): (1) reduction in leachate treatment and disposal costs; (2) greater flexibility in leachate management and treatment; (3) relatively faster

biodegradation of waste resulting in increased gas production and quicker waste stabilization and settlement; (4) reduction in the risk associated with contamination from spills during off-site transportation, treatment, and disposal of leachate; and (5) potential reduction in the post-closure care period of the landfill. Trucking and leachate treatment costs can add up significantly. Depending upon the site-specific leachate quantities generated, leachate recirculation can save hundreds of thousands of dollars for a typical medium size landfill over its design life.

Leachate recirculation also has few disadvantages. These disadvantages include: (1) reduction in the shear strength of MSW potentially reducing the factor of safety against slope stability of the landfill; (2) potential leachate breakouts from the sides of the landfill; and (3) increase in the leachate head build up on the liner potentially increasing the risk for ground water contamination. Hence, designers and landfills owners are expected to weigh the advantages and disadvantages on a site-specific basis before a leachate recirculation system (LRS) is implemented. Preferential flow paths in MSW increase the potential for leachate breakout. In this numerical study, we have presented the non-uniform wetting in heterogeneous and anisotropic MSW due to leachate recirculation.

Conventional subsurface application techniques for leachate recirculation are (Khire and Haydar 2003; Qian et al. 2002): (1) vertical wells; and (2) horizontal trenches (HTs). Currently, there are no specific design guidelines available for considering the effect of heterogeneity and anisotropy of MSW properties when designing a LRS using HTs. Haydar and Khire (2005) have presented guidelines for designing a LRS consisting of HTs for homogeneous and isotropic MSW. The key objective of this study is to evaluate the effect of heterogeneity and anisotropy of MSW properties when designing a LRS consisting of HTs.

HYDRAULIC PROPERTIES OF MSW

Particle size of MSW constituents ranges over many orders of magnitude due to the presence of materials having orders of magnitude different dimensions, such as food waste, plastic bags, carpet, plastic sheeting, white appliances, etc. This results in significant heterogeneity and anisotropy in the hydraulic conductivity, k_w , and other physical properties of MSW. Such variation can exist not only among landfills, but also within a landfill cell. Furthermore, as waste undergoes settlement, hydraulic properties of waste may change. Thus, spatial and temporal variations in k_w are abundant in a typical MSW landfill.

Leachate recirculation does not wet the waste matrix uniformly due to the heterogeneity in waste and also due to the hydraulic limitation(s) of recirculation system(s) used (Haydar and Khire 2005). A non-uniform distribution of moisture content in MSW landfills can result in non-uniform biodegradation of waste. This can influence the operational performance of a typical landfill intended to be an efficient bioreactor. Many field investigations have reported a spatial variation of moisture content within the waste (McCreanor and Reinhart 1998; Zornberg et al. 1999; Oweis et al. 1990). Zeiss and Uguccioni (1995) found that channeling results in the downward movement of leachate through interconnected pores at rates faster than the uniform wetting front under Darcian flow. The presence of preferential flow paths leads to an increase in the bulk hydraulic conductivity of waste. Even though we have insufficient data on the flow of leachate through channels as waste settles due to degradation or due to increased vertical stress, we expect that hydraulic conductivity of MSW will decrease under such conditions.

We believe that the deposition and compaction of waste in relatively thin lifts leads to horizontal stratification within a landfill. The horizontal hydraulic

conductivity of the waste in landfills has been estimated to be an order in magnitude higher than the vertical hydraulic conductivity (Powrie and Beaven 1999). The application of daily and intermediate soil covers adds to the anisotropy and heterogeneity within a landfill. Field-scale tracer studies in landfills have shown that significant amount of tracer was transported laterally out from the landfill compared to that in the vertical direction (Rosqvist and Destouni 2000). This is due to preferential flow of leachate through horizontal layers. Leachate is expected to flow through channels created by the heterogeneous nature of waste and through preferential paths created by stratification of waste and the presence of horizontally oriented relatively impervious materials such as plastic foils (Fellner et al. 2003). Vertical stress in a landfill increases with the depth of waste. Hence, as depth increases, waste density increases and hydraulic conductivity decreases (Bleiker et al. 1995).

The aim of this study is to evaluate the effect of heterogeneity or spatial variation and anisotropy in hydraulic conductivity of MSW on (1) the leachate flux that can be recirculated in a landfill at a steady-state flow condition; and (2) leachate flow patterns.

Waste in landfills is spread and compacted in lifts with repeated passages of compactor to reduce the volume of voids. As per the U.S. federal regulations, at the end of the working day, the waste placed in the landfill cell is required to be covered using a 150-mm-thick soil or an equivalent material to reduce odors and control vermin and pests. For the model we used to simulate the spatial variation of waste, the correlation lengths in the lateral and vertical direction were used to discretize the spatial distribution of k_w . The thickness of waste lift and the process of spreading and compacting waste dictate the correlation lengths of k_w . In addition, the lateral

dimensions, thickness, and hydraulic properties of daily cover placed on waste also influence the correlation lengths and the spatial variation in hydraulic properties. However, there are no published values for the correlation lengths for k_w . Measurement of k_w in the field that is representative of the waste matrix is relatively challenging and expensive. In addition, due to significant heterogeneity and anisotropy of waste, k_w measured for one landfill cell may not be representative of another cell in the same landfill

Fenton and Griffiths (1996) studied the effect of spatially random soil hydraulic conductivity on the seepage flow rate and surface drawdown of an earth dam. The earth dam was simulated as a heterogeneous and isotropic porous medium. Monte Carlo analysis (MCA) was conducted for a spatially random field using a lognormal distribution for the soil hydraulic conductivity with prescribed mean, variance, and correlation length. Simulation results showed that the mean seepage flow rate increased as the correlation length increased.

HORIZONTAL TRENCH LEACHATE RECIRCULATION SYSTEM

Various cross-sectional dimensions of HTs have been reported in the literature including 0.6 m wide by 1.0 m deep (Maier and Vasuki 1996), 1.0 m wide by 1.0 m deep (Miller and Emge 1997), and 0.9 to 1.2 m wide by 1.2 to 1.8 m deep (Reinhart and Carson 1993). Unlike surface application of leachate, HTs do not cause odors and direct leachate exposure unless leachate seeps out from the sides of the landfill. HTs are backfilled with relatively high hydraulic conductivity drainage material (e.g. gravel, coarse sand, crushed glass, shredded tires) with a 50 to 150 mm diameter perforated pipe installed at the center of the trench. Leachate is recirculated by injecting leachate in the perforated pipe at positive pressures ranging from 0 to 5 m

(SWANA 2002). Typical horizontal spacing of HTs varies from 3 to 30 m (SWANA 2002). In this paper, in order to meet the key objective, we have evaluated the effect of heterogeneity and anisotropy in the hydraulic conductivity of MSW on the leachate flux that can be recirculated under a steady-state flow condition (Q_s). We have conducted over 50 numerical simulations using HYDRUS-2D model which is capable of generating heterogeneity and anisotropy for given values of vertical and horizontal correlation lengths and standard deviation for a lognormal distribution of hydraulic conductivities.

METHODOLOGY

Leachate recirculation in MSW landfills has often been modeled using 2-D models assuming that the hydraulic properties of waste are homogeneous and isotropic. This assumption is overly simplistic. Due to significant heterogeneity of waste, various approaches have been considered to describe the effect of waste heterogeneity on the leachate flow. The effect of anisotropy and heterogeneity of k_H on the lateral and vertical moisture distribution was modeled by McCreanor and Reinhart (1998). They found that compaction may promote anisotropy in k_H , which extenuates horizontal spreading and retards the downward movement of leachate. Bendz (1998) used a kinetic wave model to describe the channeling of leachate flow through waste.

In this study we have conceptualized a model domain to simulate the LRS consisting of horizontal trenches in MSW landfills. The finite-element model HYDRUS-2D was used to simulate the hydraulics of leachate flow. The waste was simulated as a homogenous and isotropic as well as a heterogeneous and anisotropic porous material using two sets of geostatistical realizations.

Conceptual Model

Figure 1 presents the conceptual model used to simulate leachate recirculation using horizontal trenches for a MSW landfill. The model domain represents a vertical cross-section through a typical landfill cell. The LRS consists of three 0.6 m wide by 1.0 m deep trenches, backfilled with gravel and installed at 20 m horizontal spacing. The trenches are located 15 m above the liner and 5 m below the landfill surface. A perforated pipe having 100 mm diameter is installed at the center of each trench to inject leachate for recirculation. The gravel backfill has a saturated hydraulic conductivity, $k_{HT} = 1 \text{ cm/s}$. The leachate collection system (LCS) consists of 0.3 m thick gravel layer with two 150-mm-diameter perforated pipes embedded at 60 m horizontal spacing (Figure 1). The detailed hydraulic properties of the simulated landfill units are presented in Table 1. All external boundaries were assumed as zero-flux boundaries. The pressurized pipe in the trench is modeled as a constant pressure head boundary. The LCS pipes were modeled as seepage face boundaries.

Numerical Model

The finite-element flow model HYDRUS-2D was selected for this study due to its capability to simulate saturated/unsaturated flow. Other key reasons for selecting HYDRUS-2D are: (1) it can be used to implement a scaling procedure to approximate hydraulic variability in a given soil profile; (2) it simulates such variability by means of a set of lognormal scaling transformations, which relate the individual soil hydraulic characteristics to those of a specified reference soil; (3) it is supported by an interactive graphics-based interface for data-preprocessing, generation of a structured mesh, and post-presentation of the results; and (4) it also includes a parameter optimization algorithm for inverse estimation of a variety of soil hydraulic parameters (Simunek et al. 1999).

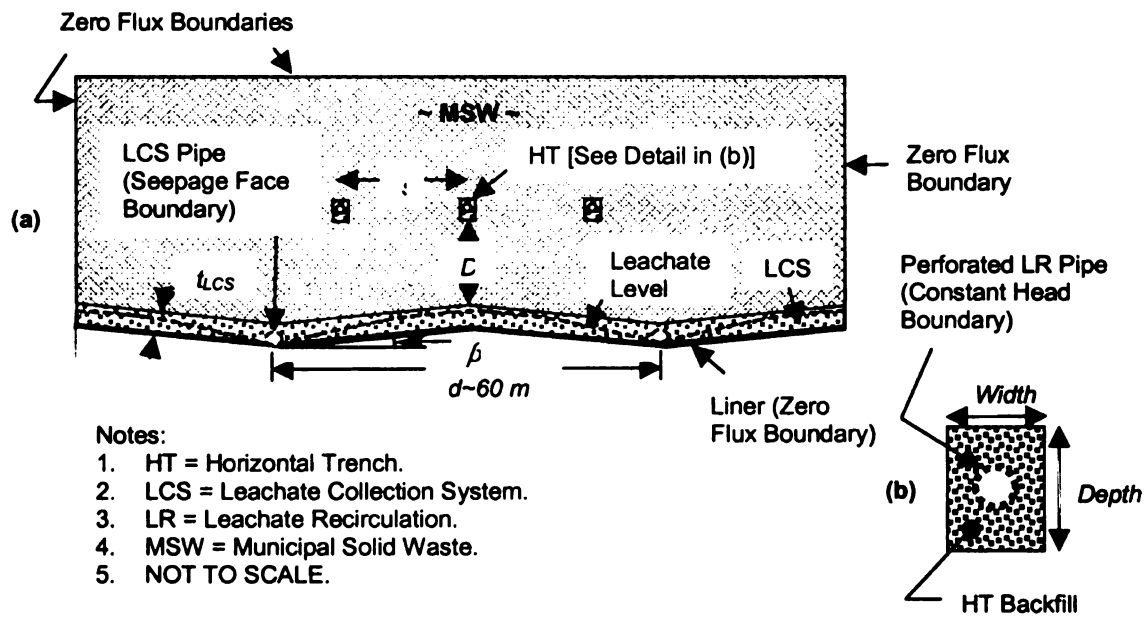


Figure 1. Conceptual model for HYDRUS-2D simulation of leachate recirculation in MSW landfill using horizontal trench system (a); and detail of a horizontal trench (b).

Table 1. Hydraulic properties of simulated landfill components.

Landfill Units	Material	θ_r	θ_s	α (1/m)	n	k (cm/s)
Waste	Silt loam	0.067	0.45	2	1.41	10^{-4}
HT Backfill & Leachate Collection System	Gravel	0.01	0.3	57.4	2.4	1

In HYDRUS-2D, the flow of leachate through waste is modeled as flow through any porous material by using the Richards' equation (Richards 1931) presented below,

$$\frac{\partial \theta}{\partial t} = -\nabla[k(\psi)\nabla\psi] + \frac{\partial k(\psi)}{\partial z} - S \quad (1)$$

where θ is volumetric water content; ψ is matric suction head; $k(\psi)$ is the unsaturated hydraulic conductivity function for the porous material which is a function of soil suction head; z is vertical dimension; S is sink term, and t is time. The soil-water characteristic curves for the materials simulated are represented by the van-Genuchten model (van Genuchten 1980) as follows,

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{\left(1 + |\alpha\psi|^n\right)^m} \quad (2)$$

where ψ = matric suction head; θ = water content; θ_s = saturated water content; θ_r = residual water content; and α , n , and m ($m = 1 - n^{-1}$) are fitting parameters. HYDRUS-2D model uses the van Genuchten-Mualem (Mualem 1976) function to predict the unsaturated hydraulic conductivities using the van Genuchten fitting parameters and the saturated hydraulic conductivities. The unsaturated hydraulic conductivities are estimated by using van Genuchten-Mualem model (Mualem 1976) presented in Equation 3,

$$k(\psi) = k_w S_e^{0.5} \left[1 - \left(1 - S_e^{\frac{1}{m}} \right)^m \right]^2 \quad (3)$$

where S_e is effective degree of saturation; k_w is saturated hydraulic conductivity; $k(\psi)$ is unsaturated hydraulic conductivity function; and m is the fitting parameter for the soil-water characteristic curve.

Throughout this numerical study, we assumed the reference hydraulic conductivity of waste, k_w , equal to 10^{-4} cm/s. k_w was selected based on the typical values published by Hughes et al. (1971), Fungaroli and Steiner (1979), Korfiatis et al. (1984), Oweis et al. (1990), and Bleiker et al. (1993). Hydraulic conductivities of HT backfill and LCS drainage material (k_{HT} and k_{LCS}) were assumed equal to 10^{-2} cm/s. k_{HT} and k_{LCS} were selected based on the values for pea gravel, shredded tires, or coarse sand which are commonly used materials for the HT backfill and LCS drainage layer (Doran 1999). The unsaturated hydraulic properties for waste were selected from HYDRUS-2D database corresponding to a soil having saturated hydraulic conductivity closest to the assumed k_w of 10^{-4} cm/s.

Monte Carlo Analysis

The spatial variation in hydraulic conductivity was simulated by generating stochastically lognormally distributed scaling factors. This technique assumes that the hydraulic variability in a given area can be approximated by means of a set of linear scaling transformations that relate the individual hydraulic conductivity to the reference characteristics. This technique is similar to the one introduced by Miller and Miller (1956) and is also explained in detail by Vogel et al. (1991).

Figure 2 presents a schematic of the conceptual model of a random hydraulic conductivity realization simulated by HYDRUS-2D, where the correlation length in the horizontal direction, λ_x , is greater than the correlation length in the vertical direction, λ_z . A lognormal distribution was used for the scaling factors generated for the hydraulic conductivity. The spatial correlation was accommodated using correlation lengths in both horizontal and vertical direction (x and z directions in the

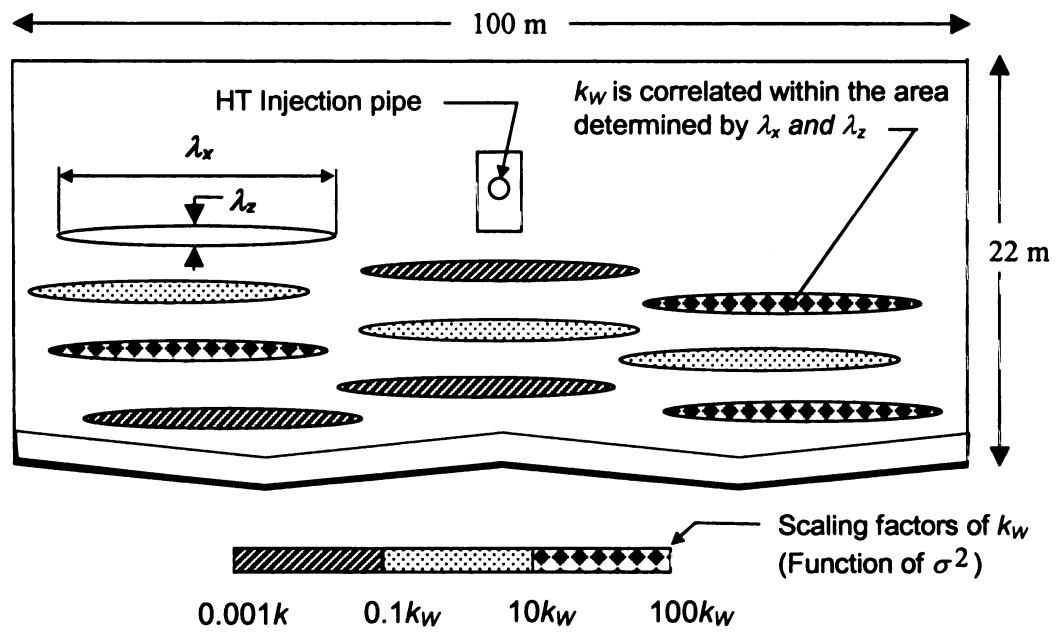


Figure 2. Conceptual model for generation of a random hydraulic conductivity realization using correlation lengths λ_x and λ_z , where $\lambda_x > \lambda_z$, and hydraulic conductivity variance (σ^2) is lognormally distributed.

2-D waste domain). Depending upon the type, composition, and compaction methods, we believe that the hydraulic conductivity of waste in a landfill cell varies. We assumed λ_x to range from 2 m to 10 m. The lower end of this range (2 m) corresponds to the average size of relatively large objects such as plastic sheets, large equipment, and furniture that are typically in MSW. The higher end of this range (10 m) corresponds to the typical width of the working face of a landfill. Based on the typical thickness of waste lift, we used λ_y equal to 0.5 m.

The variance in lognormally distributed hydraulic conductivities reflects the spatial variation in the properties of waste. The presence of relatively impermeable objects, such as plastic foils, increases variance as it reduces hydraulic conductivity and enhances channeling.

We used the correlation lengths and log variance sets presented in Table 2 to simulate the effect of spatial variation in the hydraulic conductivity of waste on the leachate flux that can be recirculated at steady-state flow condition (Q_s) and on leachate flow patterns. In Table 2, λ_x and λ_z are the correlation lengths in horizontal and vertical directions, respectively, and σ^2 is the variance of lognormally distributed k_w . For each of these sets, 25 realizations were simulated using HYDRUS-2D. Each of these realizations had a unique hydraulic conductivity field.

The leachate flux at steady-state (Q_s) was estimated for each realization using HYDRUS-2D. A steady-state condition was assumed to have reached when the total flux collected in the two LCS pipes equalized the total flux injected in the three HTs. At steady-state, Q_s is independent of the initial water content of the model domain.

Following the simulation of each realization simulated by HYDRUS-2D, MCA was used to determine the recursive average of Q_s (denoted as Q_a) using Equation 4 as follows,

Table 2. Summary of recursive Q_s and standard deviation in Q_s for realizations using heterogeneous and anisotropic waste properties.

Scaling Factors and variance to simulate heterogeneous and anisotropic waste	Recursive Q_s ($\text{m}^3/\text{m/d}$)	Standard Deviation in Simulated Q_s ($\text{m}^3/\text{m/d}$)
Set 1: $\lambda_x = 10 \text{ m}$, $\lambda_z = 0.5 \text{ m}$, and $\sigma^2 = 0.42$	3.12	1.27
Set 2: $\lambda_x = 2 \text{ m}$, $\lambda_z = 0.5 \text{ m}$, and $\sigma^2 = 0.42$	3.44	1.14

$$Q_{a_i} = \frac{i-1}{i} \times Q_{a_{i-1}} + \frac{Q_{s_i}}{i} \quad (4)$$

where i is the iteration number or the realization count that ranges from 1 to N ; N is the number of realizations used to estimate Q_a by MCS; Q_{a_i} is the recursive average of Q_s at the i^{th} iteration; $Q_{a_{i-1}}$ is the recursive average of Q_s at the $(i-1)^{\text{th}}$ iteration, and Q_{s_i} is the leachate flux for i^{th} iteration.

Due to the significant amount of time required for each simulation (about 5-10 days for each simulation), we limited total number of simulation (N) to 25 for each set of geostatistical parameters listed in Table 2. More simulations would have reduced the uncertainty in Q_a . However, 25 simulations were enough to satisfy the key objectives of this study.

RESULTS

Homogeneous and Isotropic Properties

First set of simulation was carried out where waste was simulated as homogenous and isotropic material having $k_w = 10^{-4}$ cm/s. A leachate injection pressure head, H_i , equal to 2 m was used for the three horizontal trenches (Figure 1). Figure 3 presents the leachate flow distribution at steady-state for the case where waste is modeled as homogenous and isotropic material. “Dry zones” or relatively low moisture content zones between horizontal trenches can be observed in Figure 3. Dry zones could be reduced by reducing the horizontal trench spacing or by applying a greater injection head (Haydar and Khire 2005).

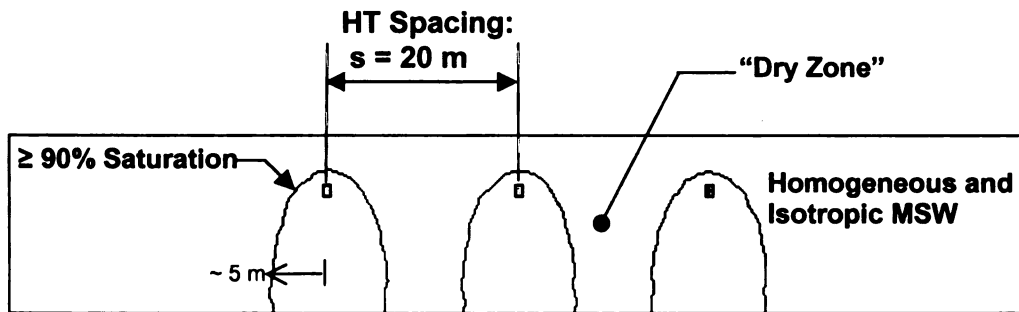


Figure 3. Distribution of wetted area corresponding to degree of saturation $\geq 90\%$ at steady-state using homogeneous and isotropic properties of waste having $k_w = 10^{-4}$ cm/s and $H_i = 2$ m.

Heterogeneous and Anisotropic Properties

The next set of simulations were carried out where waste was simulated as a heterogeneous and anisotropic material using realizations that correspond to the correlation lengths and variances for three sets presented in Table 2. For each set in Table 2, more than 25 realizations were simulated. The reference hydraulic conductivity of waste, k_w , was set at 10^{-4} cm/s and the leachate injection pressure head, H_i , was set at 2 m. For each set, the simulated steady-state leachate flux, Q_s , for each realization was converted into a recursive average, Q_a , using Equation 4. Figure 4 presents the recursive average of leachate flux at steady-state for each realization for the two sets of correlation length.

After sorting the simulated Q_a , the ascending trend presented in Figure 4 for the 25 simulations of each set was sufficient to deduce the effect of spatial variation on Q_s . When the correlation lengths are relatively short, the injected leachate does not have to travel far before channeling or finding a zone having relatively large k_w . When the correlation lengths are relatively short and the magnitude of variance is relatively large, it simulates a waste matrix where waste pockets having relatively high k_w are interconnected. Injected leachate will avoid low k_w pockets and follow preferential flow through high k_w channels. Such interconnected pockets having relatively high k_w will lead to a shorter flow path for leachate resulting in greater hydraulic gradient and, hence, greater steady-state leachate flux. The area wetted by the recirculated leachate for all simulations in Set 2 is relatively narrow. When the correlation lengths are relatively short, the risk of leachate break outs is minimal.

Table 2 presents the resulting Q_s after 25 realizations and its standard deviation. The standard deviation for Q_s obtained from Sets 1 and 2 decreased with decrease in

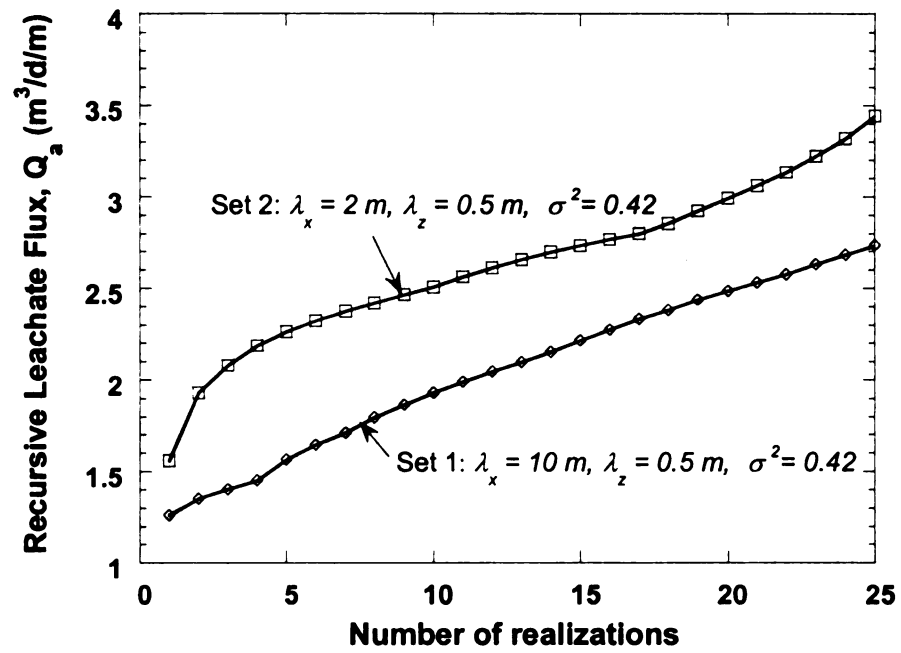


Figure 4. Simulated recursive average leachate flux versus number of realizations for geostatistical realizations corresponding to Sets 1 and 2.

the correlation length. This occurs because a decrease in the correlation length causes shortening of flow path, thus reducing variation in the estimation of Q_s . If more realizations were conducted, it would reduce the standard deviation or uncertainty in recursive Q_s . However, it would have significantly increased the computational time.

Simulation results presented in Table 2 indicate that, if horizontal correlation length is increased, it reduces recursive Q_s . This occurs because the increase in the horizontal correlation length results in stratification of the system into low and high hydraulic conductivity layers. In such stratified system, when leachate flow is perpendicular to the layers, overall hydraulic conductivity is skewed towards the lower hydraulic conductivity layers. Thus, stratification lowers the leachate flux when leachate has to flow perpendicular to the stratified layers. However, such stratification can create conduits made of zones having relatively high k_w . This may lead to leachate break outs from the side slopes of a landfill if sufficient buffer is not maintained between the leachate injection point and the sides of the landfill.

Leachate Flow Patterns

Figure 3 presents the wetted area corresponding to greater than or equal to 90% degree of saturation when the hydraulic properties were simulated as homogeneous and isotropic. Figure 3 also shows that the wetted area for each HT is fairly uniform. The maximum lateral spread of leachate from the leachate injection point (the center of HT) is about 5 m for leachate injection head equal to 2 m.

Figure 5 presents the wetted areas at steady-state flow condition for a typical realization when the hydraulic properties of waste were simulated with heterogeneity and anisotropy using correlation lengths and variance corresponding to Sets 1 and 2. Each realization yielded a different wetted area pattern. The key difference between Set 1 and Set 2 is that Set 1 uses λ_x equal to 10 m and Set 2 uses λ_x equal to 2 m.

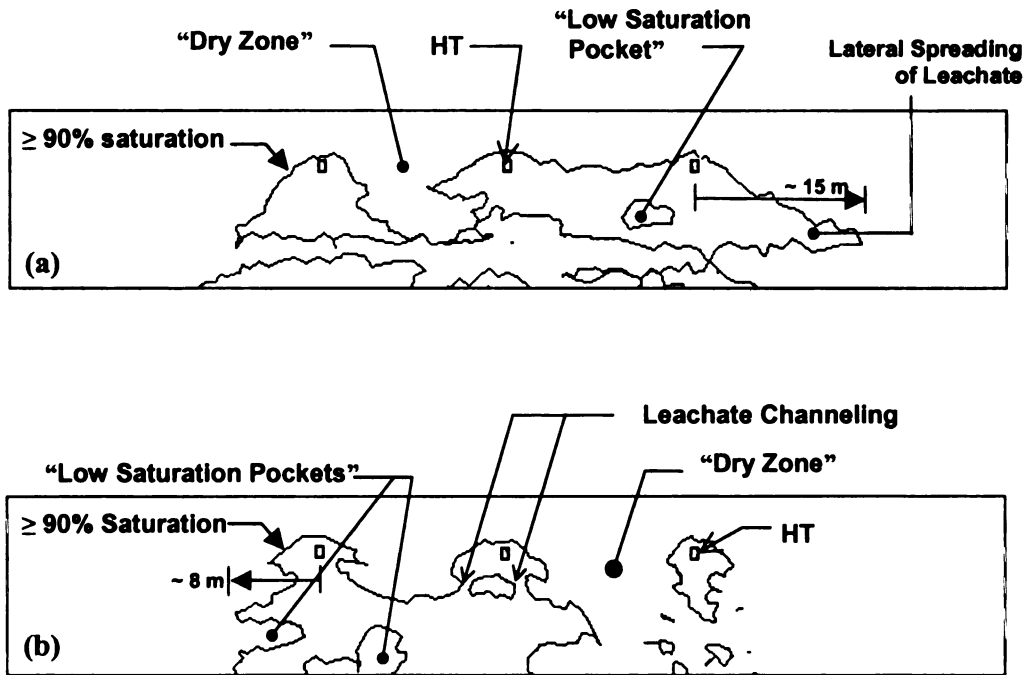


Figure 5. Distribution of wetted area corresponding to degree of saturation $\geq 90\%$ for geostatistical realizations corresponding to Set 1 ($\lambda_x = 10$ m, $\lambda_z = 0.5$ m, and $\sigma^2 = 0.42$) (a); and Set 2 ($\lambda_x = 2$ m, $\lambda_z = 0.5$ m, and $\sigma^2 = 0.42$) (b) for lognormal average $k_W = 10^{-4}$ cm/s and $H_i = 2$ m.

Thus, λ_x for Set 1 is greater than λ_x for Set 2. Due to greater λ_x , the maximum lateral spread of the injected liquid for Set 1, which is equal to 15 m (Figure 5a) is greater than the maximum lateral spread of 8 m for Set 2 (Figure 5b). However, dry zones and low saturation pockets were observed in both sets.

The non-uniform wetted area distribution demonstrates how heterogeneity and anisotropy can lead to potential leachate break out(s) from the sides of a landfill. This finding suggests that maintaining sufficient buffer distance between the leachate injection point and the side slopes of a landfill is critical for minimizing the potential for leachate break outs. The leachate breakout distance was defined as the distance traveled by the injected leachate beyond an “imaginary” side slope of the landfill. Figure 6a presents a schematic to illustrate the leachate break out distance. The side slope of the landfill was assumed equal to 1V:4H based on the typical side slopes used for landfills.

Figure 6b presents the leachate breakout distance measured for each of the simulations for Sets 1 and 2. The leachate breakout distance ranged from 2 to 8 m as shown in Figure 6b. Although, the leachate breakout distance was similar for both Sets of simulations, it was noted that the lateral travel of injected leachate for simulations in Set 1 was relatively greater than that for Set 2. This is due to the greater correlation length in Set 1 compared to Set 2. Figure 6b shows that buffer distance shall be greater than 10 m to minimize leachate breakouts. Because λ (λ_x , λ_y , or λ_z) cannot be measured for a given waste matrix or MSW cell in the field, the correlation lengths listed in Table 2 were used to provide an initial estimate for what buffer is appropriate to minimize leachate breakouts. Field data on leachate breakouts and buffer distance needs to be collected to verify or estimate correlation lengths.

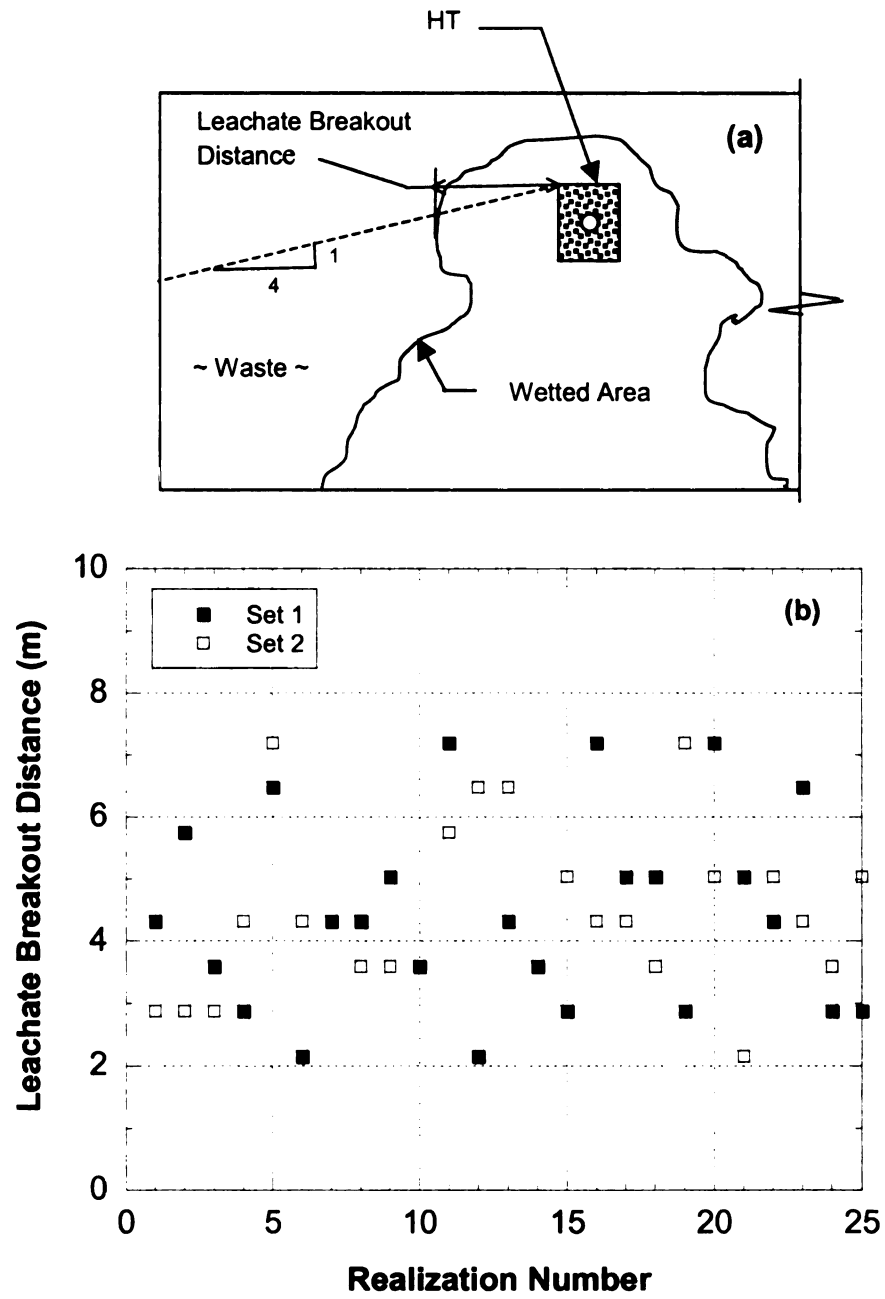


Figure 6. Schematic of leachate breakout distance (a); and simulated leachate breakout distance for simulations using Sets 1 and 2 for $k_w = 10^{-4}$ cm/s and $H_i = 2$ m (b).

Hence, in order to reduce leachate breakouts from the sides of a landfill, we recommend these design and operational guidelines: (1) buffer distance between the leachate injection point and the sides of a landfill shall be greater than 15 m. If leachate injection pressure is greater than 2 m, further increase in buffer is necessary; (2) daily covers consisting of relatively low hydraulic conductivity soil shall be avoided; (3) daily cover layers made up of soils shall be scraped off to make the daily cover layer not continuous for greater than 10 m distance; and (4) hydraulically impermeable plastic sheets or tarps used as daily covers shall be removed prior to placing the next lift of waste. We also recommend design engineers to use the results presented in this study as a guideline. However, site-specific data should be used to optimize the buffer distance and other design issues related to LRS.

SUMMARY AND CONCLUSIONS

In this numerical study, the effect of heterogeneity and anisotropy in the hydraulic properties of waste on the magnitude of leachate flux recirculated using a LRS consisting of horizontal trenches was evaluated. Over 50 realizations were simulated using HYDRUS-2D to evaluate the leachate flux as a function of heterogeneity and anisotropy expressed by three sets of horizontal and vertical correlation lengths and variance in the hydraulic properties of waste. The MCA was used to evaluate the effect of heterogeneity and anisotropy.

Increasing horizontal correlation length resulted in more lateral spreading of leachate and relative decrease in leachate flux. The magnitude and the pattern of wetted area was greatly affected when heterogeneity and anisotropy of waste was considered. Introduction of heterogeneity and anisotropy resulted in non-uniform leachate wetting. Increase in the horizontal correlation length resulted in greater

wetting in the horizontal direction with greater potential for leachate breakouts. A minimum buffer distance of 15 m between the side slopes of landfill and the leachate injection point is needed to minimize leachate breakouts assuming the horizontal correlation length is less than or equal to 15 m.

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PAPER NO. 3: NUMERICAL EVALUATION OF PERMEABLE BLANKETS FOR LEACHATE RECIRCULATION IN MSW LANDFILLS

ABSTRACT

Leachate recirculation in municipal solid waste (MSW) landfills is commonly achieved by using horizontal trenches and/or vertical wells. This paper presents a numerical modeling study of a leachate recirculation alternative using permeable blanket. The performance of permeable blanket was evaluated by comparing recirculated leachate flux under steady-state conditions to that for horizontal trench. The finite-element saturated/unsaturated flow model HYDRUS-2D was used for the numerical evaluation. The effect of hydraulic properties of permeable blanket material on the recirculated leachate flux was also evaluated. The numerical modeling results indicate that significantly higher leachate flux can be recirculated using permeable blankets compared to an equivalent system of horizontal trenches spaced at 10m center to center. Field-scale testing of permeable blankets alternative is in progress.

INTRODUCTION

Recirculation of leachate in MSW landfills offers many benefits (Maier and Vasuki 1997), including: (1) reduction in leachate treatment and disposal costs; (2) acceleration and increase in waste settlement resulting in creation of airspace; (3) acceleration in the generation of landfill gas and hence potential for higher short-term revenues from gas-to-energy system (Mehta et al. 2002); and (4) reduction in the risk associated with contamination during off-site transportation, treatment, and disposal of leachate.

The most commonly used leachate recirculation system (LRS) in MSW landfills consists of horizontal trenches (HT) filled with high conductivity material with a perforated pipe at the center. Leachate is recirculated by injecting leachate at positive pressures ranging from 0 to 5 m. Typical dimensions of a horizontal trench are 0.6m wide by 1m deep (Figure 1). A horizontal trench may be the most commonly used LRS, however, it is not the most efficient method to recirculate leachate. Horizontal trench typically creates “dry pockets” between adjacent horizontal trenches where recirculated leachate may not reach [Figure 2(a)]. Such dry pockets increase differential settlement of waste and reduce the quantity and the rate of landfill gas generation. Differential settlement potentially increases the cost of maintaining the final cap.

The permeable blanket (PB) alternative evaluated in this paper consists of a 0.1 to 0.15m thick layer of relatively high hydraulic conductivity material laid on waste surface with a perforated pipe running through the center of the layer [Figure 1(b)].

A permeable blanket can be made of coarse sand, gravel, or permeable recycled materials such as, crushed recycled glass or shredded tires. The widths of permeable blankets evaluated in this paper ranges from 30 to 60 m. Permeable blankets offer these advantages over conventional horizontal trenches: (1) significant increase in quantity of leachate that can be recirculated per unit mass of waste; (2) can achieve relatively uniform distribution of moisture (or leachate) reducing dry pockets and hence reducing differential settlement; (3) increased gas production rate; and (4) can also be used for extracting landfill gas. A schematic of simulated water content distributions and resulting dry pockets for an LRS consisting of horizontal trenches is presented in Figure 2(a). A schematic of simulated water content distributions for a LRS consisting of a permeable blanket is presented in Figure 2(b). Figure 2(a) and

2(b) represent progressive snap shots of water content as the system reaches steady-state. The material properties were assumed homogeneous and isotropic for waste and other components.

NUMERICAL MODELING

HYDRUS-2D Computer Model

HYDRUS-2D is a computer model that can simulate water, heat, and solute movement in unsaturated, partially saturated, or fully saturated porous media (Simunek et al. 1999). The program numerically solves the Richards' Equation for saturated-unsaturated water flow. A 2-D form of Richards' equation can be expressed as follows:

$$\frac{\partial \theta}{\partial t} = -\nabla \cdot [k(\psi) \cdot \nabla \psi] + \frac{\partial k}{\partial z} - S \quad (1)$$

where, θ = volumetric water content; ψ = matric suction head; k = hydraulic conductivity, which is k_s for saturated soil but is strongly dependant on the soil suction; z = vertical dimension; S = volume of water removed per unit time per unit volume of soil by plant water uptake (sink term); and t = time.

The model uses van-Genuchten function for soil-water characteristic curves and van-Genuchten-Mualem model for predicting the unsaturated hydraulic conductivity function. The governing flow and transport equations are numerically solved using Galerkin-type linear finite-element schemes. Depending upon the scale of the problem domain, the matrix equations resulting from the discretization of the governing equations are solved using either Gaussian elimination for banded matrices, a conjugate gradient method for symmetric matrices, or the ORTHOMIN method for asymmetric matrices.

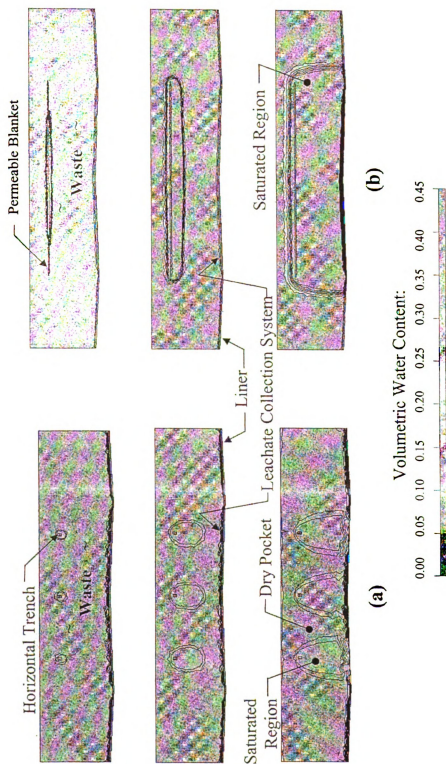


Figure 2. Moisture distribution for leachate recirculation system containing (a) 3 horizontal trenches; and (b) a permeable blanket.

Conceptual Model and HYDRUS-2D Input

The conceptual model used for the simulation of moisture dynamics for LRS consisting of a horizontal trench and permeable blanket is presented in Figure 1. Figure 1(c) presents the detail for the horizontal trench and Figure 1(b) presents the details for the permeable blanket. Leachate was simulated as pure water and the effect of biochemical reactions that occur within a landfill on the hydraulics of leachate recirculation was ignored. Waste and other materials were assumed to be porous, homogeneous, and isotropic.

Boundary Conditions and Mass Balance

All external boundaries were simulated as zero flux boundaries [Figure 1(a)]. Leachate movement as a result of percolation from the cap or waste above model domain was not simulated. The perforated pipe used for leachate injection was simulated as a constant head boundary. The simulated leachate injection heads ranged from zero (gravity application) to 5 m. The leachate injection head assigned as the constant head is exclusive of head loss in pipes, joints, manifolds, and pumps used in a typical LRS. Leachate collection pipes embedded in the leachate collection system (LCS) were simulated as seepage face boundaries. For a seepage face boundary, the hydraulic pressure head is always maintained zero or less. The diameter of such LCS pipes was assumed equal to 0.15 m.

The minimum size of the finite-elements used for discretization of the problem domain, the time step, and the error tolerances for pressure head and water content were selected such that cumulative water balance error does not exceed 0.1%.

Hydraulic Properties

Total three material types were used for simulating horizontal trench and permeable blanket LRS. These three materials were simulated as homogeneous and isotropic soils. The saturated hydraulic conductivities of these materials are listed as follows in the parentheses.

- Solid waste (saturated hydraulic conductivity, $k_W = 10^{-6}$ to 10^{-5} m/s)
- horizontal trench or permeable blanket drainage material (k_{HT} or $k_B = 10^{-3}$ to 10^{-2} m/s)
- LCS drainage material ($k_{LCS} = 10^{-2}$ m/s)

The unsaturated hydraulic properties for the materials listed above consisted of van Genuchten fitting parameters for the soil-water characteristic curves. The unsaturated hydraulic properties were selected from the database of HYDRUS-2D for soils having saturated hydraulic conductivities close to the assumed hydraulic conductivities.

Geometry and Dimensions

The dimensions of the simulated horizontal trench were 0.6 m wide by 1 m deep. The thickness of the simulated permeable blanket was 0.15 m. The width of the permeable blanket ranged from 30 to 60 m. The thickness of the LCS layer, t_{LCS} , was assumed equal to 0.3 m. The spacing between the adjacent leachate collection pipes, d , was assumed equal to 60 m. The slope (s) of the LCS was assumed equal to 3%. The LCS design parameters (t_{LCS} , k_{LCS} , d , and s) were selected such that the maximum leachate pressure head of leachate on the liner did not exceed the U.S. Subtitle D requirement of 0.3 m. The vertical distance (D) between the horizontal trench or permeable blanket and the top of the LCS was assumed equal to 15 m. Distance from top of the horizontal trench or

permeable blanket to the upper zero flux boundary was assumed equal to 10 m to contain all leachate movement under the leachate injection heads not exceeding 5 m.

SIMULATION RESULTS

HYDRUS-2D simulation output was analyzed to compare performance of permeable blanket to horizontal trench. The steady-state recirculated leachate flux (hereafter, referred to as leachate flux) was used as the primary criterion for the comparison. In addition, the effect of saturated hydraulic conductivity and the width of permeable blanket on leachate flux was also evaluated.

Horizontal Trench

The plot of leachate flux for a single horizontal trench as a function of leachate injection pressure head (hereafter, referred to as injection head) is presented in Figure 3. The leachate flux at injection head equal to zero for k_w equal to 10^{-6} m/s is about 0.3 m³/d per meter length of the LR pipe perpendicular to the plane of the paper. Leachate flux increases with the increase in injection head. This relationship is curvilinear. The effect of k_w on leachate flux is also presented in Figure 3. The simulation results indicate that the leachate flux is directly proportional to k_w . Thus, if k_w is increased or decreased by an order of magnitude, assuming all other parameters constant, the leachate flux would also increase or decrease by an order of magnitude.

Permeable Blanket

The simulation results for LRS using permeable blanket and comparison of the results with horizontal trench are presented in Figures 4 to 6. All permeable blanket simulations

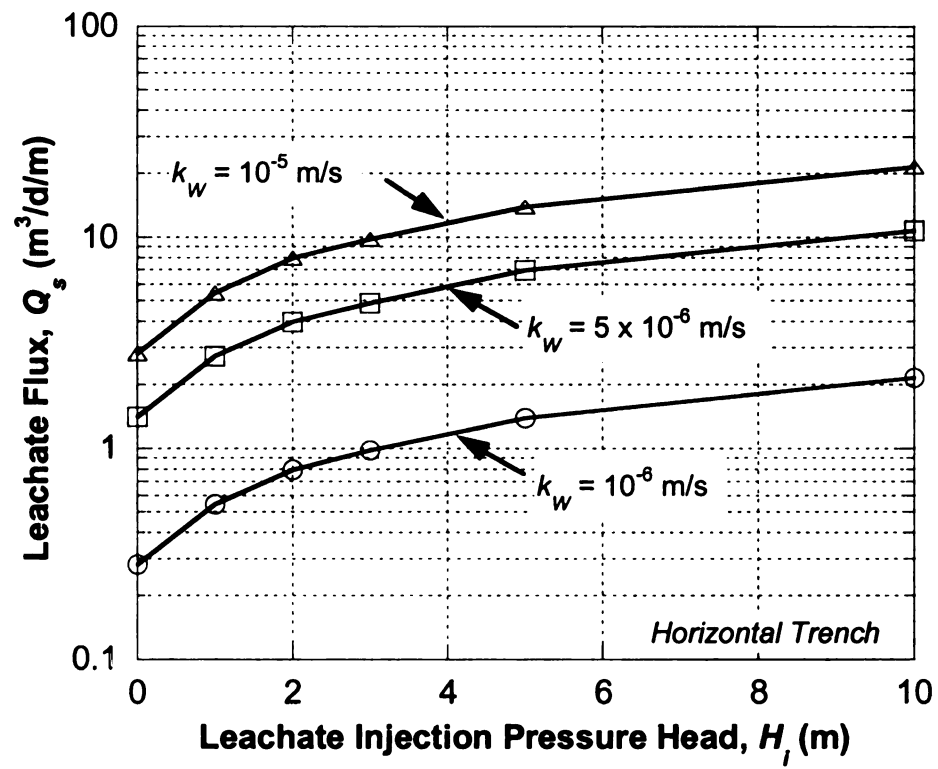


Figure 3. Simulated steady state recirculated leachate flux versus leachate injection pressure head for single horizontal trench for $k_w = 10^{-6}$, 5×10^{-6} , and 10^{-5} m/s.

were conducted for k_W equal to 10^{-6} m/s. Unless specified differently, k_B was assumed equal to 10^{-2} m/s and width of permeable blanket was assumed equal to 60 m.

Effect of Injection Head

Similar to the horizontal trench, as the injection head is increased, the leachate flux increased for the permeable blanket. However, the increase is log-linear for injection heads greater than the breakthrough pressure head (Figure 4). The breakthrough pressure head is the minimum injection head (greater than zero) required for leachate to breakthrough or flow across the entire width of the permeable blanket. Theoretically, for a perfectly horizontal permeable blanket, an injection head slightly greater than zero will cause breakthrough across the width of the blanket. At injection head equal to 1 m and 5 m, the simulated leachate flux for a 60-m-wide permeable blanket is 6.5 and 8.5 m³/d per meter length of the blanket.

At injection head equal to zero, permeable blanket behaves similar to a horizontal trench. At injection head equal to zero, the saturated region at steady-state is narrow at the top and widens for the lower portion. At injection heads greater than zero, the width of the saturated region is constant equal to the width of the permeable blanket [refer to Figure 2(b)].

Effect of Width of Permeable Blanket

The leachate flux increases linearly with increase in the width of the permeable blanket. Figure 4 presents the leachate flux as a function of injection head for permeable blankets having 30 m and 60 m widths. At injection heads greater than 0m, the leachate flux for 60-m-wide permeable blanket is exactly two times the leachate flux for 30-m-wide

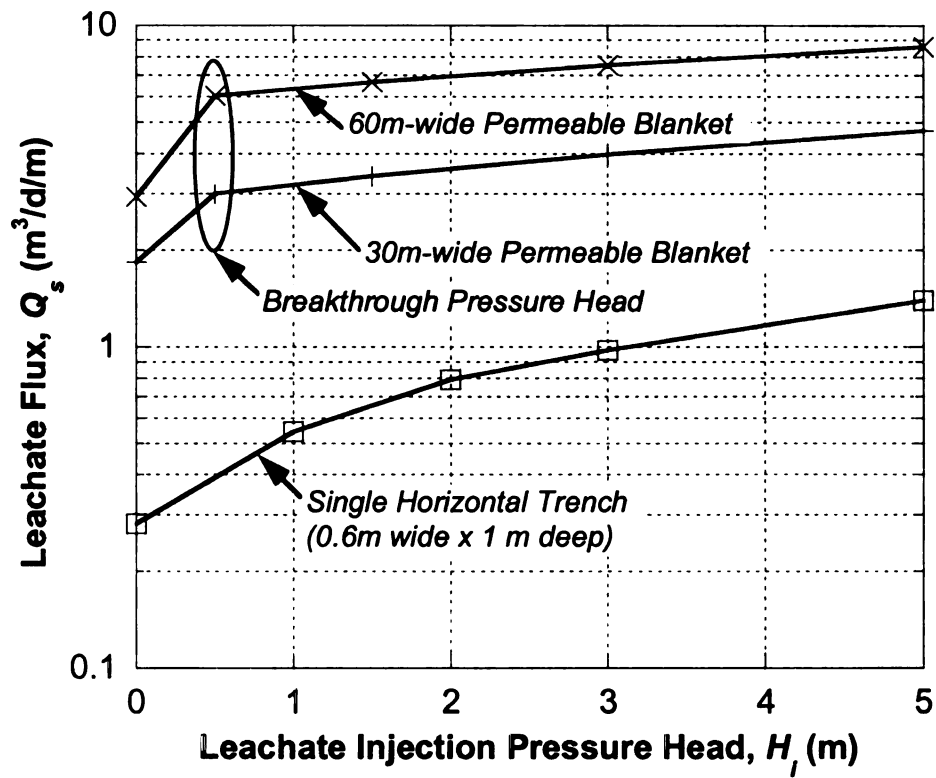


Figure 4. Simulated steady-state recirculated leachate flux versus leachate injection pressure head for single horizontal trench and for 30-m-wide and 60-m-wide permeable blankets for $k_w = 10^{-6}$ m/s and $k_{HT} \& k_B = 10^{-2}$ m/s.

permeable blanket at equal injection heads. The authors believe that if the width of the permeable blanket is reduced below 30 m, the leachate flux will continue to reduce linearly until the width is small enough for the permeable blanket to behave similar to a horizontal trench. At that point, the linear relationship will not hold. The authors have not completed these simulations to evaluate the smallest width of permeable blanket at which it would behave similar to a horizontal trench.

Effect of Hydraulic Conductivity of Permeable Blanket

Figure 5 presents the leachate flux as a function of injection head for the saturated hydraulic conductivities of the permeable blanket, k_B , equal to 10^{-3} , 5×10^{-3} , and 10^{-2} m/s. Hydraulic conductivities of gravel and sand range from 10^{-3} to 10^{-2} m/s and 10^{-5} to 10^{-3} m/s, respectively. The leachate flux increases as k_B increases. However, once k_B is equal to or greater than 5×10^{-3} m/s or when the injection head is equal to or greater than 1.5 m, the increase is negligible. Simulation results presented in Figure 5 indicate that if k_B is equal to 10^{-3} m/s, the injection head shall be greater than or equal to 1.5 m to achieve leachate flux similar in magnitude to that for k_B equal to or greater than 5×10^{-3} m/s.

Permeable Blanket and Horizontal Trench Equivalency

Figure 5 indicates that the amount of leachate flux that can be recirculated using a 60-m-wide permeable blanket is about one order magnitude higher than a single horizontal trench at zero injection head and about 6 times higher at 5 m injection head. In order to evaluate how many single trenches, if used simultaneously, would result in leachate flux similar in magnitude to a 60-m-wide permeable blanket, seven trenches spaced at 10 m center to center were simulated. The spacing between the farthest trenches was

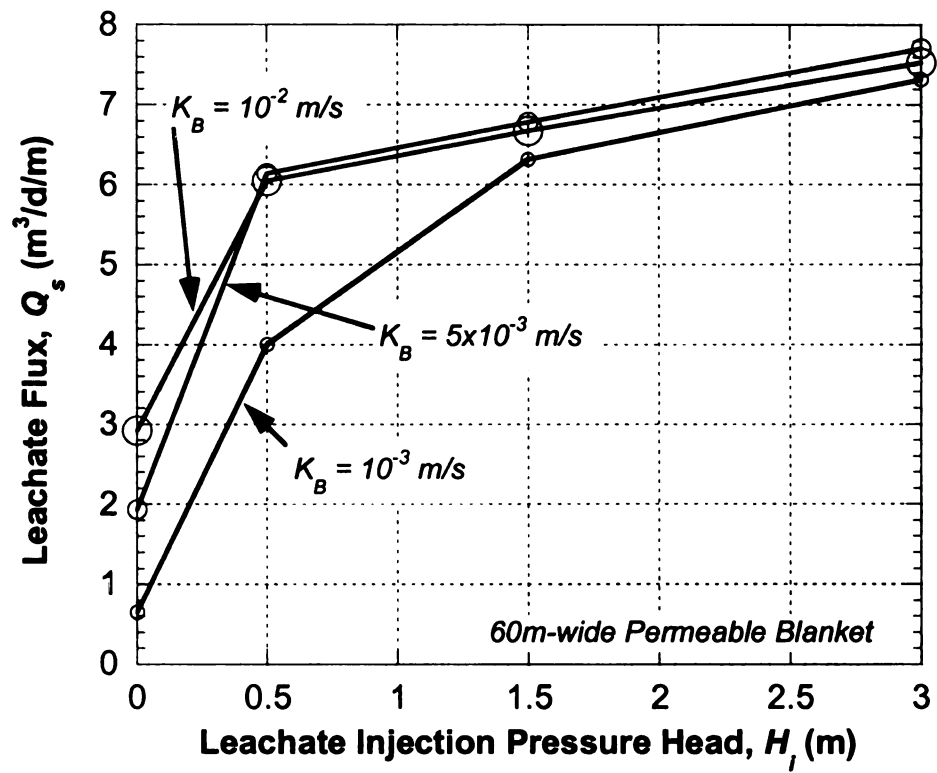


Figure 5. Simulated steady-state recirculated leachate flux versus leachate injection pressure head for 60-m-wide permeable blankets having $k_B = 10^{-3}$, 5×10^{-3} , and 10^{-2} m/s.

maintained at 60 m – same as the width of the permeable blanket. The total leachate flux from the seven horizontal trenches is presented in Figure 6. The leachate flux that can be recirculated using a 60m-wide permeable blanket exceeds the total flux from seven horizontal trenches at all injection heads ranging from 0 to 5m. The difference reduces as the injection head increases.

Effect of Settlement of Permeable Blanket

The total settlement of MSW in landfills ranges from 10% to 30% of initial thickness (Sowers 1972). The composition of waste, climate, leachate recirculation, and other physical and biochemical factors impact the settlement. Due to settlement of waste, permeable blankets constructed within waste will also undergo settlement. The effect of settlement of waste on the leachate flow through a 60-m-wide permeable blanket was evaluated by simulating a 3-m-deep sag at the center of the permeable blanket. The 3-m-deep sag simulates a 3 m differential settlement of waste. The simulation results indicate that for leachate injection head less than the magnitude of sag (3 m in this case), the leachate flux is less than that for a perfectly horizontal permeable blanket (zero sag). However, for injection heads greater than or equal to the sag, the leachate flux is equal to the leachate flux for a perfectly horizontal permeable blanket.

SUMMARY AND CONCLUSIONS

This study presents a numerical evaluation of permeable blankets – an alternative developed by the authors for leachate recirculation in MSW landfills. The steady-state leachate flux that can be recirculated at injection heads ranging from 0 to 5 m was simulated using the computer program HYDRUS-2D for the conventional horizontal

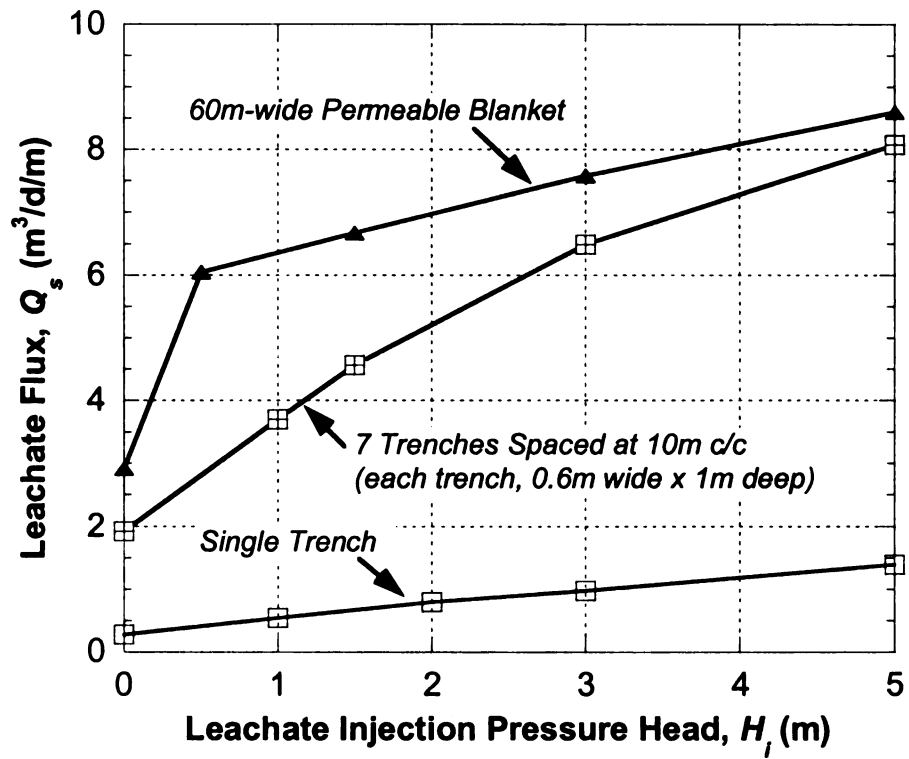


Figure 6. Simulated steady-state recirculated leachate flux versus leachate injection pressure head for single horizontal trench, seven horizontal trenches spaced at 10m c/c, and a 60-m-wide permeable blanket having k_B and $k_{HT} = 10^{-2}$ m/s.

trench and permeable blanket. Based on the numerical evaluation, a 60m-wide permeable blanket can recirculate greater amount of leachate flux at injection heads less than 5m, compared to total flux in seven horizontal trenches spaced at 10 m center to center.

The capital cost for the construction of a 60-m-wide permeable blanket is expected to be less than that for seven horizontal trenches for most sites. However, economical gains shall be evaluated on a site-specific basis. A permeable blanket distributes leachate more evenly compared to a set of horizontal trenches. Thus, dry pockets and hence differential settlement of waste is expected to be smaller for landfills where LR is done using permeable blankets. The summary of the key results is as follows:

As the injection head is increased, the leachate flux increases for both horizontal trench and permeable blanket. The relationship is curvilinear for horizontal trench. The relationship is log-linear for permeable blanket for injection heads greater than the breakthrough pressure head. Permeable blankets can recirculate relatively larger leachate flux at lower injection pressures. Thus, a pump with relatively small head but high flow shall be necessary.

The leachate flux linearly increases with increase in the width of permeable blanket.

The increase in the hydraulic conductivity of permeable blanket material results in increase in leachate flux. However, for hydraulic conductivities greater than or equal to 5×10^{-3} m/s, the difference is negligible.

Effect of sag in permeable blanket as a result of settlement of waste indicated reduction in leachate flux for injection heads less than the magnitude of the sag. For

injections heads greater than the magnitude of sag, the leachate flux is similar to a perfectly horizontal permeable blanket.

Field verification of performance of permeable blankets must be conducted to verify the numerical modeling results presented in this study.

ACKNOWLEDGEMENTS

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PAPER NO. 4: LEACHATE RECIRCULATION USING HORIZONTAL PERMEABLE BLANKETS IN BIOREACTOR LANDFILLS

ABSTRACT

Conventional subsurface leachate recirculation or liquid injection methods for municipal solid waste (MSW) landfills are horizontal trenches and vertical wells. In this study, we have presented numerical modeling and field-scale testing of a recently developed leachate recirculation system (LRS) called permeable blankets (PBs). HYDRUS-2D, a saturated/unsaturated water flow model was used to simulate the travel of injected leachate in PBs. These parameters were numerically evaluated in this study: (1) hydraulic properties of PB and waste; (2) geometry of PB; (3) settlement of PB; (4) leachate dosing frequency; and (5) initial degrees of saturation of PB and waste. In the field, at an MSW landfill located in Michigan, the migration of injected leachate in a 60-m-wide by 9-m-long by 0.15-m-deep blanket made up of crushed glass was measured using an automated sensing system consisting of sensors embedded in the blanket. Leachate injection rates simulated in this study and used in the field ranged from 1.1 m³/hr to 3.6 m³/hr per meter length of the injection pipe embedded in the PB. The key findings of the study are: (1) the rate and maximum distance of travel of injected leachate are a strong function of the hydraulic properties of the PB and underlying waste and the rate and frequency of leachate injection; and (2) the maximum pressure head in the blanket due to liquid injection does not exceed the injection pressure. The numerical modeling results and the field data indicated that PBs can be designed to inject liquids or recirculate leachate in MSW landfills. Long-term performance of such blankets needs to be evaluated.

BACKGROUND

Environmental and economical benefits of leachate recirculation for municipal solid waste (MSW) landfills are well documented (Reinhart and Al-Yousfi 1996; Reinhart and

Townsend 1998; Pohland and Kim 1999). These benefits include: (1) a reduction in the leachate treatment and disposal costs; (2) accelerated decomposition and settlement of waste resulting in an airspace gain; (3) an increase in the rate of gas production; (4) improvement in the quality of recirculated leachate; and (5) potential reduction in the post-closure care period and associated maintenance costs. Risks and drawbacks of leachate recirculation include: (1) potential decrease in the factor of safety for slope stability of landfills; (2) potential increase in the leachate head on the liner if leachate collection system is not designed to efficiently drain injected leachate; (3) potential flooding of the gas collection system; and (4) leachate seeps from the landfill side slopes if adequate buffer distance is not provided. Hence, before implementation, landfill operators should weigh the advantages and risks associated with leachate recirculation on a site-specific basis (Haydar and Khire 2005a).

Leachate recirculation techniques can be broadly divided into surface and subsurface application. Surface application consists of: (1) direct application of leachate or spray irrigation of leachate on the landfill surface; and (2) surface ponding of leachate. Climate dependency, odor problems, interference with daily operations, poor aesthetics, and potential runoff of applied leachate into storm water management system are the drawbacks of these surface application techniques. Conventional subsurface application methods are: (1) vertical wells; and (2) horizontal trenches (Koerner 2000, Qian et al. 2002).

Vertical wells and horizontal trenches (HTs) are the most commonly used leachate recirculation methods for relatively old and relatively new, MSW landfills, respectively (Maier and Vasuki 1997; Miller and Emge 1997; Haydar and Khire 2005a).

Disadvantages and limitations of vertical wells and horizontal trenches include: (1) during installation, excavation of waste may cause odor problems; (2) relatively high capital cost of construction; and (3) formation of “dry zones” if spaced too far apart where injected leachate cannot reach and hence cannot wet the waste. Such dry zones can lead to differential settlement of waste and hence can result in greater landfill cap maintenance costs. Design guidelines for LRS consisting of horizontal trenches are presented by Haydar and Khire (2005a). Haydar and Khire (2005a) suggested that HTs should be spaced at 10 m or less spacing for injection heads ≤ 5 m to ensure a relatively uniform wetting of the waste. Vertical wells can interfere with landfill daily operations. However, key advantages of using vertical wells LRS is that such wells can be installed after a landfill is capped or for retrofit landfills. It is most cost effective to install horizontal trenches before the landfill is capped at the design elevation in the landfill cell.

LEACHATE RECIRCULATION USING PERMEABLE BLANKETS

Design and Construction Aspects

Permeable blankets are constructed by laying a relatively thin layer of permeable material having relatively high hydraulic conductivity on a horizontal or inclined waste surface in a landfill. Geotextiles placed directly above and below the blanket to separate the PB from the surrounding porous material (e.g., soil, waste, etc.) and to prevent clogging of the blanket. The thickness of such blankets can vary depending upon the material used (e.g., shredded tires, pea gravel, crushed glass, GDL, etc.) and site-specific design and operational variables. A perforated pipe is embedded in the blanket in the direction parallel to the shorter or longer plan view dimension of the blanket where leachate is injected under a positive pressure. The relatively high hydraulic conductivity of the PB

allows preferential travel of injected leachate or liquids within the blanket and wetting of the underlying waste as the injected leachate infiltrates. The aerial dimensions and the shape of the PB can vary depending upon the leachate recirculation needs, shape of the landfill cell, relative contrast in the hydraulic conductivities of the blanket and underlying waste, and leachate injection pressure or leachate injection rates.

Khire and Haydar (2003) conducted preliminary numerical modeling to compare the hydraulic performance of HTs versus PBs. A constant injection pressure head was used to simulate leachate flux under steady-state condition. This flux and the wetted areas were used to evaluate the hydraulic performance of the simulated LRSs. The results demonstrated that PBs are hydraulically more efficient compared to HTs to uniformly wet the underlying waste. Khire and Haydar (2005) presented data from an instrumented field-scale PB made up of geocomposite drainage layer (GDL). Moisture content sensors embedded just beneath the GDL blanket indicated that the injected leachate traveled at a rate ranging from 8 to 18 m/hr for leachate injection rates ranging from 0.9 to 2.6 m³/hr/m. Long-term monitoring of the performance of the GDL blanket is ongoing.

Objectives

Even though the field-scale test has demonstrated that PBs can be used to inject leachate in MSW landfills, there are no comprehensive design guidelines available for designing PBs for MSW landfills. Hence, the key objectives of the study presented in this manuscript are to: (1) prepare preliminary design guidelines for the use of PBs to inject liquids or recirculate leachate in MSW landfills; and (2) present field-scale testing results of an instrumented PB made up of crushed glass installed at an active MSW landfill use the data to validate the modeling approach presented in this study. PBs can be horizontal

or inclined (Khire and Haydar 2003). In this paper, we have focused on horizontal PBs. In order to accomplish Objective No. 1, we have numerically simulated the effect of these parameters on the wetted width, rate of travel of injected liquid, and liquid pressure head in the blanket: (1) hydraulic properties of waste; (2) geometry of PB; (3) hydraulic properties of PB; (4) settlement of PB; (5) leachate dosing frequency; and (6) initial degrees of saturation of waste and PB. Wetted width and the rate of travel are key parameters to design the areal extent of a PB. Liquid pressure head is a key parameter to evaluate the effect of liquid injection on the slope stability of the landfill. Hence, these parameters were selected to develop the design guidelines.

Advantages of Permeable Blankets

Key advantages of PBs over conventional leachate recirculation methods are: (1) excavation of waste is not needed during the construction of blanket, resulting in no odors; (2) A PB can substitute multiple HTs or vertical wells resulting in lower installation cost from an equivalent design performance; (3) relatively uniform distribution of injected leachate below the PB resulting in potential reduction in differential settlement and related post-closure maintenance costs; and (4) PBs made up of granular materials (e.g., pea gravel, crushed glass, etc.) provide an ideal platform to embed sensors for monitoring the pressure, temperature and other physical, chemical, or biological parameters associated with the migration of injected liquids (Haydar and Khire 2005c).

LEACHATE FLOW IN WASTE

Korfiatis et al. (1984) have demonstrated success when the authors applied Richards' equation for saturated and unsaturated flow to a lab-scale MSW sample having diameter and height equal to 0.5 m and 1.5 m, respectively. A wide range (size and composition) of organic and inorganic constituents in MSW exhibited heterogeneity and anisotropy in hydraulic properties of MSW. The physical and hydraulic properties of waste may typically not only vary between landfills, but also within the same cell of a landfill. The saturated hydraulic conductivity of MSW, k_w , has been reported to range from 10^{-8} m/s to 10^{-4} m/s (Hughes et al. 1971; Fungaroli and Steiner 1979; Korfiatis et al. 1984; Oweis et al. 1990; Bleiker et al. 1993). The field capacity of MSW in landfills ranges from 20% to 35% (Oweis et al. 1990; Korfiatis 1984; Noble and Arnold 1991). McCreanor (1998) used SUTRA-2D to simulate the hydrodynamics of an LRS consisting of a single HT. The author modeled the lateral and vertical migration of leachate by simulating both, continuous and intermittent (8 hr on/16 hr off) applications of leachate. The initial degree of saturation of MSW was assumed equal to 40%. MSW was simulated as a homogeneous and isotropic medium using $k_w = 10^{-5}$, 10^{-6} and 10^{-7} m/s. The modeling results showed that the lateral and vertical spread of wetted area is almost similar for continuous or intermittent applications. McCreanor (1998) showed that, the use of daily and intermediate covers short-circuits the leachate flow along the cover material. The flow pattern of leachate is also affected by channeling (Zeiss and Uggucciioni 1995).

In this numerical study, we assumed MSW as a homogeneous and isotropic porous medium having k_w ranging from 10^{-7} m/s to 10^{-5} m/s. Effect of channeling was not considered in this study. Even though this assumption may not be completely in line with

field conditions, the results from this numerical study would be useful in comparing designs or to investigate alternatives during iterative design phases of an LRS (Straub and Lynch 1982). Similar approach has been used by Haydar and Khire (2005a) for preparing preliminary design guidelines for liquid injection using HTs. The effect of heterogeneity and anisotropy on the hydraulic performance of LRS consisting of HTs is presented in detail by Haydar and Khire (2005b). Haydar and Khire (2005b) showed that the introduction of heterogeneity and anisotropy resulted in lower leachate pressure heads for a given leachate injection rate compared to that when waste was assumed homogenous and isotropic. This finding would result in conservative design and can be extended to LRS consisting of PBs.

NUMERICAL MODELING OF PERMEABLE BLANKETS

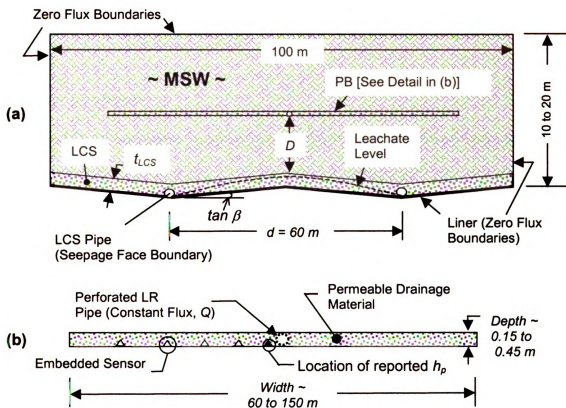
HYDRUS-2D Computer Model

Haydar and Khire (2005a) used HYDRUS-2D to simulate the flow of injected leachate using HTs in bioreactor landfills. HYDRUS-2D is a computer model that can simulate water, heat, and solute migration in unsaturated, partially saturated, or fully saturated porous media (Simunek et al. 1999). The program numerically solves the Richards' Equation for saturated and unsaturated water flow and uses van-Genuchten function (van Genuchten 1980) for soil-water characteristic curves and van-Genuchten-Mualem model (Mualem 1976) for predicting the unsaturated hydraulic conductivity function. This model has been used for saturated/unsaturated liquid and solute transport through porous media in several studies (Scanlon et al. 2002; Henry et al. 2002; Pang et al. 2000; Rassam and Cook 2002).

Conceptual Model

Khire and Haydar (2003) developed a conceptual model to numerically evaluate the use of PBs as a leachate recirculation alternative to conventional HTs. This conceptual model is presented in Figure 1. The conceptual model consisted of a PB and a leachate collection system (LCS). The simulated PB consisted of a 15-mm-thick permeable layer with a perforated pipe having diameter equal to 0.1 m. The perforated pipe ran perpendicular to the plane of the paper through the center of the PB. The width of the PB ranged from 60 m to 150 m (Figure 1b). The vertical distance, D , between the PB and the top of the LCS ranged from 5 m to 20 m. Distance from the top of the PB to the upper zero flux boundary was assumed equal to 5 m to contain all injected leachate and to prevent possible artesian conditions for the simulated leachate injection rates. The LCS consisted of two 0.15-m-diameter perforated pipes embedded in a 0.3-m-thick gravel layer at a horizontal spacing, d , equal to 60 m. The slope ($\tan \beta$) of the LCS was assumed equal to 3.5%. The hydraulic conductivity of the LCS drainage material (k_{LCS}) was assumed equal to 10^{-2} m/s. The chosen LCS design parameters (t_{LCS} , k_{LCS} , d , and $\tan \beta$) resulted in less than 0.3-m-leachate pressure head on the lining system for all simulations presented in this study.

The simulated saturated hydraulic conductivities of MSW, k_w , ranged from 10^{-7} m/s to 10^{-5} m/s. However, an average k_w equal to 10^{-6} m/s was used in most simulations. These values were selected according to typical values published by Hughes et al. (1971), Fungaroli and Steiner (1979), Korfiatis et al. (1984), Oweis et al. (1990), and Bleiker et al. (1993). The saturated and unsaturated hydraulic properties of the simulated waste, PB material, and LCS gravel layer input to HYDRUS-2D are presented in Table 1.



Notes:

1. h_p = Simulated Pressure Head
2. LCS = Leachate Collection System
3. LR = Leachate Recirculation
4. MSW = Municipal Solid Waste
5. PB = Permeable Blanket
6. NOT TO SCALE

Figure 1. (a) Conceptual model used for numerical simulation of leachate recirculation in MSW landfill using a horizontal permeable blanket; and (b) detail of a permeable blanket.

We simulated leachate as pure water. Hence, any reference to leachate flow henceforth corresponds to water flow. The results of this study can be applied to any injected liquids for bioreactor landfills as long as the liquid's physical and hydraulic properties are similar to that of water. The effect of gas flow, temperature and biochemical reactions occurring within a landfill was ignored.

Boundary Conditions

All external boundaries were simulated as zero flux boundaries. The perforated pipe used for leachate injection was simulated as a constant flux boundary. The flux (dimensions: $M^0L^1T^{-1}$) assigned to the boundary was calculated by dividing the leachate injection rate (dimensions: $M^0L^3T^{-1}$) by the perimeter of the pipe for a unit length of the pipe. The simulated leachate injection rates (Q) ranged from 1.1 to 3.6 $m^3/hr/m$. These rates were selected based on leachate injection rates used in the field for PBs tested in this study and other studies (Khire and Haydar 2005). The maximum leachate injection rate of 3.6 $m^3/hr/m$ corresponded to the maximum rate the pump at the site could deliver for the total head that existed for the system. Note that Q in $m^3/hr/m$ represents the leachate injection rate in cubic meters per hour per linear meter length of the pipe perpendicular to the plane of the paper.

Leachate collection pipes embedded in the LCS were simulated as seepage face boundaries. Leachate flow as a result of percolation from the cap or waste above the model domain was assumed zero. We believe that this assumption is reasonable because our key objective in this study was to simulate the subsurface hydraulics of injected leachate.

Table 1. Saturated and unsaturated hydraulic properties used in HYDRUS-2D simulations.

Landfill Unit	Material	θ_r	θ_s	α (1/m)	n	k_s (m/s)
Waste	Silt loam	0.078	0.45	3.6	1.54	10^{-5} , 10^{-6} and 10^{-7}
Permeable Blanket	Pea gravel	0.01	0.3	57.4	2.44	10^{-2} and 10^{-3}
	Crushed Glass	0.02	0.47	12	5	3×10^{-2}
Leachate Collection System	Pea gravel	0.01	0.3	57.4	2.44	10^{-2}

MODELING RESULTS

Leachate recirculation in the field is often carried out in on/off dosing cycles. The dosing cycles simulated in this study ranged from 2 hours on/22 hours off to 8 hours on/16 hours off to cover various dosing volumes and frequencies for a typical MSW landfill. Leachate injection was simulated as constant flux under a positive leachate injection pressure.

Figure 2 presents a schematic of the wetting front of injected leachate traveling in the PB. We defined the wetted width as the distance traveled by the injected leachate from the injection pipe in the PB. We differentiated between the wetted width of the underlying waste and the saturated wetted width of the PB as shown in Figure 2. The wetted width of waste (W_w) was defined as the maximum distance traveled by the injected leachate from the injection pipe in the PB just above the underlying waste. W_w dictates the lateral extent of infiltration of injected leachate through the underlying waste. The saturated wetted width of PB (W_B) was defined as the one-half of the width of the PB where the entire depth of the PB is 100% saturated. W_B is always less than W_w . The difference between W_w and W_B varies depending upon the leachate injection rate, the thickness of the PB and the hydraulic properties of the PB and waste.

When a 60-m-wide blanket is fully saturated, W_B equals 30 m. The injected leachate also temporarily increases the degree of saturation of the PB and the pressure head in the PB (h_p).

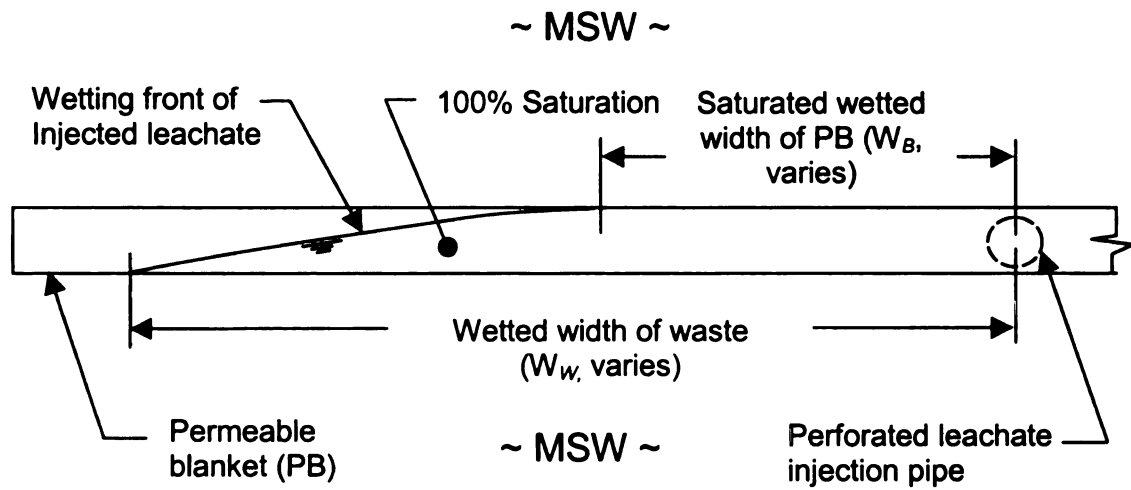


Figure 2. Schematic of wetting front of injected leachate in permeable blanket.

Because one of the key parameters that impact the shear strength of the waste is the effective stress, the pressure head distribution in the blanket is a key input for slope stability analysis of bioreactor landfills. We have simulated h_p by measuring the pressure head in the proximity of the injection pipe (within 0.5 m) at the bottom of the PB as shown in Figure 1b. The pressure head in the PB is always greater near the injection pipe. Hence, the use of this pressure head for slope stability analysis would yield conservative results. Note that h_p is different from the injection pressure head in (h_i) side the injection pipe and is a function of the leachate injection rate and the hydraulic properties of PB and waste. We have presented h_p because we also believe that it can be used to interpret and monitor the hydraulic performance of the LRS. For example, if the magnitude of h_p is close h_i , it indicates a good hydraulic continuity between the injection pipe and the PB. If the difference between h_i and h_p increases over time for a given magnitude of leachate injection rate, it indicates a decrease in the hydraulic conductivity of the blanket or potential clogging of the leachate injection pipe.

Over 150 simulations using HYDRUS-2D were conducted to evaluate the effect of the design parameters on the wetted width and pressure head of injected leachate in PB. The following design parameters were evaluated: (1) hydraulic properties of waste; (2) geometry of PB; (3) hydraulic properties of PB; (4) settlement of PB; (5) leachate dosing volume and frequency; and (6) degree of saturation of waste and PB.

Unless specified otherwise, all simulations were conducted using the following parameters as input: (1) PB width = 60 m; (2) PB depth = 0.15 m; (3) initial degree of saturation of PB (S_B) = 50%; (4) initial degree of saturation of waste (S_W) = 45%; (5) hydraulic properties of PB are those of pea gravel presented by Khire et al. (2000) with a

saturated hydraulic conductivity (k_B) = 10^{-2} m/s; (6) hydraulic properties of MSW are those of loam from HYDRUS-2D's database with a saturated hydraulic conductivity (k_W) = 10^{-6} m/s; and (7) vertical spacing between PB and LCS (D) = 5 m.

Hydraulic Properties of Waste

Due to the heterogeneity in the composition of MSW, the measurement of representative hydraulic properties (saturated and unsaturated) of MSW remains challenging till this day. We evaluated the effect of unsaturated hydraulic properties of MSW on the W_w and h_p . In order to do so, MSW was simulated as sand and loam in two separate simulations. The saturated hydraulic conductivities of sand and loam were assigned equal to 10^{-6} m/s. However, different soil-water characteristic curves were assigned for sand and loam from HYDRUS-2D database. In one scenario, leachate was continuously injected at an injection rate equal to $1.1 \text{ m}^3/\text{hr}/\text{m}$ for an injection period of 8 hours and in the second scenario, leachate was injected in 4 hours on/20 hours off dosing cycles for a total period of 7 days. The initial degrees of saturation for PB and MSW were equal for all simulations in these scenarios. The simulation results indicated that unsaturated hydraulic properties of the waste are critical only if simulations are conducted to evaluate wetted width and leachate pressure head for relatively short-term (less than 2 to 3 days) leachate injection scenarios.

For long-term and recurring leachate injection scenarios, which are most typical in the field, unsaturated hydraulic properties of the material used to simulate MSW have virtually no influence on the wetted width and the pressure head of injected leachate in the PB. Hence, unsaturated hydraulic properties of loam were used for all simulations conducted in this study, unless it is specified otherwise.

Saturated Hydraulic Conductivity of MSW

Figure 3 presents the effect of k_w on the simulated W_B and h_p in a 60-m-wide PB. The simulated values of k_w were 10^{-5} , 10^{-6} , and 10^{-7} m/s. These values were selected based on the typical reported values for MSW (Haydar and Khire 2005a). Q was assumed equal to: (1) $1.1 \text{ m}^3/\text{hr}/\text{m}$ for an injection period of 8 hours (Figure 3a); and (2) $3.6 \text{ m}^3/\text{hr}/\text{m}$ for an injection period of 3 hours (Figure 3b).

Figure 3a shows that for $k_w = 10^{-5}$ m/s, the simulated W_B was about 6 m after 8 hours of continuous leachate injection. The simulated h_p remained below 0.3 m throughout the leachate injection period. For $k_w = 10^{-7}$ m/s, W_B reached the maximum possible value of 30 m for the 60-m-wide PB after 6 hours of continuous leachate injection. h_p rose as the injected leachate traveled within the PB and increased its degree of saturation. Once the injected leachate reached the 30-m-distance and it saturated the entire blanket, h_p sharply increased as the storage capacity of the blanket was exceeded. It was also noted that this increase in the pressure head was more for a lower hydraulic conductivity of the underlying MSW.

Figure 3b shows that for $k_w = 10^{-5}$ m/s, the simulated W_B was about 17 m after an injection period of 3 hours for $Q = 3.6 \text{ m}^3/\text{hr}/\text{m}$ compared to about 6 m for $Q = 1.1 \text{ m}^3/\text{hr}/\text{m}$ after an injection period of 8 hours. The simulated h_p was about 1.5 m, whereas it was 0.3 m for the lower Q . For $k_w = 10^{-6}$ and 10^{-7} m/s, W_B was 30 m after an injection period of 2.5 and 1.5 hours, respectively. For $Q = 3.6 \text{ m}^3/\text{hr}/\text{m}$, the h_p values were greater than those for $Q = 1.1 \text{ m}^3/\text{hr}/\text{m}$.

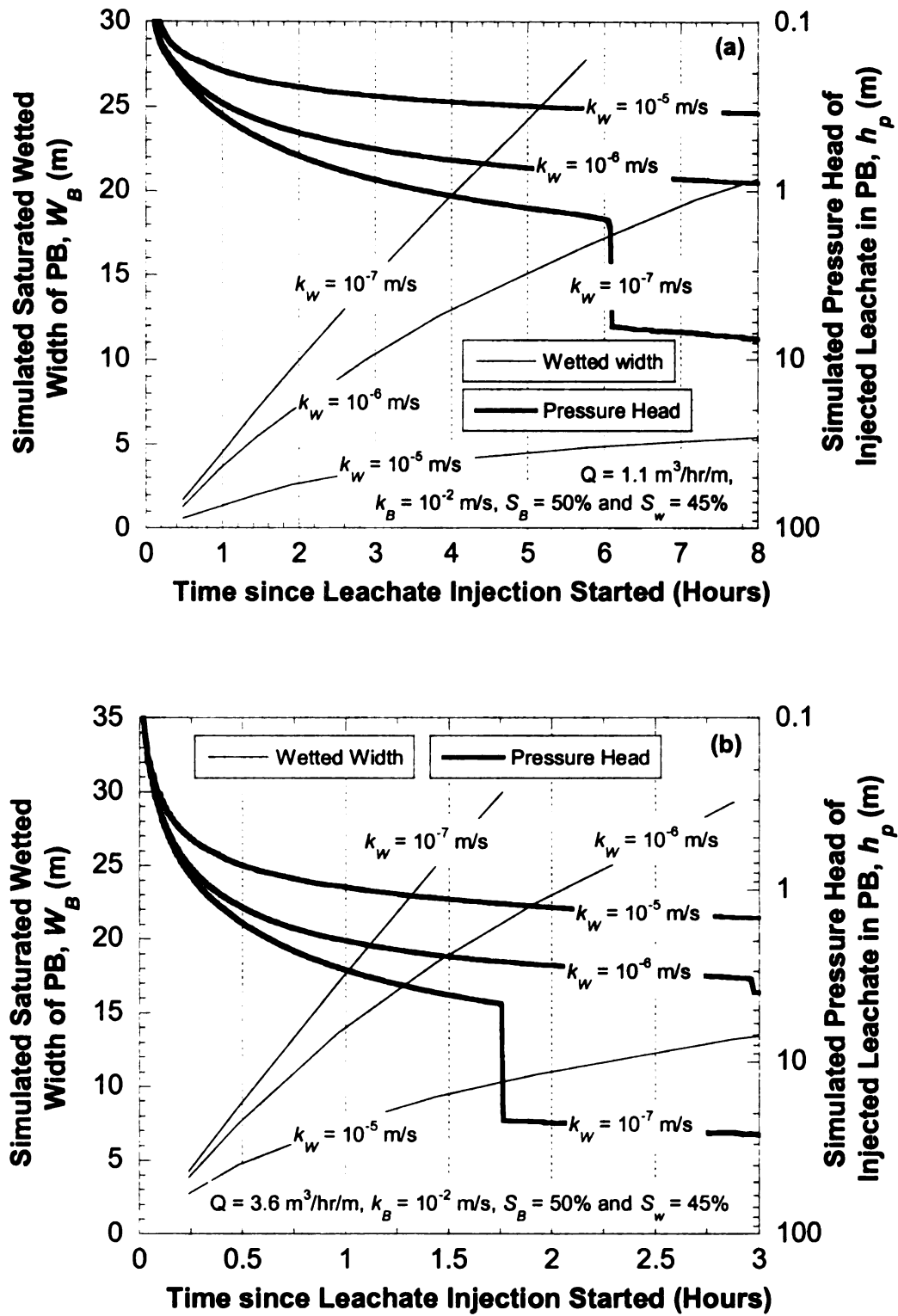


Figure 3. Effect of k_w on simulated wetted width and pressure head of injected leachate for a 60-m-wide PB for $Q = 1.1 \text{ m}^3/\text{hr/m}$ (a); and $Q = 3.6 \text{ m}^3/\text{hr/m}$ (b).

Unsaturated Hydraulic Properties of Waste

Measurement of the unsaturated hydraulic properties of MSW remains challenging till today because these properties can vary significantly within a landfill or a landfill cell. However, these properties influence the estimation of W_w and h_p . To simulate the effect of unsaturated hydraulic properties on W_w and h_p , soil water characteristic curves (SWCCs) of loam and sand were used to simulate waste, while maintaining the saturated hydraulic conductivity of the waste constant to allow for comparison. Figure 4 presents the effect of waste SWCC on W_w and h_p in a 60-m-wide PB for $k_w = 10^{-6}$ m/s. Q was assumed equal to $1.1 \text{ m}^3/\text{hr}/\text{m}$ for a dosing frequency of 4 hours on/20 hours off. Figure 4 shows that W_w and h_p were greater when waste was simulated as sand compared to loam. This was because sand has a lower unsaturated hydraulic conductivity than loam. For the remainder of this study, SWCC of loam has been used to simulate waste. Designers should consider a SWCC close to that of the targeted waste in the design.

Saturated Hydraulic Conductivity of Permeable Blanket

The saturated hydraulic conductivity of PB (k_B) may vary depending on the permeable material used for constructing the PB. The effect of k_B on W_B and h_p was evaluated using k_B values equal to 10^{-2} and 10^{-3} m/s. Figure 5 presents the effect of k_B on the simulated W_B and h_p in a 60-m-wide PB for $k_w = 10^{-6}$ m/s. Q was assumed equal to $1.1 \text{ m}^3/\text{hr}/\text{m}$ for an injection period of 8 hours (Figure 5a) and $3.6 \text{ m}^3/\text{hr}/\text{m}$ for an injection period of 3 hours (Figure 5b). Figure 5 shows that the injected leachate travels at a slower rate for a

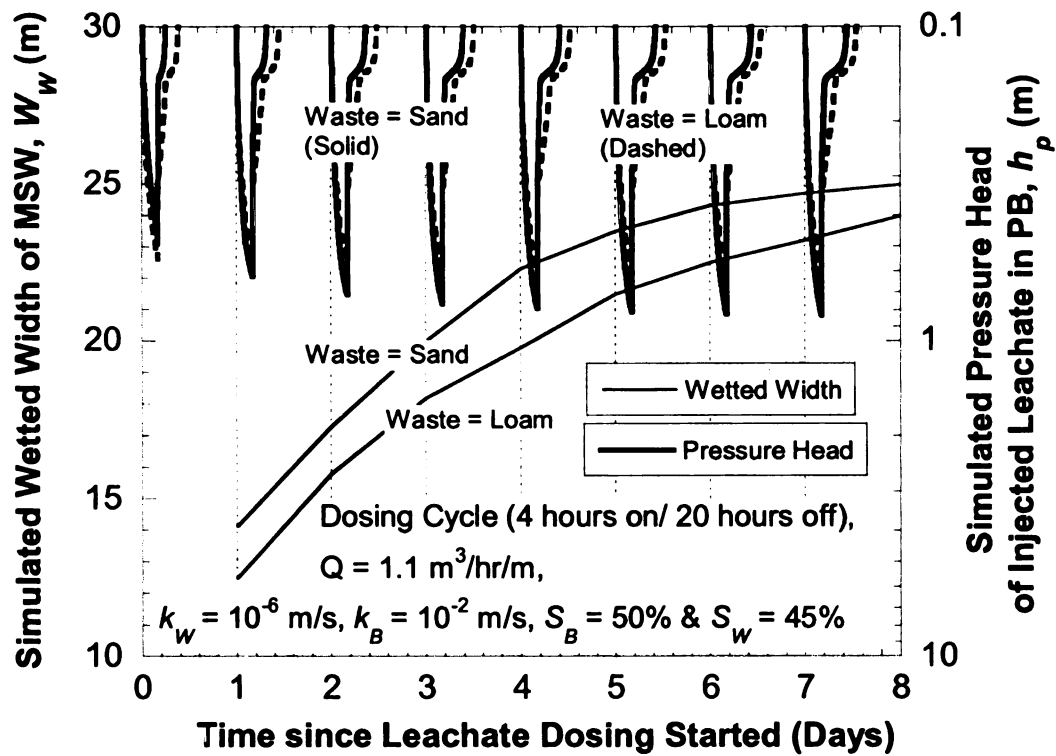


Figure 4. Simulated wetted width of waste and simulated pressure head in the PB as a function of the soil water characteristic curve used in simulating the waste.

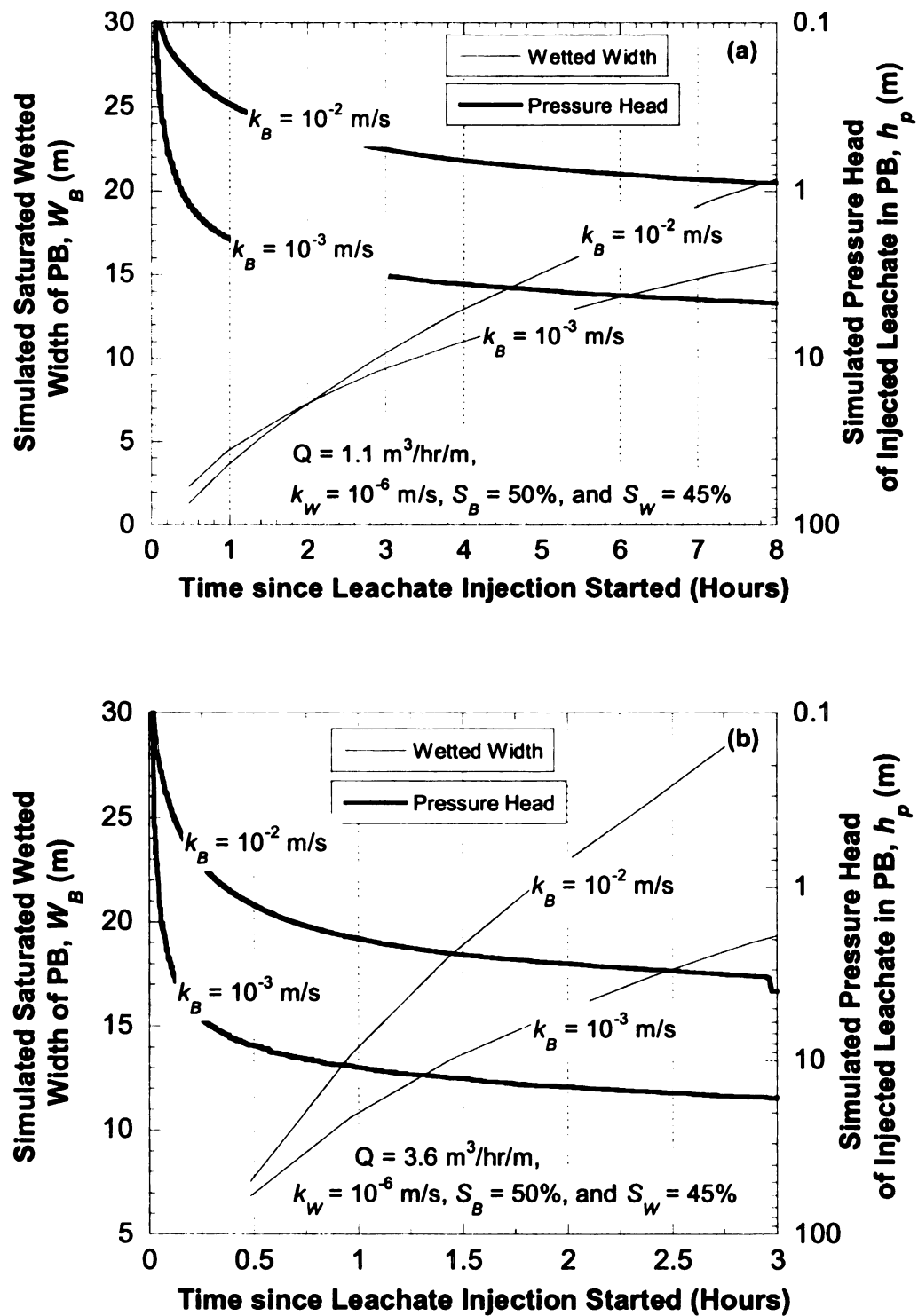


Figure 5. Effect of k_B on simulated wetted width and pressure head of injected leachate for a 60-m-wide PB for: (a) $Q = 1.1 \text{ m}^3/\text{hr/m}$; and (b) $Q = 3.6 \text{ m}^3/\text{hr/m}$.

lower k_B and results in a greater h_p for a given leachate injection rate. Thus, a greater k_B is preferable when selecting a suitable material for the PB under consideration.

Hysteresis in Hydraulic Conductivity of Permeable Blanket

The effect of hysteresis in k_B on W_W and h_p was evaluated by simulating the SWCC of the PB for wetting and drying, one at a time. HYDRUS-2D model incorporates hysteresis in the soil hydraulic properties. When a hysteretic description of the soil hydraulic properties is selected, a selection must be made for whether the initial condition is associated with the wetting or drying SWCC. For this evaluation, the simulated PB material was gravel (Table 1). The hydraulic parameters of the drying SWCC are presented in Table 1. The HYDRUS-2D model generated the wetting curve of the SWCC by multiplying the α parameter in the drying curve by a factor of two. This resulted in assigning $\alpha = 114.8$ for the wetting SWCC. For this evaluation, a 60-m-wide PB was simulated. k_W was assumed equal to 10^{-6} m/s and Q was assumed equal to $1.1 \text{ m}^3/\text{hr}/\text{m}$ for an injection period of 8 hours when liquid was injected continuously. The simulated values of S_B and S_W were equal to 50% and 45%. Simulations showed that hysteresis in k_B had no influence on W_W and h_p .

Geometry of Permeable Blanket

Permeable Blanket Depth

The depth of a PB can be influenced by the material used for constructing the PB. For example, a GDL blanket can be relatively thin (~ 10 mm), whereas blankets made up of shredded tires can be as thick as 0.6 m depending on the size of the tire shreds. Figure 6 presents the effect of PB depth on W_B and h_p in a 60-m-wide PB. The simulated PB depth

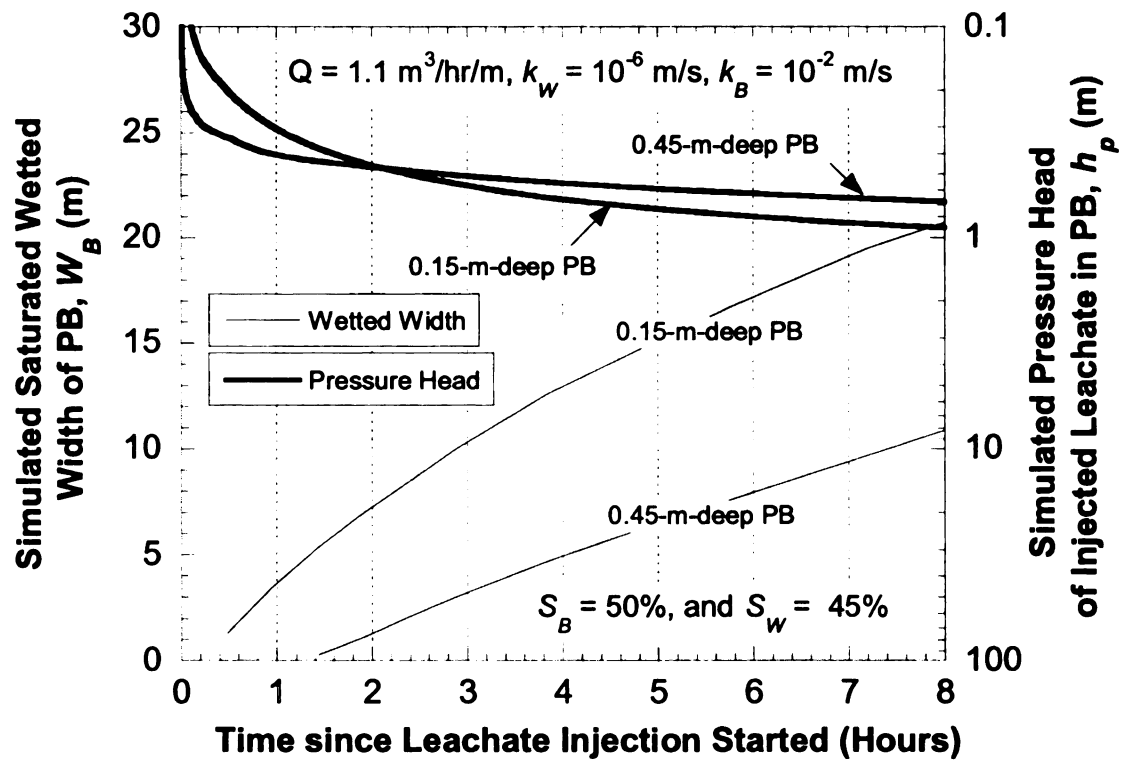


Figure 6. Effect of PB depth on simulated wetted width and pressure head of injected leachate for a 60-m-wide PB.

values were assumed equal to 0.15 m and 0.45 m. k_w was assumed equal to 10^{-6} m/s and $Q = 1.1 \text{ m}^3/\text{hr}/\text{m}$ for an injection period of 8 hours. Simulation results presented in Figure 6 indicate that W_B decreases as the PB depth increases. However, W_w did not differ significantly between the two simulated depths of the PB (W_w not shown in Figure 6). As the depth of PB increased, the storage capacity of the blanket also increased. This increase in storage capacity resulted in a lower h_p for the deeper PB. These results are consistent with a flow problem where two circular pipes having different diameters are connected in series. The liquid pressure is less in the larger diameter pipe. Thinner blanket is preferable to keep the capital cost down, whereas thicker blanket is preferable to keep h_p in an acceptable range for slope stability concerns.

Permeable Blanket Width and Vertical Spacing

The planar dimensions of PBs may vary according to the landfill cell shape and its leachate recirculation needs. PBs can be installed at any filling stage of a landfill before it is capped. Thus, PBs can be installed at various surface elevations of an MSW landfill. We simulated 60-m-wide and 150-m wide PBs for k_w equal to 10^{-6} m/s and $Q = 1.1 \text{ m}^3/\text{hr}/\text{m}$ for an injection period of 8 hours. The simulation results indicated that the PB width had no effect on the simulated wetted width or h_p . We also evaluated the effect of vertical spacing between the PB and the LCS by simulating a vertical spacing (D) equal to 5 m and 20 m. k_w was assumed equal to 10^{-6} m/s and $Q = 1.1 \text{ m}^3/\text{hr}/\text{m}$ for an injection period of 8 hours. The simulation results indicated that D did not influence the simulated wetted width or h_p .

Settlement of Permeable Blanket

Settlement of waste in landfills has been reported to range from 10% to 30% of its initial thickness (Sowers 1972; Wall and Zeiss 1995). The composition of waste, climate, presence or absence of leachate recirculation, and other physical and biochemical factors impact the settlement of waste in landfills. Due to the differential settlement of waste, PBs constructed within waste will also undergo differential settlement.

The effect of settlement of waste on the leachate flow through a 60-m-wide PB was evaluated by simulating 3-m-deep sag at the center of the PB. The 3-m-deep sag simulated differential settlement equal to 3 m. The simulation results indicated that for leachate injection pressure heads less than the magnitude of the simulated sag (3 m in this case), the injected leachate could not fill up the entire blanket. Hence, in such cases, corresponding leachate injection rate needs to be increased to create an additional injection pressure head that can compensate for the sag. Once the injection pressure head was greater than or equal to the magnitude of the sag, the injected leachate filled up the entire blanket resulting in a greater W_w and W_B . Haydar and Khire (2005c) have presented a sensing and monitoring system that can be used to monitor the leachate injection rate and pressure and the rate of travel of injected leachate in the PB. Such sensing and monitoring system can be used to manipulate the leachate injection rate (or pressure) to compensate any differential settlement in the PB.

Leachate Dosing Frequency

In order to prevent buildup of liquid pressure head and leachate breakouts, and possible slope instabilities, leachate is not continuously injected in landfills. Instead, leachate is injected in on/off dosing cycles. The dosing volume and frequency for leachate injection

may vary depending on the daily leachate generation volume and the operational needs of the landfill. We evaluated the effect of dosing frequency for $Q = 1.1 \text{ m}^3/\text{hr}/\text{m}$ on W_w by simulating leachate injection for 2 hours on/22 hours off, 4 hours on/20 hours off, and 8 hours on/16 hours off. Figure 7a presents the effect of dosing frequency on W_w for $k_w = 10^{-6} \text{ m/s}$ and $S_w = S_B = 30\%$. Figure 7a indicates that W_w is a function of the ratio of on to off leachate injection duration. The wetted width of waste was greater for a dosing cycle where the on to off times ratio was greater. For a given dosing frequency, W_w increased as the number of leachate dosing days increased until W_w reached a constant maximum value ranging from 15 to 45 m depending on the on to off duration ratio after almost ten days (Figure 7a).

Figure 7b presents the simulated h_p for the dosing frequencies of 2 hours on/22 hours off and 4 hours on/20 hours off for the same simulations presented in Figure 7a. However, for a given dosing frequency, h_p increased and then remained almost constant as the leachate dosing continued and the system almost reached a steady-state. The initial increase was due to the increase in the degree of saturation of the waste and the PB. The magnitude of h_p was a function of the on to off duration ratio. Greater the on to off duration ratio, greater was the magnitude of h_p .

Even though it is not customary to continuously inject leachate in landfills, we evaluated the effect of continuous leachate injection (until steady-state is reached) on W_w to obtain the maximum possible wetted width for a given leachate injection rate. Figure 8 shows a contour map that presents simulated W_w for a 150-m-wide PB using continuous leachate injection at $Q = 1.1 \text{ m}^3/\text{hr}/\text{m}$ (Figure 8a) and $Q = 3.6 \text{ m}^3/\text{hr}/\text{m}$ as a function of k_w

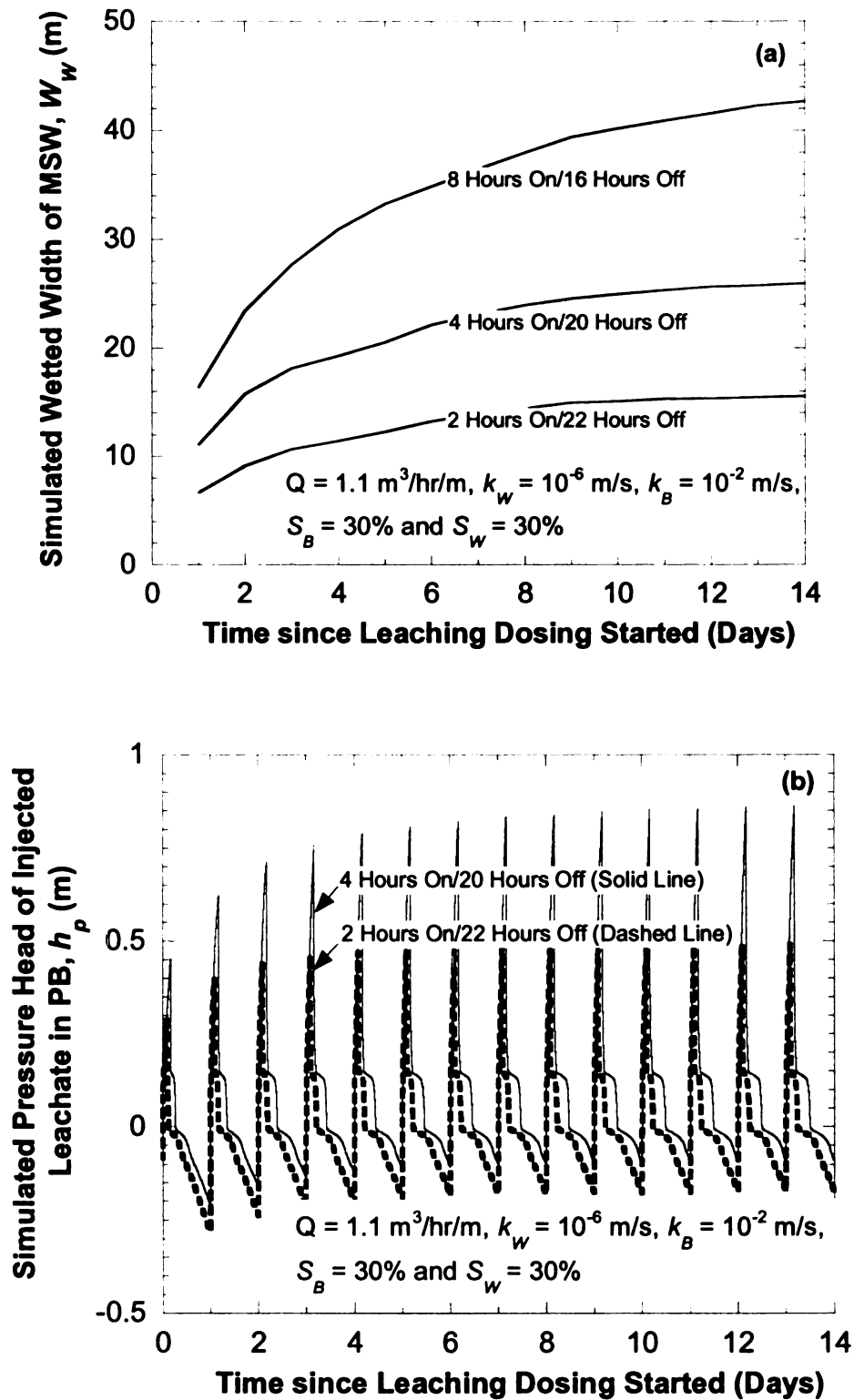


Figure 7. Simulated wetted width of waste as a function of leachate dosing frequency for a 150-m-wide PB (a); and corresponding simulated pressure head in the PB (b).

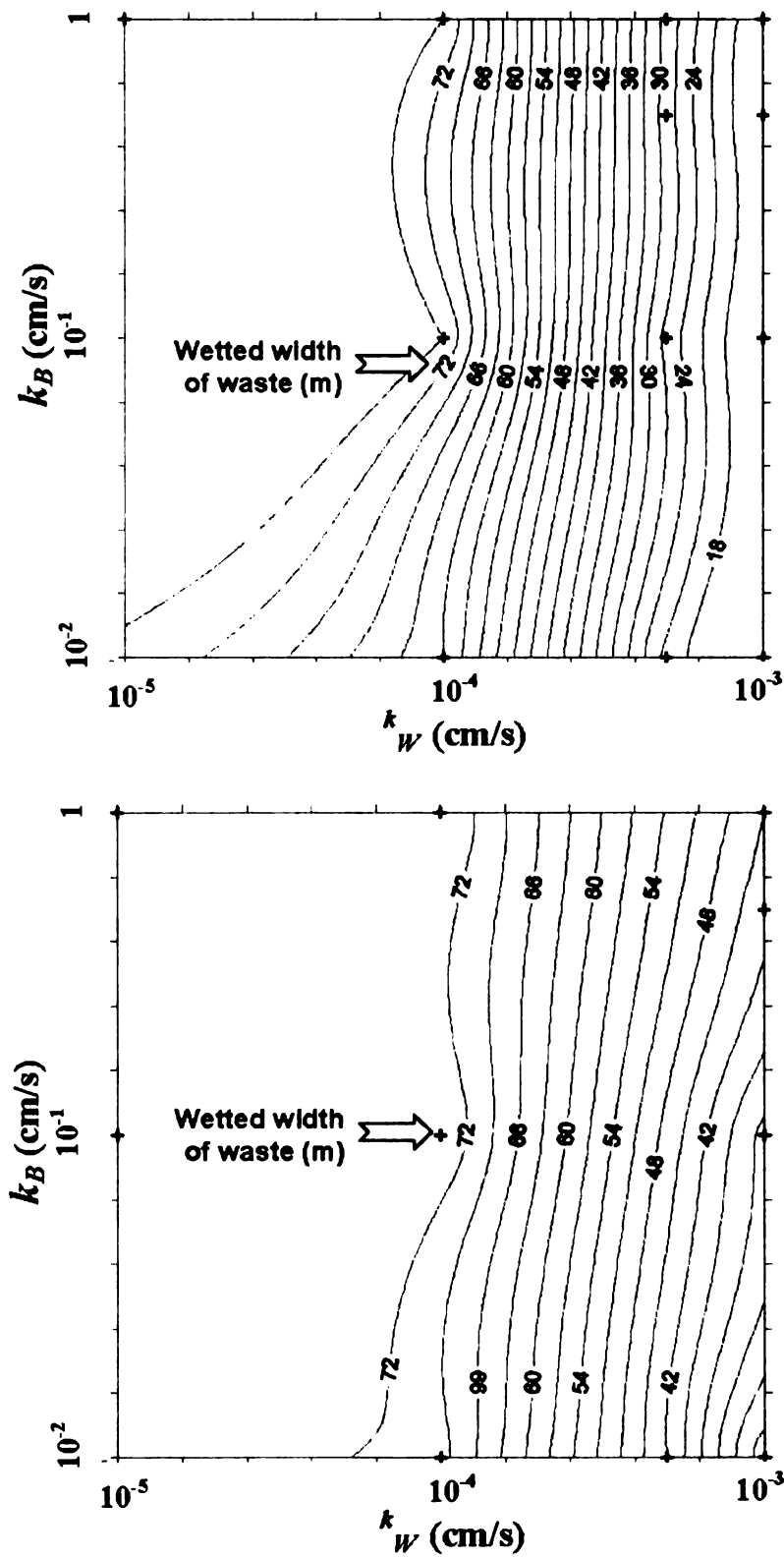


Figure 8. Contours of Simulated maximum wetted width of waste at steady-state as a function of k_B and k_W for continuous leachate injection rates: (a) $Q = 1.1 \text{ m}^3/\text{hr/m}$; and (b) $Q = 3.6 \text{ m}^3/\text{hr/m}$.

and k_B (Figure 8b). k_W was varied from 10^{-7} m/s to 10^{-5} m/s and k_B was varied from 10^{-4} m/s to 10^{-2} m/s. The simulated W_W was mainly a function of k_W as long as k_B was greater than k_W . The simulated maximum W_W increased as k_W decreased. The key finding from Figure 8 is that either increasing Q or reducing k_W can increase W_W . Because k_W in the field typically cannot be controlled, Q is the key parameter that needs to be controlled to achieve a certain W_W .

Degrees of Saturation of Waste and Permeable Blanket

The rate of travel of injected leachate in a PB is a function of the initial degrees of saturation of waste (S_W) and the PB (S_B). The initial degrees of saturation are input to HYDRUS-2D as an initial condition in the form of water content or matric suction head. Figure 9 presents the effect of initial conditions (S_W and S_B) on the simulated W_W for a 150-m-wide PB for $k_W = 10^{-6}$ m/s and $Q = 1.1$ m³/hr/m for a dosing frequency of 4 hours on/20 hours off. The x-axis of the plot in Figure 9 represents the number of days since leachate dosing started. The y-axis represents the maximum W_W at the end of the daily leachate injection event. We assumed four possible sets of initial conditions with S_W ranging from 30% to 65% and S_B ranging from 30% to 95%. This range of initial degrees of saturation was selected based on the typical range of values observed in the field for bioreactor landfills (Zhao et al. 2004; Haydar and Khire 2005c). Figure 9 shows that for all four sets of simulations, W_W increased as the number of leachate dosing days increased. However, irrespective of the initial degrees of saturation of the waste and the PB, the maximum W_W was about the same after a few days (long-term) of leachate dosing for a given value of Q and dosing frequency. It took progressively longer time to reach the maximum W_W for lower values of S_W and S_B (Figure 9).

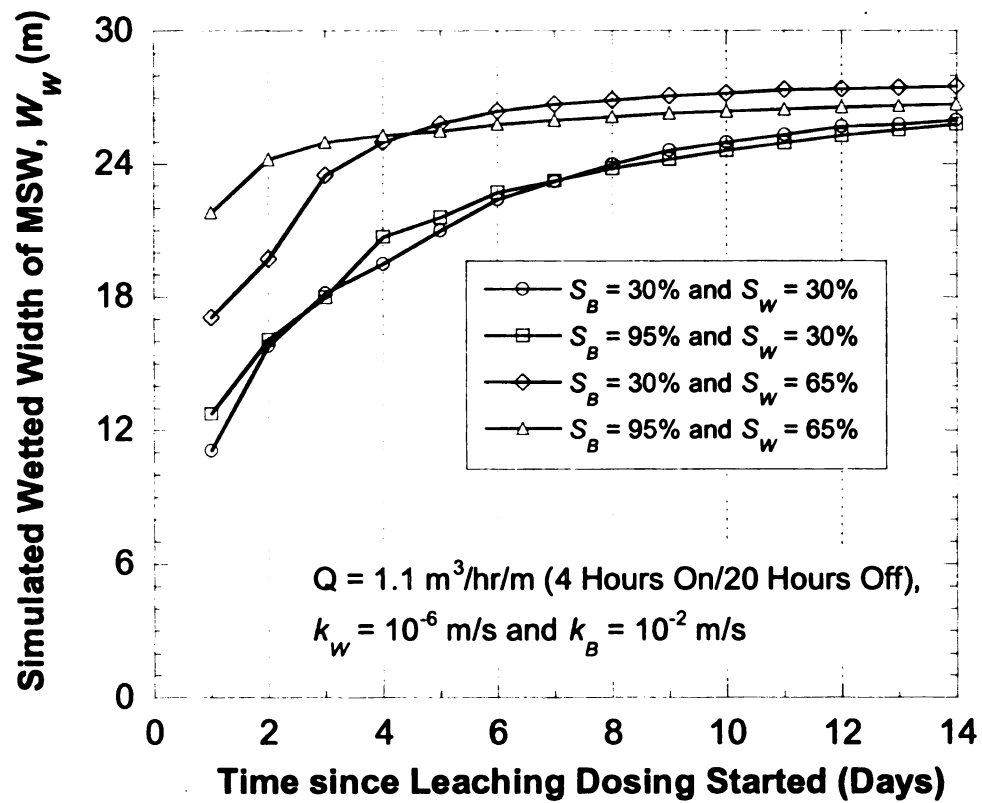


Figure 9. Simulated wetted width of waste as a function of the initial degrees of saturation of the waste and permeable blanket for a 150-m-wide PB.

Initial Degree of Saturation of Waste

The degree of saturation of waste plays a key role in operating an efficient bioreactor landfill. The effect of initial degree of saturation of waste was evaluated by simulating S_w values equal to 30%, 45%, and 65%. Porosity of the simulated waste assumed equal to 0.45, the simulated S_w values corresponded to volumetric water contents ranging from 0.15 to 0.3. Figure 10 presents the effect of S_w on the simulated W_B and h_p in a 60-m-wide PB for $k_w = 10^{-6}$ m/s and $Q = 1.1$ m³/hr/m over a period of 8 hours of continuous leachate injection. S_B was maintained at 50% for all simulations. Figure 10 shows that greater the S_w , faster the rate of travel of the injected leachate. When the simulated leachate injection was continued beyond 8 hours (not shown in Figure 10), W_B and W_w reached a maximum value that was about the same for various S_w values indicating that a steady-state was reached.

Initial Degree of Saturation of Permeable Blanket

The degree of saturation of the PB varies and depends upon the rate, duration and frequency of leachate dosing cycle, infiltration of precipitation, and the hydraulic properties of the surrounding waste and PB. Haydar and Khire (2005c) reported that S_B varies significantly over the operational life of the PB. Figure 11 presents the effect of S_B on the simulated W_B and h_p in a 60-m-wide PB for $k_w = 10^{-6}$ m/s and $Q = 1.1$ m³/hr/m during an injection period of 8 hours. The simulated values of S_B were equal to 30%, 65%, and 95%. Note that the initial degree of saturation of waste (S_w) was maintained constant at 45%. Figure 11 shows that the injected leachate traveled faster for a greater S_B . However, the difference in the rate of travel of injected leachate for the various

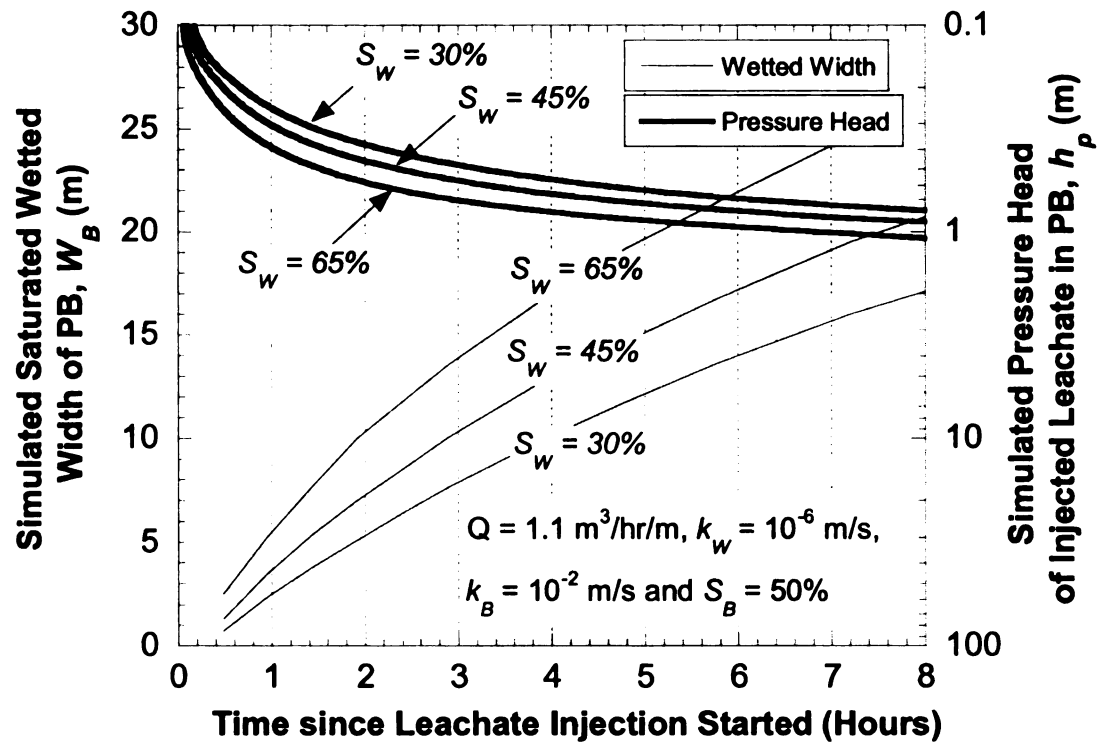


Figure 10. Simulated wetted width and pressure head of injected leachate as a function of the degree of saturation of waste (S_w) for a 60-m-wide PB.

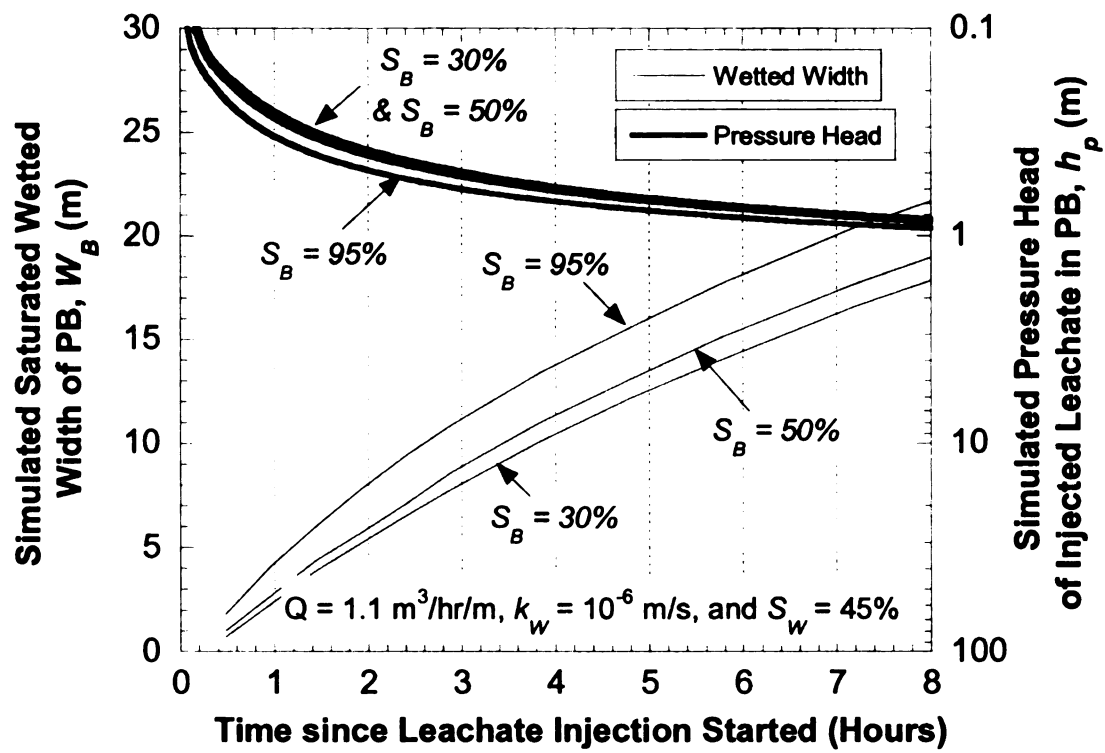


Figure 11. Simulated wetted width and pressure head of injected leachate versus leachate injection period as a function of the initial degree of saturation of blanket (S_B) for a 60-m-wide PB.

values S_B was relatively small. Similarly, the simulated h_p did not differ much for the various values of S_B .

FIELD-SCALE TESTING OF PERMEABLE BLANKET

Field Installation of PB

In order to validate the use of PBs, a horizontal instrumented PB was constructed at an MSW landfill located in Jackson, Michigan. The landfill is currently active and generates on average 45 m³ of leachate per day. The blanket installed is 60-m-long, 9-m-wide, and 0.15-m-deep. The PB is made up of crushed recycled glass having average particle diameter, $D_{50} = 10$ mm and hydraulic conductivity equal to 3×10^{-2} m/s. The blanket was constructed using the following sequenced procedure: (1) waste surface was leveled; (2) a non-woven GT fabric was laid on the waste surface; (3) about 0.15-m-deep layer of crushed glass was placed on the GT; (4) an additional GT fabric was placed above the glass; and (5) about 3-m-deep waste was placed on the upper GT fabric before leachate recirculation was turned on. Below the blanket, from top to bottom, there is: (1) about 50-mm-deep silty soil (loess) used as a daily soil cover; (2) about 20-m-deep MSW; and (3) leachate collection and lining systems.

A 9-m-long perforated high density polyethylene (HDPE) leachate injection pipe having an internal diameter (ID) equal to 75 mm was installed at the center of the blanket, parallel to the width of the PB. One end of the perforated pipe was capped and the other end was connected to a hydraulic pump followed by three interconnected leachate storage tanks having a total storage capacity equal to approximately 115 m³. A leachate flow control valve, a digital pressure gauge, and a magnetic flow gauge were

installed in the leachate pipe to control and monitor the pressure head and flow rate of injected leachate.

Automated Monitoring System

An automated sensing system was installed to monitor the hydraulic performance of the PB. The glass blanket was instrumented with the following sensors: impedance moisture content sensors; time domain reflectometry (TDR) moisture content sensors; vibrating wire pressure transducers (piezometers); and thermocouple and thermistor temperature sensors. These sensors were used to monitor the travel of injected leachate in the blanket. No sensors were installed in the underlying waste. A detailed discussion on the monitoring system is presented in Haydar and Khire (2005c).

All sensors including the leachate flow gauge and pressure gauge were connected to a data logger located at the site. The data logger was programmed to take readings at 1 to 5-minutes frequency to allow relatively precise monitoring of the injected leachate and h_p .

Field Data versus Simulated Results

During the period from September 2003 to April 2004, about 3,200 m³ of leachate was injected in the glass blanket corresponding to approximately 90 leachate recirculation events at leachate injection rates ranging from 1.1 to 3.6 m³/hour per meter length of the embedded injection pipe. The maximum leachate injection rate equal to 3.6 m³/hr/m corresponds to the maximum rate the pump at the site could deliver for the total head that exists for the system.

Because hydraulic conductivity and degree of saturation of the waste underlying the blanket are unknowns, in order to simulate the wetted width measured in the field, we simulated W_w for the 60-m-wide glass PB for k_w ranging from 10^{-7} m/s to 10^{-5} m/s and for $S_w = 45\%$ and 65% to cover the most commonly reported range of k_w . We simulated $Q = 1.1 \text{ m}^3/\text{hr}/\text{m}$ because a majority of leachate injection events corresponded to this rate at the site. The saturated and unsaturated hydraulic properties of the PB measured for crushed glass in the lab were input to HYDRUS-2D (Table 1). For all simulations, S_B was assumed equal to 50% based on the measured water content of the PB. Separate sets of simulations were conducted for $S_w = 45\%$ (Figure 12a) and 65% (Figure 12b). Figure 12 presents a strong correlation between the W_w measured by the sensing system in the field for leachate injection events conducted using $Q = 1.1 \text{ m}^3/\text{hr}/\text{m}$ in Sep. and Oct. 2003 and W_w simulated for the measured and assumed sets of input parameters. Due to leachate recirculation during Sep. 2003, the degree of saturation of the waste increased during Sep. to Oct. 2003 period. Hence, as per Figures 9 and 11(b), the injected leachate traveled at a faster rate during the Oct.

h_p values measured in the field in the close proximity of the leachate injection pipe [Figure 1(b)] were simulated for the blanket for three leachate injection events corresponding to $Q = 1.1 \text{ m}^3/\text{hr}/\text{m}$ (Figure 13). The rate of increase of h_p during a leachate injection event is primarily a function of S_B , S_w , k_B , and k_w . Soil water characteristic curves (SWCCs) for the underlying waste and PB and hysteresis in the SWCCs play a relatively minor role for accurately simulating h_p during a leachate injection event.

In the field, we believe that S_w most likely increased during the period from 24 Sept. 2003 to 27 Feb. 2004 due to continuing leachate recirculation. Similar to observed in the

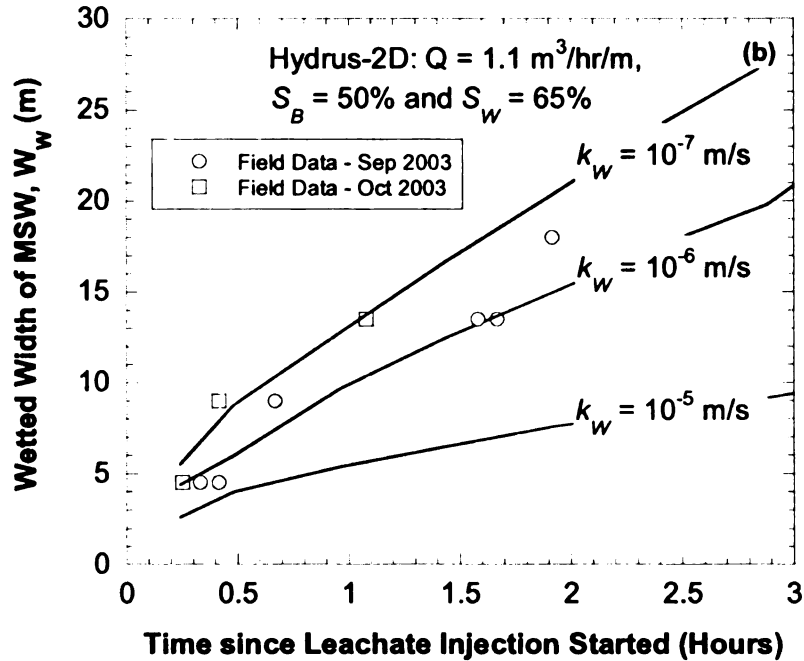
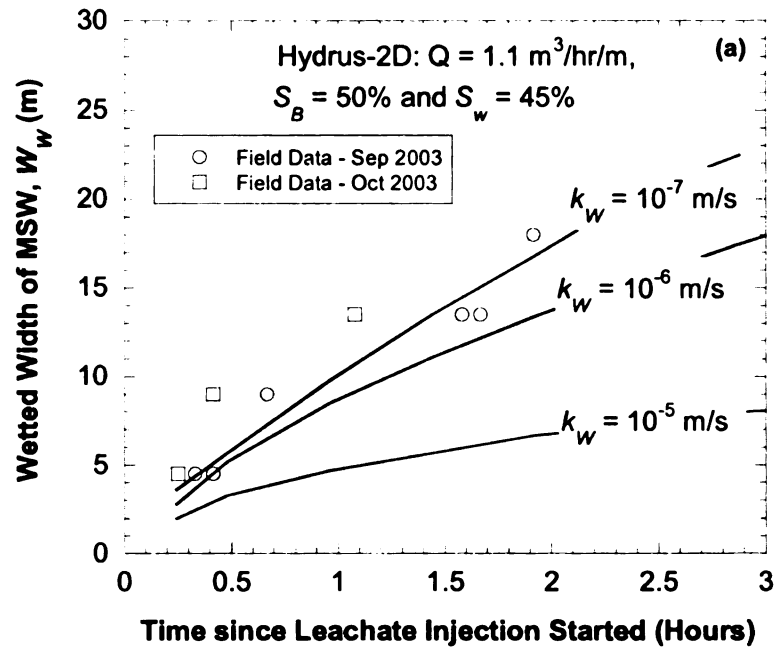


Figure 12. Correlation between the wetted width of waste measured in the field and the simulated wetted width of waste for a 60-m-wide PB for k_w ranging from 10^{-7} m/s to 10^{-5} m/s , $S_B = 30\%$, $Q = 1.1 \text{ m}^3/\text{hr/m}$, $S_w = 45\%$ (a); and $S_w = 65\%$ (b).

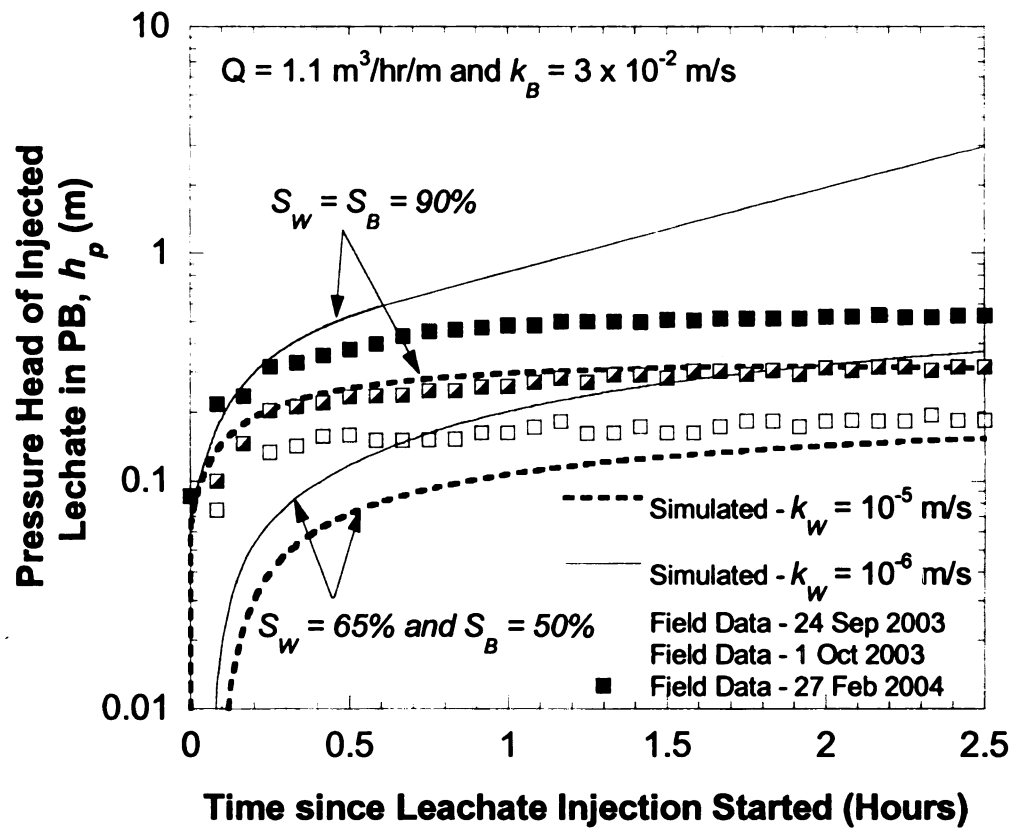


Figure 13. Measured and simulated pressure head of injected leachate in the glass permeable blanket for three leachate injection events corresponding to $Q = 1.1 \text{ m}^3/\text{hr}/\text{m}$.

field, simulated data (Figure 13) indicated that as S_w increased, h_p also increased. The magnitude of simulated maximum h_p was less for a greater k_w . The maximum h_p in the field measured by the pressure transducer remained below 1.5 m, which is in the same range of h_p simulated by assuming k_w equal to 10^{-6} and 10^{-5} m/s presented in Figure 3.

Because k_w , S_w , and SWCCs of the underlying waste are unknowns, the field data collected in this study cannot be simulated any more accurately. However, Figures 11 and 12 indicate that the data measured in the field is in the ballpark of simulated results for the assumed input. Hence, we believe that the modeling approach presented in this study is appropriate to design PBs.

SUMMARY AND PRACTICAL IMPLICATIONS

This paper presents a numerical evaluation of key design parameters that are used for the design of leachate recirculation system consisting of PBs. The saturated-unsaturated flow model HYDRUS-2D was used to simulate the effect of these parameters on the hydraulic performance of PBs: (1) hydraulic properties of waste and PB; (2) geometry of PB; (3) settlement of PB; (4) leachate dosing frequency; and (5) degrees of saturation of waste and PB. In addition to the numerical modeling, data from an instrumented field-scale PB made up of crushed glass was used to evaluate the application of PB for leachate recirculation. The key findings of this study are as follows.

- In order to maintain the liquid pressure build up in the blanket as little as possible and to achieve the greatest wetted width, it is important to select a material having the highest possible hydraulic conductivity to construct a PB. Thus, gravel is preferable to sand.

- Increase in the PB depth decreases h_p . Hence, a thicker PB is preferable if slope stability evaluation of the landfill requires lower pressure heads in the blanket. A thicker blanket, however, does not result in a greater wetted width of waste and hence does not offer greater wetting of the underlying waste.
- Greater the hydraulic conductivity of the underlying waste, lower the wetted width and lower the h_p .
- The coarser the SWCC of the waste, the greater W_w and h_p .
- The greater the degrees of saturation of the waste and/or the PB, the faster the rate of travel of injected leachate in the PB and greater the h_p . When leachate is injected in on/off dosing cycles, S_w and S_b increase until a steady-state approaches. W_w and h_p are directly proportional to the on to off duration ratio and the magnitude of the liquid flux during the on period. Hence, on to off duration ratio needs to be selected based on site-specific factors to balance the benefit of a greater wetting volume for a greater on to off duration ratio to a lower factor of safety against slope stability due to an increased h_p .
- If the blanket settles, a greater leachate injection rate (or head) is needed to compensate for the loss in elevation head to maintain the same W_w .

Even though not specifically evaluated in this study, we recommend designers to consider the following key design-related issues: (1) maintain sufficient distance (> 15 m) between the edges of the blanket and the side slopes of the landfill to minimize the potential for leachate breakouts (Haydar and Khire 2005b); (2) inject leachate in quantities or rates that will not jeopardize the slope stability of the landfill due to an increase in the liquid pressure head; (3) instrument the blanket and monitor the long-term

performance of the blanket for potential clogging, settlement, or physical integrity jeopardizing the hydraulic performance of the blanket; and (4) more closely monitor the liquid pressure head at critical locations in the LCS to make sure that the LCS is appropriately draining the injected liquids.

ACKNOWLEDGEMENTS

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PAPER NO. 5: GEOTECHNICAL SENSING SYSTEM TO MONITOR INJECTED LIQUIDS IN LANDFILLS

ABSTRACT

A field-scale horizontal permeable blanket made up of crushed recycled glass was built in an active municipal solid waste (MSW) landfill to recirculate leachate. The permeable blanket is a new method developed by the authors for subsurface leachate recirculation or liquid injection. Leachate injection rates in the blanket ranged from 1.1 m³/m/hr to 3.6 m³/hr/m. An automated sensing system consisting of moisture content sensors, pressure transducers, and temperature sensors was designed to monitor the migration of injected leachate inside the blanket. The sensors were embedded in the blanket and connected to a data logging system. All sensors were able to detect the leachate migration within the blanket. The TDR and impedance moisture content sensors could not detect the migration of injected leachate once the surrounding medium got saturated. The pressure transducers and temperature sensors were able to detect leachate migration irrespective of the degree of saturation of the blanket. Unlike thermistor sensors, temperature readings measured by thermocouple sensors were influenced by air temperature.

INTRODUCTION

Leachate recirculation has become a relatively common leachate management option for MSW landfills because it offers the following benefits (Reinhart and Al-Yousfi 1996; Miller and Emge 1997; Mehta et al. 2002; Haydar and Khire 2005): (1) a reduction in leachate treatment and disposal costs; (2) accelerated decomposition and settlement of

waste resulting in a gain in airspace; (3) an increase in the rate of landfill gas production; and (4) a potential reduction in the post-closure care period and maintenance costs. Risks and drawbacks of leachate recirculation include: (1) a potential decrease in the factor of safety for slope stability of landfills; (2) a potential increase in the leachate head on the liner if the leachate collection system is not designed to drain recirculated leachate; (3) potential long-term clogging of the leachate recirculation and leachate collection systems; (4) potential flooding of the gas collection system; and (5) leachate seeps from the sides of the landfill if an appropriate buffer between the leachate injection point and the sides of the landfill is not maintained. Hence, before implementation, landfill operators should weigh the advantages and risks associated with leachate recirculation on a site-specific basis.

Subsurface leachate recirculation in MSW landfills is commonly practiced using conventional methods such as horizontal trenches and vertical injection wells. Khire and Haydar (2003) have proposed the use of permeable blankets as an alternative for subsurface leachate recirculation systems. Khire and Haydar (2003) have presented a numerical study that compares hydraulic aspects of permeable blankets and horizontal trenches and A field-scale permeable blanket was constructed and instrumented at a landfill located in Michigan to test the concept of leachate recirculation using permeable blankets. Such testing was done using embedded sensors providing data on flow and fate of injected leachate in the blanket. The key objective of the field-scale study presented was to evaluate the feasibility of using an automated geotechnical sensing system to monitor the migration of recirculated leachate in permeable blankets.

Leachate Recirculation Using Permeable Blankets

This design concept consists of a relatively thin and high hydraulic conductivity layer of permeable material sandwiched between non-woven geotextile sheets laid on a relatively flat waste surface in a landfill. A schematic of a permeable blanket is presented in Figure 1. Thickness of such a blanket can vary depending upon the material used and site-specific design and operational variables. A perforated pipe is embedded at the center of such blanket in the direction parallel to the shorter or longer plan view dimension where leachate is injected under a positive pressure. Installation of an injection pipe along the short plan view direction would typically yield in financial savings in the pipe related costs. The areal dimensions and shape of the blanket can vary depending on the leachate recirculation needs, shape of the landfill cell, relative contrast in the hydraulic conductivities of the blanket and the underlying waste, and leachate injection rate and pressure. Khire and Haydar (2003) have presented specific details on the design variables for permeable blankets used for leachate recirculation.

When leachate recirculation is practiced at MSW landfills, it is important to monitor migration of injected leachate due to the concerns associated with slope instabilities of the landfill as a result of potential liquid head build up resulting in reduction of waste shear strength (Qian et al. 2003). In addition, U.S. federal regulations require that liquid head on the landfill lining system does not exceed 30 cm.

Common Sensors Used in Landfills

The sensors most commonly used in landfills can be grouped depending upon the application as follows.

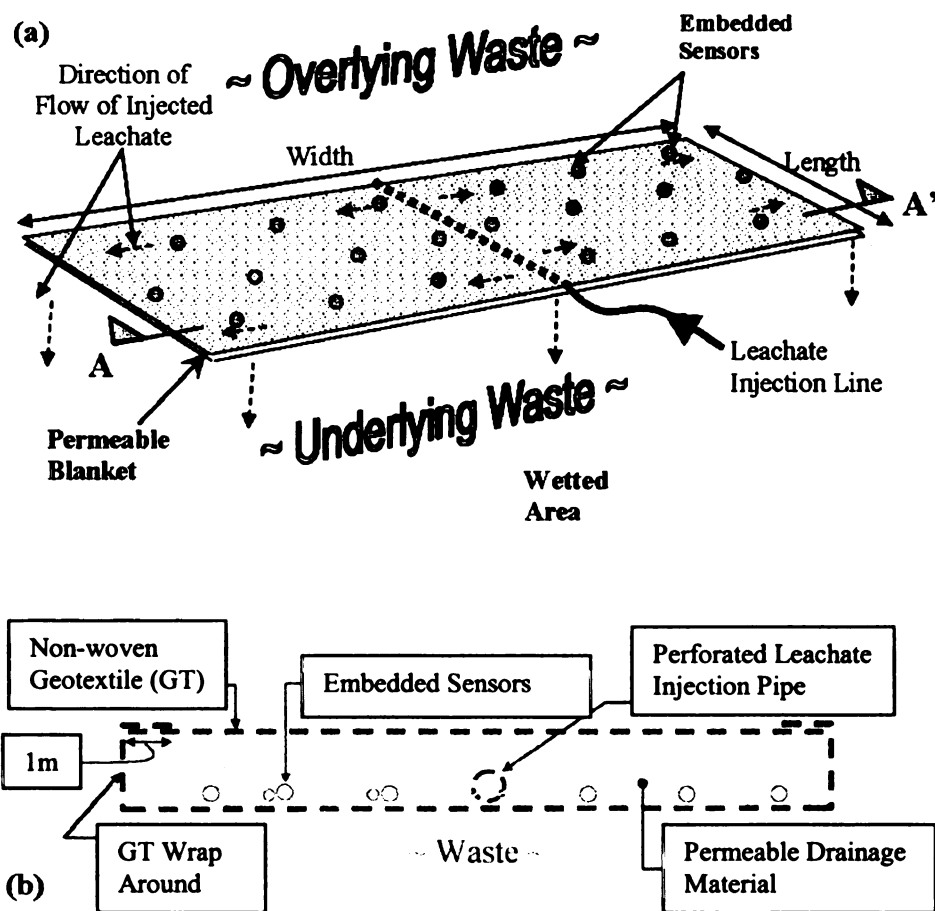


Figure 1. Schematic of a permeable blanket (a) perspective view; and (b) cross section AA'.

Moisture Content Sensors

Moisture content sensors commonly used in geotechnical applications include:

- Time domain reflectometry (TDR): commonly used for agriculture and environmental applications. Li and Zeiss (2000), among others, have investigated the use of TDR to measure the volumetric water content of waste;
- Time domain transmissometry (TDT): similar to TDR in operation and application;
- Neutron probe: commonly used to estimate the moisture content of its surrounding medium (Yuen et al. 2000) in shallow inorganic soils; and
- Electrical resistance or impedance sensors: these sensors are either gypsum block sensors (McCann et al. 1992) which use resistance to direct current (DC) or customized electrical impedance sensors (Gawande et al. 2003) which use resistance to an alternating current (AC) to measure the moisture content of surrounding medium. The gypsum block sensors do not function well in acidic or corrosive environments of landfills (Zhao et al. 2003). However, the impedance sensors designed by Gawande et al. (Gawande et al. 2003) are not susceptible to corrosion and hence perform better in landfills. Impedance moisture content sensors are cheaper compared to TDR or TDT sensors.

Temperature Sensors

Temperature sensors commonly used in geotechnical applications can be divided broadly into thermocouple or thermistor sensors. Within the relatively narrow temperature range expected in landfills, thermistors are reported to be relatively stable and more accurate

compared to thermocouples (Reinhart et al. 2003). However, thermistor sensors are more expensive.

Pressure Sensors

Monitoring wells and stand-pipe piezometers are conventional field devices used to monitor leachate pressure head or leachate level in landfills. There are many landfills where pressure transducers are used to monitor leachate pressure. Reinhart et al. (2003) have reported that pressure transducers can fail if appropriate precautions are not taken to protect these sensors from lightening strikes and crushing or damage due to pressure of waste compactor and overlying waste.

AUTOMATED SENSING SYSTEM

The required key characteristics of embedded sensors used for monitoring the migration of injected leachate in permeable blankets in landfills are: (1) the sensors are economical and are durable in physically and chemically challenging environment of a landfill; and (2) the sensor and the sensor system can be automated to make reliable measurements at a frequency as high as once every few seconds. The automated sensing system used in this field-scale study considered all of the requirements presented above. The automated sensing system consisted of the following sensors: (1) TDR sensors; (2) electrical impedance moisture content sensors; (3) vibrating wire pressure transducers; and (4) thermocouple and thermistor temperature sensors.

TDR Sensors

TDR sensors were chosen for this study because of their relatively well known history in detecting moisture content of soils in the field. The TDR sensor functions by emitting a voltage signal. This signal is partially reflected when encountering a change in the dielectric properties. From the travel time of the reflected signal and the length of the TDR sensor, the bulk dielectric constant of the medium surrounding the TDR can be determined. The bulk dielectric constant for permeable materials is the combined dielectric constant of water, air, and solids. Because the dielectric constant of water (~ 80) is much higher than that of air (~ 0) and soil solids (~ 2 to 4), the TDR sensor can detect moisture content changes in surrounding medium. The TDR output readings can be calibrated to obtain the volumetric water content of the surrounding medium. Robinson et al. (1994), among others, have presented a detailed review on the progress made in TDR sensor technology. Common factors that affect the TDR sensor measurements in the field are summarized below:

- organic content (McBean et al. 1994; Robinson et al. 1994);
- presence of ferrous metal (Robinson et al. 1994; Dalton 1992);
- saline soils or materials having higher electrical conductivity, which results in an overestimation of moisture content (Herkelrath et al. 1991);
- porosity. For a greater porosity, the TDR sensor readings increase due to greater space for water to fill in;
- cable length. An increase in cable length decreases the magnitude of the reflected signal and thus reduces the accuracy of the measurement (Robinson et al. 2003); and

- variation in the ambient temperature of the cable. This might produce errors in measurement especially when the cable is relatively long (≥ 35 m).

There are many commercial TDR sensors available for field use (Roth et al. 1992). The TDR sensor selected for this study consisted of a single rod (Figure 2) sealed in a plastic casing. The reflected signal of the TDR sensor is translated into a current signal to differentiate the small changes in the bulk dielectric constant. The output measurement ranges from 0 to 1,000 mA for de-ionized (DI) water and increases as the electrical conductivity (EC) of the surrounding liquid increases. The TDR sensor used in this study is about 69-cm-long and has a diameter of 2 cm (Figure 2).

The use of electrical impedance concept to measure the moisture content of soils has been in practice (e.g., gypsum block sensors) for many decades (McCann et al. 1992). A photo of the electrical impedance moisture content sensor used in this study is presented in Figure 2. This sensor, which was presented by Gawande et al. (2003), measures the electrical impedance between two electrodes embedded in an uniformly graded sand (average particle diameter, $D_{50} = 1$ mm) pack that is about 50 mm in diameter.

Electrical Impedance Moisture Content Sensors

The electrical impedance moisture content sensors have been commonly referred to in the literature as electrical resistance moisture content sensors. However, because an alternating current is used, these sensors measure impedance and not resistance.

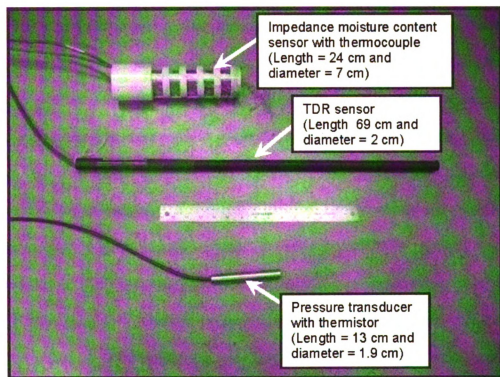


Figure 2. Geotechnical sensors used in this study.

The selection of the impedance moisture content sensors to detect the leachate migration in the permeable blanket was based on the following reasons: (1) the sensors are durable in physically and chemically challenging environment of a landfill (Gawande et al. 2003; Zhao et al. 2003); (2) good correlation exists between moisture content and electrical impedance; and (3) the sensors are relatively cheap and unlike TDR sensors, there is no limitation associated with the maximum cable length.

The electrical impedance measured between the electrodes is a function of the moisture content of the sand pack and the surrounding medium. Liquids are absorbed into the sand by capillary action enhanced by glass fiber wicks attached to the sensor body. The impedance of the sensor is inversely proportional to the moisture content of the sand pack. Liquid or leachate is absorbed into the sand from the surrounding material (waste) or released depending on the matric potential difference between the sand pack and the medium surrounding the sensor. The impedance moisture content sensor can capture the changes in moisture content instantaneously. Gawande et al. (2003) reported that an impedance value of $0.05\text{ k}\Omega$ or less represents that the sand pack is saturated. In order to convert the impedance into moisture content of the surrounding medium, calibration curves are required. A thermocouple of type T was added to the impedance moisture content sensor to allow measurement of temperature.

Vibrating Wire Pressure Transducers

Vibrating wire pressure transducers measure the pressure head and serve as a substitute for stand-pipe piezometers or monitoring wells. Unlike standpipe piezometers which can clog up or interfere with daily landfill operations, the pressure transducers do not. If gas pressure exists, these sensors measure combined gas and liquid pressure. When

barometric pressure is measured, vented pressure transducers can detect a change in the pressure head irrespective of the moisture content. Pressure transducers cannot detect moisture content. The pressure transducers made up of stainless steel are corrosion resistant and advances in sealing technology have extended the life of these sensors in challenging subsurface environments. The measurements from vibrating wire pressure transducers have relatively low thermal sensitivity, are independent of the cable length, and are relatively consistent and accurate (Duncliffe 1988). A thermistor is embedded within the pressure transducer to record temperature and to correct the pressure transducer measurement.

The pressure transducers use a pressure sensitive diaphragm attached to a vibrating wire element. The diaphragm is welded to a capsule, which is evacuated and hermetically sealed. When liquid pressure is exerted, the diaphragm is deflected and changes occur in the tension and frequency of the vibrating wire. The changed frequency is sensed and transmitted by electrical coil acting through the walls of the capsule to the readout device. The pressure transducers selected for this study are not vented. Hence they required correction for barometric pressure changes. This correction is significant especially when the pressure to be measured is relatively low.

Temperature Sensors

Because bacteria responsible for degradation of the waste and gas generation from a landfill are most efficient over a narrow temperature range, monitoring temperature within a landfill can be useful in understanding or manipulating the operation of a landfill to achieve an optimum performance. The role of temperature becomes even more important when operating bioreactor landfills (Tchbanoglous et al. 1993). The

temperature sensors selected in this study consisted of thermocouples and thermistors which were built into the impedance moisture content sensors and the pressure transducers, respectively. Because the temperature of the injected leachate is invariably different compared to the background temperature of the blanket, these sensors could be used to monitor the migration of the injected leachate within the blankets.

A thermocouple sensor consists of a junction of dissimilar metal wires. These wires are of equal length and are soldered together. When both ends of the wires are at the same temperature, there is no voltage generated. However, when the open ends are at a fixed temperature and the temperature of the junction changes, a voltage is generated across the two wires. The temperature difference between the two ends of the wires is correlated with the voltage difference. Hence, thermocouples require measuring the reference temperature. The reference temperature is usually measured by a thermistor located inside the datalogger box. The thermocouples used in this study were of type T which is made of a positive copper wire and a negative constantan wire with a temperature range of -200 °C to 350 °C.

Thermistors are made of semi-conductor materials. The electrical resistance of these materials changes with temperature. The resistance of the thermistor decreases as the temperature increases. Unlike thermocouple sensors, thermistors measure the absolute temperature so they do not require a reference temperature to make the measurements.

FIELD INSTRUMENTATION

A field-scale horizontal permeable blanket made up of crushed recycled glass was constructed at a municipal solid waste landfill located in Michigan to manage leachate by leachate recirculation. This blanket is about 60-m-wide by 9.5-m-long. The average

thickness of the blanket is 150 mm. Installation of the blanket consisted of these steps in the presented order: (1) laid a non-woven geotextile on a leveled waste surface of the landfill cell; (2) placed crushed glass on the geotextile using a front end loader; (3) installed sensors used for monitoring the migration of injected leachate; and (4) covered the glass blanket by a non-woven geotextile followed by placement of waste on the blanket. The upper and lower geotextiles have a thickness of about 2 mm (ASTM D 5199), mass per unit of 270 g/m^2 , and a hydraulic conductivity of 0.3 cm/s (ASTM D 4491).

Hydraulic conductivities of the crushed glass were measured using a constant-head test (ASTM D 2434-68) in loose and dense conditions (Table 1). Coefficients of uniformity and curvature (C_u and C_c), and the average particle size (D_{50}) for the crushed are equal to 1.4, 2.2 and 10 mm, respectively.

A 75-mm-diameter and 9.5-m-long perforated high-density polyethylene (HDPE) leachate injection pipe was installed at the center of the blanket to inject leachate. The end of the perforated pipe inside the blanket was capped and the other end was connected to a pump to draw leachate from a series of interconnected above ground leachate storage tanks having a total storage capacity of about 115 m^3 . A leachate flow control valve, a digital pressure gauge, and a magnetic flow gauge were installed in the leachate pipe to control and monitor the pressure head and flow rate of injected leachate.

Monitoring System

The glass blanket was instrumented with embedded sensors consisting of TDR sensors, impedance moisture content sensors with thermocouples, and vibrating wire vented pressure transducers with thermistors. Barometric pressure sensor was also installed at

Table 1. Hydraulic conductivity of loose and dense crushed glass.

Property → State of Glass ↓	Dry Density ρ_d (g/cm³)	Porosity n	Hydraulic Conductivity K (cm/s)
Loose	1.26	0.48	3.1
Dense	1.39	0.42	2.9

Note: Specific gravity of the glass $G_s = 2.41$

the site to separate the barometric pressure component from the total pressure measurement. Figure 2 shows a photo of these sensors and presents their dimensions. Based on the topographic survey data and the dry weight of the crushed glass used for the blanket, we estimated the field porosity of the glass blanket to be about 0.45. The sensors were installed at the bottom of the blanket just above the lower geotextile as presented in Figure 1(b). A vertical pressure sensor was installed just outside the boundary of the blanket to monitor the vertical stress of waste overlying the glass blanket. Meteorological sensors including a rain gauge, an air temperature sensor, and a barometric pressure sensor were installed at the site. All sensors including the leachate flow and pressure gauge were connected to a data logger located at the site to continuously monitor and log the data. The data logger was programmed to take readings at frequencies ranging from 1 minute to 1 hour.

Instrumentation of the blanket and sensing system took place in July 2003 followed by filling of about 3-m-thick waste above the blanket in Sep. 2003. The thickness of waste placed above the blanket before leachate recirculation trials began was greater than the maximum leachate injection pressure head to prevent potential artesian conditions. Over 80 leachate recirculation trials have been conducted since Sep. 2003 at leachate injection rates ranging from 1.1 to 3.6 m³ per hour per meter length of the injection pipe (m³/hr/m). Over 3,000 m³ of leachate has been recirculated in the landfill through the glass blanket since Sep.2003.

Laboratory Testing and Calibration

Before installation in the field, the instrumented sensors were tested in the lab to evaluate the accuracy of their measurements and to develop calibration curves specific to the landfill leachate.

In order to check the accuracy of the pressure transducer, the sensor was embedded in a container containing crushed glass and tested using solutions of DI water and potassium chloride (KCl) at liquid levels ranging from 0 to 70 cm. We observed a linear relationship between the depth of water in the container and the pressure head readings measured by the pressure transducer and it was independent of the EC of the liquid. The accuracy of the pressure transducer was within ± 2 cm over the entire measurement range of the transducer.

The TDR and impedance moisture content sensors were fully submerged in a solution of KCl and DI water having EC ranging from 0 (pure DI water) to 20 mS/cm. Figure 3 shows the response of the TDR and impedance moisture content sensors as a function of the EC of the liquid medium. This response was obtained by fully submerging the sensor in liquids having EC presented on the x-axis in Figure 3. The hatched area in Figure 3 shows a range of 5 mS/cm to 10 mS/cm for the EC of the leachate from the landfill. For this range of EC, the impedance moisture content sensor readings (R) at saturation ranged from 0.025 k Ω to 0.045 k Ω whereas the TDR sensor readings ranged from 1,320 to 1,380 μ A. The impedance moisture content sensor readings were about the same when submerged in KCl solution with or without crushed glass for a given EC. However, as presented in Figure 3, the TDR sensor readings dropped slightly (e.g., drop from 1320 to 1230 μ A for EC = 5 mS/cm) when submerged in the KCl solution with

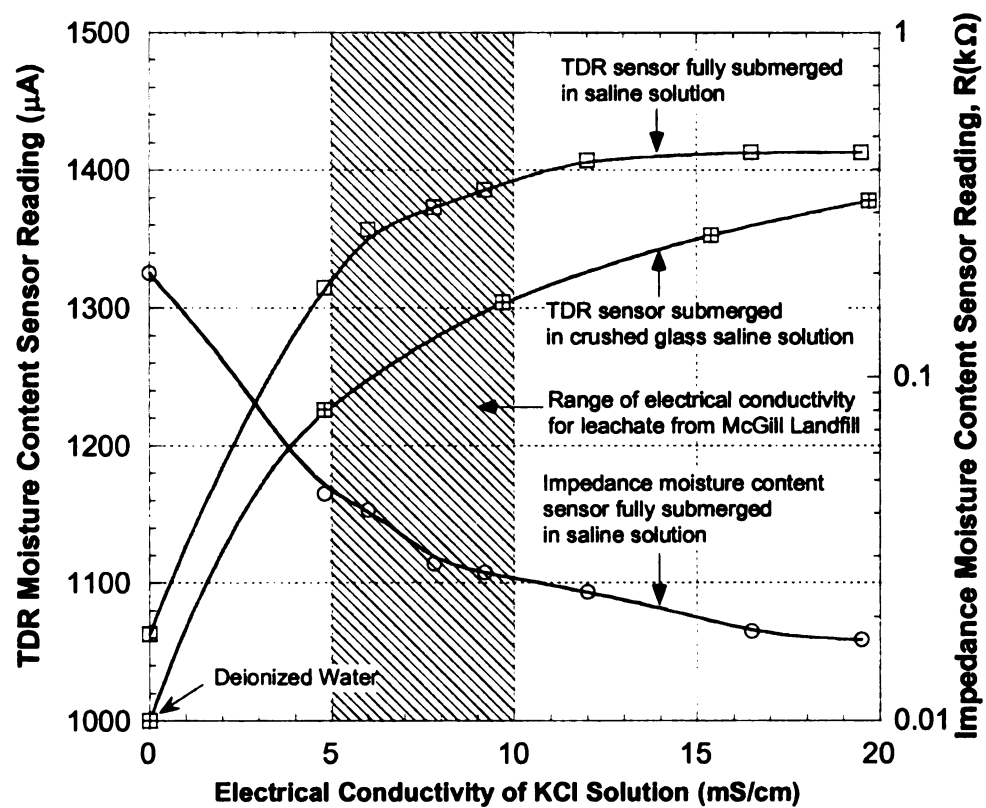


Figure 3. Lab evaluation of electrical conductivity of liquid on the measurements by TDR and impedance moisture content sensors.

crushed glass having a porosity of about 0.45. The drop in the TDR reading is because the glass particles reduced the bulk dielectric constant of the medium.

The rate of drainage of the impedance moisture content sensors is a function of the rate of drainage of the sand pack in these sensors. The rate of drainage of the sand pack is a function of the hydraulic properties of the sand as well as the material surrounding (crushed glass) and underlying (waste) the sensor (Figure 1b). Because the hydraulic conductivity of the sand pack is almost three orders of magnitude less than the surrounding crushed glass blanket, after a wetting event, the sensors drained slower than the surrounding glass did. The rate of wetting and drying (draining) of the sensor is also a function of hysteresis in the soil-water characteristic properties of the sand pack.

The TDR moisture content sensor is located in a sealed plastic casing. The rate of drainage of the TDR sensor is directly proportional to the bulk dielectric constant or the moisture content of its surrounding medium located within a 2-cm-radius.

RESULTS

Detection of Leachate Migration in Permeable Blankets

Response of TDR and Impedance Moisture Content Sensors

Figure 4 shows the response of five impedance moisture content sensors located at 4.5 to 22.5 m distance from the leachate injection pipe and two TDR sensors located at 9 and 18 m distance. This response corresponds to a leachate injection event at leachate injection rate equal to $1.1 \text{ m}^3/\text{hr}/\text{m}$. The positive values on the x-axis (0 to 300 minutes) represent the time since the leachate injection began. The negative values on the x-axis (-100

minutes to 0) represent the time before the leachate injection was started. The two arrows on the x-axis correspond to when the leachate injection was started and turned off.

During this event, about 45 m³ of leachate was injected in the glass blanket in 270 minutes. The TDR moisture content sensor readings immediately before the leachate injection were about 300 μ A and the impedance moisture content sensor readings ranged from 0.03 k Ω to 0.13 k Ω . This wide range of initial readings of the impedance moisture content sensors reflects the spatial variation in the initial water content of the blanket. The reason for this variation in the initial water content of the blanket can be attributed to many reasons including: (1) low elevation pockets in the glass blanket; and (2) spatial variation in the hydraulic properties and water content of the underlying waste. Based on the lab measurements, the TDR sensor reading of 300 μ A and impedance moisture content sensor reading of 0.13 k Ω indicated partial saturation whereas the impedance moisture content sensor reading of 0.02 k Ω indicated saturation. Even though these sensors are located relatively close to each other, the impedance sensor indicated much higher saturation and in some cases it saturated faster (Figure 4) because the impedance sensor is measuring the saturation of the sand pack inside the sensor which has a greater capillary suction. Because the hydraulic conductivity of the sand pack ($\sim 10^{-3}$ cm/s) is three orders of magnitude less than that of the surrounding crushed glass (~ 1 cm/s), the sand pack does not drain as fast as the surrounding crushed glass.

After the leachate injection began, all impedance moisture content sensors except the one located at 22.5 m distance indicated a decrease in the impedance to about 0.03 k Ω . Such a decrease in the impedance occurred progressively with time with the sensor at 4.5 m showing the decrease within 20 minutes after the injection began and the sensor at

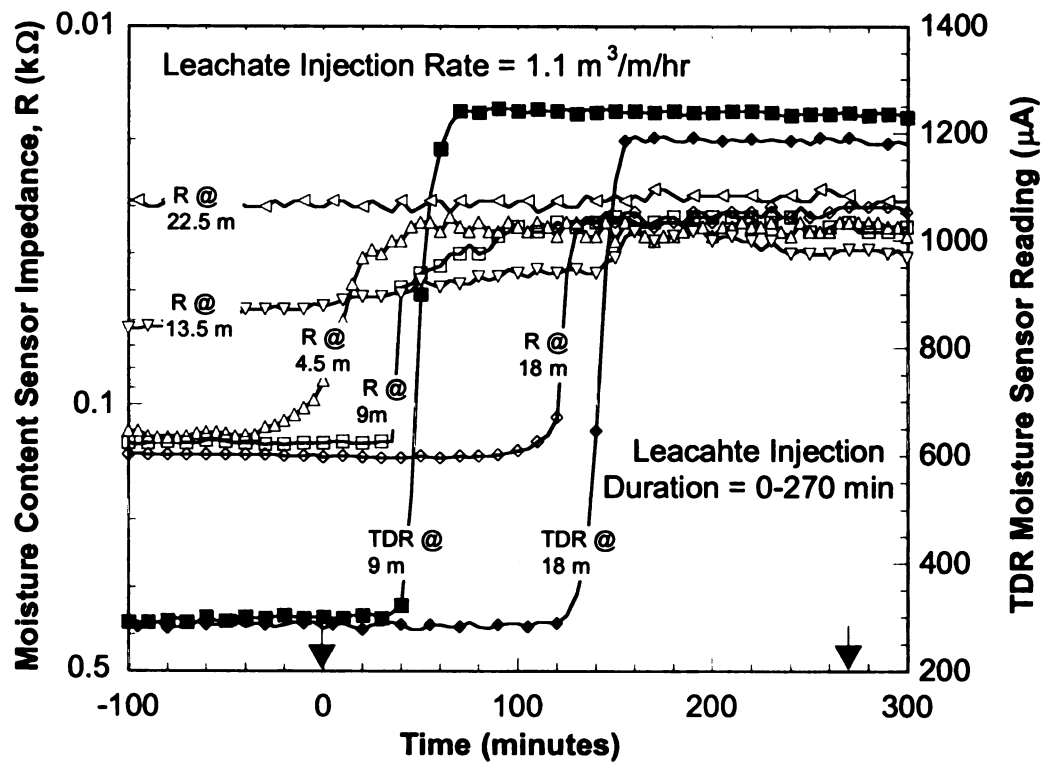


Figure. 4. Field response of TDR and impedance moisture content sensors to a leachate injection event.

18 m showing the decrease at about 150 minutes. This response is due to the arrival of the leachate front of the injected leachate. The impedance sensor located at 22.5 m distance was saturated before the leachate injection began. Hence, this sensor did not show any reduction in its impedance in response to the arrival of the injected leachate. The TDR sensors located at 9 and 18 m distance showed increase in the readings from 300 to about 1,200 μA within 10 minutes after the impedance sensors at proximity locations responded to the arrival of injected leachate.

Response of Pressure Transducers and Thermistor

Figure 5 shows the response of the thermistor and pressure transducer sensors embedded in the glass blanket at 0.5, 4.5, and 14 m distances from the leachate injection pipe. After the leachate injection began, all pressure transducers indicated a gradual increase in the pressure head (h_p) in response to the leachate injection event. The increase in the pressure head was earliest and greatest for the sensor located closest (at 0.5 m) to the leachate injection pipe. After the leachate injection stopped at about 90 minutes, all pressure transducers indicated an immediate but gradual decrease in the leachate pressure head.

For a specific leachate injection event, we believe that the increase in pressure heads recorded by the pressure transducer sensors was due to liquid pressure increase. This increase was not gas pressure buildup in the landfill because: (1) the response of all three pressure transducers was synchronized with respect to the leachate injection event; and (2) the response of thermistors in the pressure transducer sensors and of neighboring moisture content sensors was also concomitant to the leachate injection event.

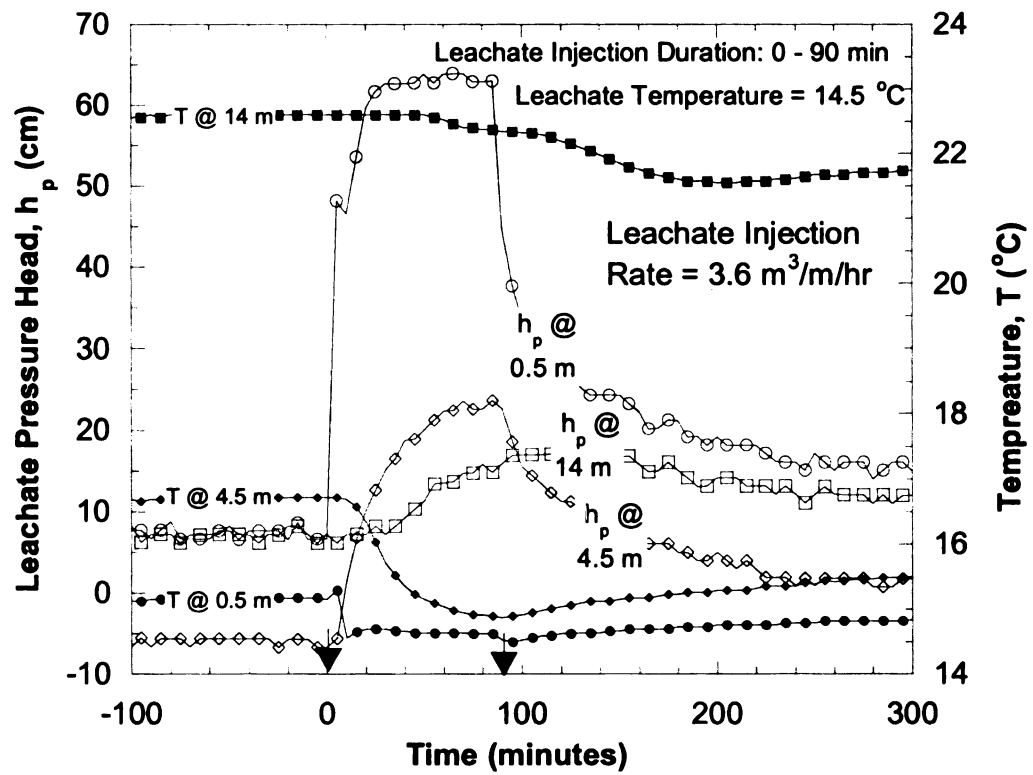


Figure 5. Field response of pressure transducers and thermistors to a leachate injection event.

The temperature of the injected leachate was about 14.5 °C for the event presented in Figure 5. In response to the leachate injection event, all three thermistor sensors built-in with the three pressure transducers indicated a slight decrease in the temperature (T). This decrease in the temperature correlates well with the increase in the pressure heads measured by the sensors. Figure 5 indicates that thermistors are capable of measuring change in temperature induced by the migration of the injected leachate.

Data presented in Figures 5 and 6 confirmed that injected leachate migrated horizontally in the permeable blanket due to relatively high hydraulic conductivity of the crushed glass in the permeable blanket. This field data verifies the key finding of the numerical evaluation of permeable blankets presented by Khire and Haydar (2003) and Haydar and Khire (2005b).

Limitations of Sensor System to Detect Leachate Migration

Figure 6 shows the response of two impedance moisture content sensors and the three pressure transducers for a leachate injection event at leachate injection rate equal to 1.1 m³/hr/m that occurred on 17 Dec. 2003. The impedance moisture content sensor readings of about 0.03 k Ω prior to the leachate injection event indicated saturation of the surrounding medium. Hence, the impedance moisture content sensors did not show an explicit response to the subsequent leachate injection event. Similarly, the TDR sensors did not show an explicit response to the leachate injection event (not shown in Figure 6). However, as presented in Figure 6, all three pressure transducers successfully detected leachate migration during the leachate injection event by measuring a sharp increase in the leachate pressure head followed by a gradual drop once leachate injection was

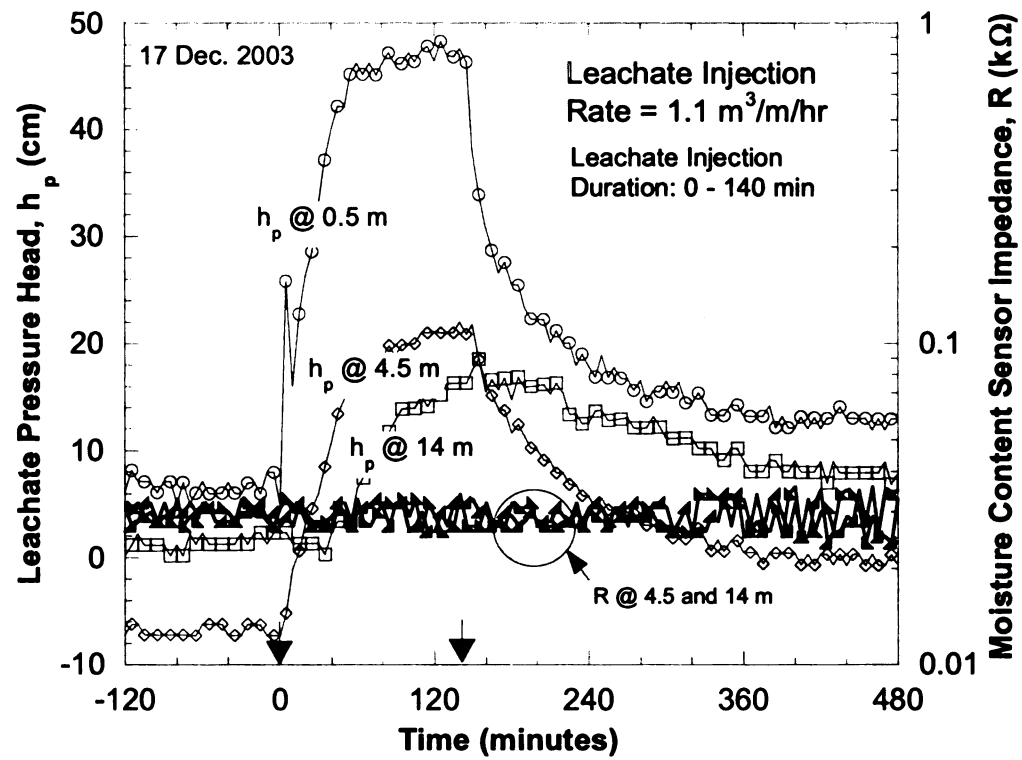


Figure 6. Field response of pressure transducers and impedance moisture content sensors to a leachate injection event.

stopped. Thus, the pressure transducers were capable of measuring increases in the leachate pressure head regardless of the initial state of saturation of the glass blanket.

This event illustrates that moisture content sensors can detect the arrival or migration of leachate only if the surrounding medium is not saturated. Once the medium gets saturated, the sensor system design needs to have redundancy built in by having pressure transducers and/or temperature sensors to detect the migration of injected leachate.

The response of temperature sensors to the migration of injected leachate depends on the temperature difference between the injected leachate and the temperature of the blanket prior to leachate injection, rate of injection and quantity of injected leachate, distance between the injection point and the sensor location, and thermal properties of the permeable blanket. Most often, a temperature sensor will detect the injected leachate as long as there is sufficient difference between the temperature of the leachate and the blanket.

Drainage of Permeable Blanket

The key function of permeable blankets is to drain or infiltrate injected leachate into the underlying waste and hence wet the waste. The rate of drainage of the injected leachate through the blanket is a function of the hydraulic properties of the blanket as well as the underlying waste and the volume and frequency of leachate dosing. Immediately after the completion of a typical leachate dosing or leachate injection event, the blanket partially drains. During the drainage of the blanket, highest moisture content within the blanket resides at the bottom, where all embedded sensors are located.

To test the drainage of the blanket, leachate injection was paused during the period from 15 Oct. to 23 Nov. 2003. The TDR sensors responded to the drainage of the blanket sooner than the impedance moisture content sensors. During this period, the TDR readings decreased from about 1200 to 200 μA . While, the impedance measured by the moisture content sensors increased by an order of magnitude from about 0.03 to 0.3 $\text{k}\Omega$ during the same period. This change in readings of the TDR and impedance moisture content sensors reflected the drying or drainage of the permeable blanket.

Drying of these sensors was interrupted by an increase in the moisture content of the glass blanket due to precipitation that occurred on 25 Oct. 2003 and 4 Nov. 2003 when a total 20 mm precipitation was recorded.

Effect of Diurnal Air Temperature on Measurements

The thermocouple sensors used in this study are built within the impedance moisture content sensors. The thermocouple junction is located between the sand pack and the PVC casing of the sensor (Reinhart et al. 2003). Hence, the thermocouple temperature readings can be impacted by relatively small changes in temperature that may occur due to the absorption and release of leachate from the sand pack. Throughout the monitoring period, the thermocouple readings were noisy and fluctuated regularly by about 2 °C.

Figure 7 shows the response of thermocouple and thermistor sensors located in the blanket on 8 Nov. 2003. The air temperature and the reference temperature measured by the datalogger are also presented in Figure 7. On 8 Nov. 2003, leachate was not injected in the blanket and no precipitation was recorded. Figure 7 indicates that the temperature readings measured by all thermistors were constant during the entire day. However, the temperature readings measured by all thermocouples showed a gradual increase followed

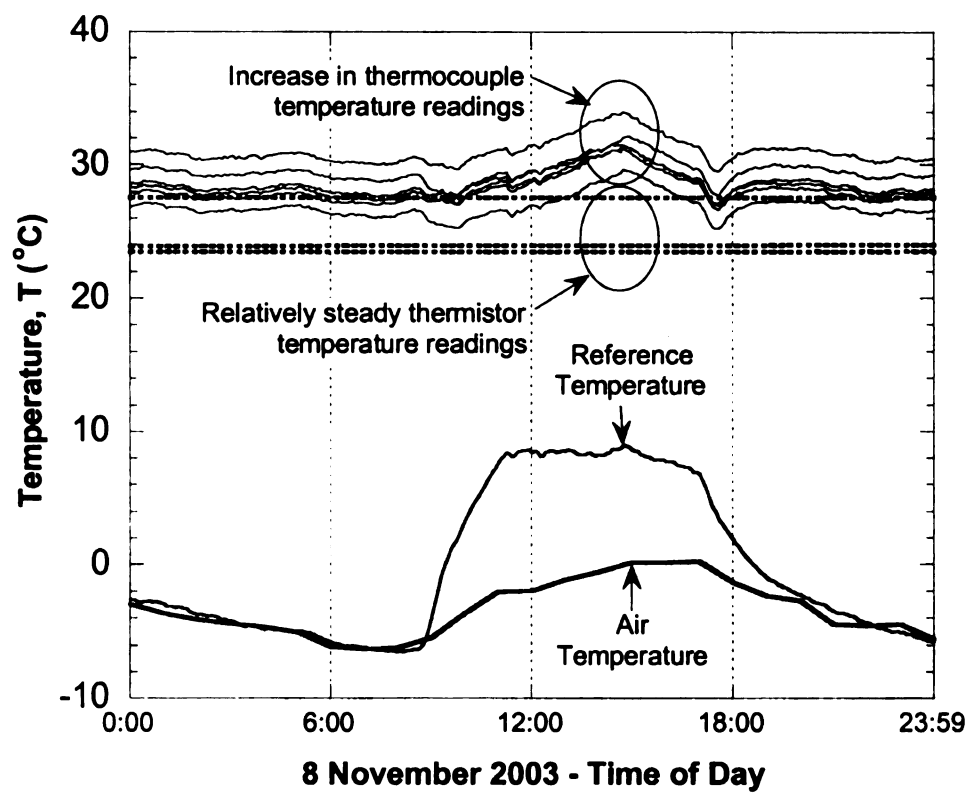


Figure 7. Effect of diurnal air temperature on the field measurements of thermistors and thermocouples.

by a gradual decrease in tune with the air temperature between 8 AM to 6 PM. The change in the temperature recorded by the thermocouple sensors is due to the changes in air temperature affecting the temperature of the thermocouple cable and hence the temperature of the reference thermistor junction. Because a typical thermistor sensor is insulated from its cable, the thermistor readings were not impacted by the changes in the air temperature.

SUMMARY AND CONCLUSIONS

Migration of injected leachate in permeable blankets can be appropriately monitored using an automated sensing system consisting of moisture content, temperature, and pressure sensors. Pressure transducers and thermistors were able to detect the migration of injected leachate in the permeable glass blanket irrespective of the initial degree of saturation of the blanket. TDR and impedance moisture content sensors detected injected leachate only when the surrounding medium was not saturated prior to leachate injection. Even though moisture content sensors will not be able to detect leachate migration once saturated, these sensors are important elements of the monitoring system because these sensors provide the state of saturation of the surrounding medium and provide redundancy in the measurement when unsaturated.

Temperature measurements by thermocouple sensors were affected by the diurnal fluctuations in air temperature affecting the reference temperature. Temperature measurements by thermistor sensors were not affected by the diurnal fluctuations in air temperature. Hence, thermistors are more reliable to measure temperature and to detect leachate migration compared to thermocouples. We recommend the use of an automated

sensing system consisting of moisture content as well as temperature and pressure transducer sensors to provide redundancy in the measurements.

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PAPER NO. 6: LEACHATE RECIRCULATION IN BIOREACTOR LANDFILLS USING GEOCOMPOSITE DRAINAGE MATERIAL

ABSTRACT

The key purpose of this study was to test the use of a permeable blanket made up of geocomposite drainage layer (GDL) for leachate recirculation in municipal solid waste (MSW) landfills. A 34-m-long by 12-m-wide permeable blanket made of geocomposite drainage layer (GDL) was constructed at an active MSW landfill located in Michigan. Leachate was injected in the GDL using a perforated pipe placed centrally above the GDL along its length. Moisture content sensors, pressure transducer, thermistor, thermocouple sensors, and a vertical load sensor were embedded immediately below the GDL blanket to monitor the flow of injected leachate. After the blanket was covered with waste, leachate was injected into the blanket at rates ranging from 0.9 to 2.6 m³/hr per meter length of the blanket. Data collected from the embedded sensors indicated that the injected leachate traveled at rates ranging from 5 to 18 m/hr through the blanket depending upon the leachate injection rate. The rate of travel of injected leachate through the GDL blanket was not uniform. Only pressure transducers and thermistors were able to detect migration of injected leachate once the blanket got saturated and moisture content sensors could not register any change in readings. Leachate injection pressure monitored over a period of two years indicated no signs of clogging of the blanket. The leachate pressures measured immediately below the blanket were less than the net leachate injection pressure indicating that there was a head loss in the GDL blanket. Based on this field data, we conclude that permeable blanket made of GDL can be used to recirculate leachate in MSW landfills. However, long term monitoring of the performance of the blanket needs to be evaluated.

BACKGROUND

Environmental and economical benefits of leachate recirculation in municipal solid waste (MSW) landfills are well documented (Reinhart and Al-Yousfi 1996; Reinhart and Townsend 1998; Pohland and Kim 1999). These benefits include: (1) reduction in leachate treatment and disposal costs; (2) accelerated decomposition and settlement of waste resulting in an airspace gain; (3) an increase in the rate of gas production; and (4) potential reduction in the post-closure care period and maintenance costs. Risks associated with leachate recirculation include: (1) potential decrease in the factor of safety for slope stability of the landfill; (2) potential increase in the leachate head on the liner if the leachate collection system is not designed to drain recirculated leachate; (3) potential flooding of the gas collection system; and (4) leachate seeps from the sides of the landfill if an appropriate buffer distance is not maintained. Before implementation of a leachate recirculation system (LRS), designer and landfill operator are expected to weigh the advantages and disadvantages on a site-specific basis.

The most common leachate recirculation techniques are broadly divided into surface and subsurface application. Surface applications consist of: (1) the direct application of leachate or spray irrigation of leachate on the landfill surface; and (2) surface ponding of leachate. Conventional subsurface application methods are: (1) vertical wells; and (2) horizontal trenches (Koerner 2000, Qian et al. 2002; Haydar and Khire 2005a). Horizontal trenches (HTs) are commonly used in relatively new landfills, while vertical wells are mostly used in retrofit landfills or where implementing HTs is not feasible or cost effective. Haydar and Khire (2005a) showed that for an LRS consisting of HTs, horizontal spacing of HTs needs to be less than 10 m for most commonly used

injection pressure heads (up to 5 m) to reduce the formation of dry zones where injected leachate cannot reach.. Khire and Haydar (2003) and Khire and Haydar(2005b) presented a numerical study that proposed the use of a new subsurface LRS called “permeable blankets” as an alternative to the conventional systems. The key advantages of permeable blankets (PBs) over conventional systems are: (1) excavation of waste is not needed during the construction of the blanket resulting in fewer odor problems; (2) a relatively uniform distribution of leachate in the landfill potentially reducing differential settlement and resulting post-closure maintenance costs; and (3) a PB can substitute multiple horizontal trenches or vertical wells and can offer better cost to overall benefit ratio.

Leachate Recirculation Using Permeable Blankets

This design concept consists of laying a relatively thin layer of permeable material (e.g., shredded tires, crushed glass, pea gravel, GDL, etc.) having relatively high hydraulic conductivity on a flat or inclined waste surface in a landfill (Khire and Haydar 2003). A perforated pipe is embedded in the blanket in the direction parallel to the shorter or longer plan view dimension of the blanket where leachate is injected under a positive pressure.

The thickness of such a blanket can vary depending upon the material used and the site-specific design and operational variables. The aerial dimensions and the shape of the blanket can vary depending on the leachate recirculation needs, the shape of the landfill cell, relative contrast in the hydraulic conductivities of the blanket and the underlying waste, and leachate injection pressure or leachate injection rate. Haydar (2005) has presented relevant details on design and performance of leachate recirculation using permeable blankets in MSW landfills.

There are key concerns that need to be considered when designing a LRS using PBs. Biological activities that occur in landfills may partially or fully clog the permeable blanket and decrease its hydraulic conductivity and hence may jeopardize the hydraulic efficiency of the LRS. When a blanket settles or sags, a higher leachate injection head is needed to compensate for the elevation head loss. If permeable blankets are subjected to relatively high non-uniform vertical loads, differential settlement may jeopardize the physical integrity and the hydraulic continuity of the blanket and can cause disruption in the flow within the blanket. When using permeable blankets, a daily cover with permeability greater than that of waste should be used to minimize excessive lateral spreading of injected leachate and allow vertical spreading (McCreanor 1998).

Field-scale data on performance of leachate recirculation systems is relatively scarce. Hence, designing a leachate recirculation system to achieve a target performance is a challenge for landfill designers. Data from an appropriately designed field-scale monitoring system would greatly benefit landfill designers. Such data is especially useful because there are potential risks including the physical stability of landfill that must be quantified on a site-specific basis before an LRS is designed and implemented.

OBJECTIVES

In this field-scale study, a permeable blanket made up of geocomposite drainage material was constructed and instrumented at an active MSW landfill. The key objectives of the field-scale study were to: (1) test the use of geocomposite drainage layer (GDL) as a permeable blanket to recirculate leachate in municipal solid waste (MSW) landfills; (2) evaluate the distribution of injected leachate in the GDL blanket; and (3) monitor the

leachate injection pressure, pressure head buildup in the blanket, and temperature change of leachate in the blanket.

GEOCOMPOSITE DRAINAGE LAYER

A GDL is a flat geosynthetic product that is used in landfill as well other civil and environmental drainage applications. GDLs in landfills have been primarily used as leachate collection layers, leak detection layer between primary and secondary liners of double lined landfills, and lateral drainage layer to drain infiltrated precipitation in landfill caps (Koerner 1999). A GDL is made up of a geonet (GN) layer sandwiched between geotextiles (GT) or geomembranes. Its purpose is to achieve relatively high transmissivity to maximize the lateral flow through the geonet. A 5-mm-thick geonet layer can be hydraulically equivalent to about a 200- to 300-mm-thick gravel drainage layer under equivalent hydraulic conditions. Most commonly, in a typical GDL, non-woven geotextiles are attached to a geonet on either sides. The key purpose of geotextiles is to separate the GN from the surrounding porous material (e.g., soil, waste, etc.) and to prevent clogging of the GN.

Eith and Koerner (1992) have summarized these advantages of geonets or GDLs over natural soils for landfill applications: (1) saving of valuable landfill air space because these products are relatively thin; (2) relatively simple construction as it does not require heavy equipment for placement and compaction; (3) cost savings depending on the proximity of good-quality natural drainage material as an alternative; and (4) possible reduction or elimination of perforated pipes to drain liquids from the system.

When compared to other permeable materials, blanket made up of GDL has these key advantages: (1) better physical integrity against differential loading or settlement;

and (2) relatively small thickness. These key factors must be considered when using permeable blankets made of GDL: (1) potential clogging of the geotextiles used in GDLs due to bacterial growth or scale formation due to the precipitation of minerals from leachate; (2) temperature of the leachate potentially impacting the physical properties of the GDL; and (3) creep under relatively large confining stresses (Giroud et al. 2000). Koerner et al. (1994) found that leachate containing greater than 2,500 g/ml of total suspended solids or biochemical oxygen demand needs laboratory simulation to assess the clogging effect on a site-specific basis.

NUMERICAL MODELING OF PERMEABLE BLANKETS

In order to illustrate the conceptual hydraulics of permeable blanket and how it compares to the conventional HTs, we have presented the wetted areas at steady-state simulated for a horizontal permeable blanket and horizontal trenches in Figure 1. The simulated wetted area for a permeable blanket placed on an inclined surface is presented in Figure 1(b). These wetted areas are simulated by Haydar and Khire (2005a, 2005b) by using the saturated/unsaturated flow model HYDRUS-2D developed by Simunek et al. 1999. The waste was assumed homogeneous and isotropic for simulating the wetted areas presented in Figure 1. Because waste is a highly heterogeneous material, this assumption is simplistic. However, it allowed us to compare the two designs. In the later part of this manuscript, we have addressed the effect of waste hydraulic conductivity on the rate of travel of leachate in the blanket.

Haydar and Khire (2005b) also have presented a numerical parametric study for horizontal permeable blankets for leachate recirculation in MSW landfills. The objective of the parametric study presented by Haydar and Khire (2005b) was to evaluate the effect

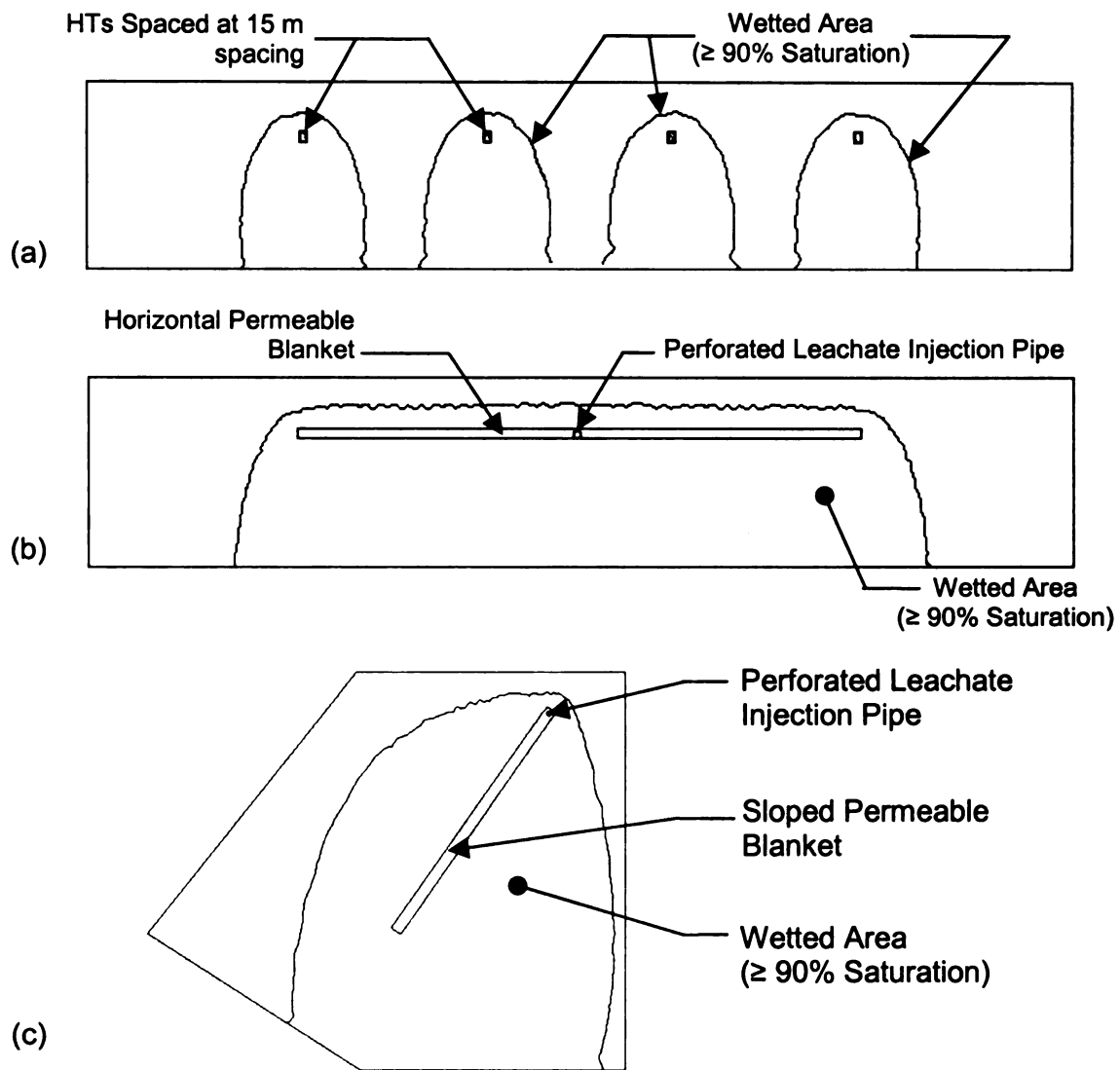


Figure 1. Schematic of wetted area at steady-state simulated by HYDRUS-2D for leachate recirculation system consisting of: (a) four horizontal trenches; (b) a horizontal permeable blanket; and (c) a sloped permeable blanket.

of key design parameters on the rate of travel and the pressure head of injected leachate in the blanket. The authors defined the wetted width as the maximum distance traveled by the injected leachate at steady-state or during a finite duration measured from the injection pipe in the blanket. The wetted width can be used to design the length of the blanket and to determine an appropriate buffer distance to the landfill side slopes to minimize leachate breakouts. The blanket width influences the liquid pressure head in the blanket. Haydar and Khire (2005b) showed that wetted width is primarily a function of the leachate injection rate, dosing frequency of injected leachate, and hydraulic conductivity of underlying waste (k_w). Assuming all other parameters constant, an increase in the liquid injection rate or dosing frequency, or a decrease in k_w results in a greater wetted width.

The thickness or depth of permeable blanket has very little effect on the wetted width. However, increase in the PB depth increase the storage capacity of the PB and hence reduces liquid pressure buildup. Thus, under equivalent conditions, a thicker PB would yield a greater factor of safety against static slope stability. Haydar and Khire (2005b) also found that decrease in the hydraulic conductivity of the blanket (k_B) requires an increase in the leachate injection pressure head (larger head pump) to maintain the injection rate constant and results in a greater liquid pressure buildup in the blanket.

The field-scale study presented in this manuscript was designed to verify the PB concept and to monitor the liquid injection pressure and the liquid pressure buildup in the blanket during and after leachate injection events. The field-scale study was not designed to verify all parameters numerically evaluated by Khire and Haydar (2003) and Haydar and Khire (2005). A complete verification is beyond the scope of this study.

FIELD TEST SECTION AND METHODOLOGY

Field-scale testing of the GDL blanket used for leachate recirculation took place at an MSW landfill located in the southern portion of Michigan. The landfill is currently active and generates on an average of 45 m³ of leachate per day.

Test Section Layout

The GDL blanket was installed by placement of the GDL on the surface of an active cell of the landfill. The GDL blanket was 34-m-long by 12-m-wide. A schematic of the GDL blanket is presented in Figure 2. Before placing the GDL blanket, the surface of the landfill cell was leveled. However, the surface could not be perfectly leveled. A topographic survey of the blanket conducted after the placement of the GDL indicated that the ground sloped towards east – southeast and had an average slope of about 3.5%. Below the surface, from the top to bottom, there is: (1) an average 50-mm-thick silty soil (loess) used as a daily cover; (2) about 20-m-thick MSW; and (3) a leachate collection and lining system. The GDL rolls used for this project were 4.6 m wide. Because the blanket is about 12-m-wide, three GDL rolls were used with a 0.6-m overlap. In the overlap zone, edges of the adjacent geonets were butted against each other and an overlap of about 0.6 m was used for the top and bottom geotextiles.

The GDL used in this project had non-woven geotextile attached on one side and a woven geotextile attached on the other side. Thus, we placed the GDL such that the non-woven geotextile faced upward to prevent an intrusion of the waste into the geonet. The woven geotextile side of the GDL was chosen to face downward to minimize potential clogging due to the underlying silt layer. However, we believe that a GDL with non-woven geotextiles on either side may be equally effective for the given application

LEGEND:

○ E 4.5 m: Location of one or more nested sensors with sensor ID (typical)

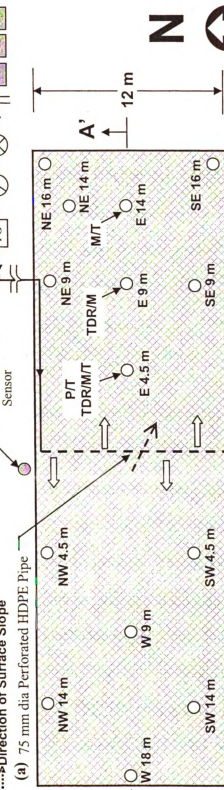
M = Electrical impedance moisture content sensor (MCS)

P/T = Piezometer with thermistor

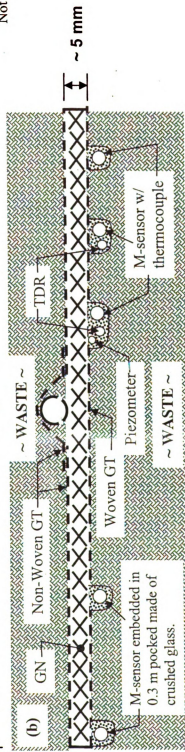
TDR/M/T = TDR and impedance MCS with thermocouple

FG = Leachate flow gauge

→ Direction of Surface Slope



Not to Scale



but needs to be tested in the field.

The key properties of the components of the GDL are presented in Table 1. A 12-m-long perforated high density polyethylene (HDPE) leachate injection pipe having an internal diameter equal to 75 mm was installed at the center of the blanket, parallel to the width as per the schematic presented in Figure 2b. This pipe divided the test section into two almost identical segments – east and west. The northern end of the perforated pipe was capped and the southern end was connected to a hydraulic pump followed by a series of three interconnected leachate storage tanks having a total storage capacity equal to approximately 115 m³. A leachate flow control valve, a digital pressure gauge, and a magnetic flow gauge were installed in the leachate pipe to control and monitor the leachate head and flow rate (Figure 2a).

Embedded Sensors

A total of 14 locations within the blanket were instrumented with these sensors: impedance moisture content sensors; time domain reflectometry (TDR) moisture content sensors; vibrating wire pressure transducers; and thermocouple and thermistor temperature sensors. The key objective of these sensors was to monitor the migration of injected leachate and the pressure and temperature changes in the blanket. The installation locations and relevant details are presented in Figure 2.

The impedance moisture content sensors are designed to measure the electrical impedance (R) between two electrodes embedded in a sand pack that is about 50 mm in diameter (Gawande et al. 2003). The impedance of the sensor is inversely proportional to the moisture content of the sand or the material surrounding the sand. A thermocouple of

Table 1. Physical Properties of the Geocomposite Drainage Material.

Component	Upper Geotextile	Lower Geotextile	Geonet
Type	Non-Woven	Woven	--
Thickness (mm) (ASTM D 5199)	2	0.5	5
Mass per Unit Area (g/m ²) (ASTM D 5261)	270	200	--
Transmissivity ^a (cm ² /s) (ASTM D 4716-00)	--	--	20
Permittivity (s ⁻¹) (ASTM D 4491)	1.5	1.1	--
Hydraulic Conductivity (cm/s) (ASTM D 4491)	0.3	0.05	--
Apparent Opening Size (mm) (ASTM D 4751)	0.18	0.6	~ 12.5
Percent Open Area (%) (CW- 02215)	--	11	80

Note: ^a gradient of 0.1, normal load of 480 kPa, water (permeant) at 20 °C, between steel plates for 15 minutes.

type T was added to the impedance moisture content sensor to allow the measurement of temperature. The TDR moisture content sensor measures the surrounding medium's dielectric constant which is directly related to the moisture content. The TDR sensor used in this study is about 685-mm-long and has a diameter equal to 19 mm.

The vibrating wire pressure transducer measures combined gas and liquid pressure. The pressure transducer used in this study was not vented and required correction for changes in the barometric pressure and temperature. A thermistor is attached to the pressure transducer to allow measurement of the temperature and to correct the measurement of the transducer. Unlike thermocouple sensors, thermistors measure the absolute temperature and they do not require a reference temperature to make the measurements. Haydar and Khire (2005c) have presented the details on the design, function and application of the sensors used in this study. Haydar and Khire (2005c) conducted lab experiments to determine the effect of electrical conductivity (EC) on the measurement of the moisture content sensors. The TDR and impedance moisture content sensors were backfilled with crushed glass (average particle diameter, $D_{50} = 12$ mm) and submerged in saline solutions having EC ranging from 5 to 10 mS/cm. Potassium Chloride was used as an electrolyte to adjust the electrical conductivity of the solutions. This range of EC represents the range of the EC of injected leachate in the field. At saturation, the TDR readings ranged from 1230 to 1300 μA and the impedance readings ranged from 0.02 to 0.03 $\text{k}\Omega$.

The prefix of the location identifications presented in Figure 2a describes the location of the sensor with respect to the leachate injection pipe (e.g., NW, W, etc.) and the suffix represents the perpendicular distance from the leachate injection pipe (e.g., 4.5

m, 12 m, etc.). At location E 4.5 m presented in Figure 2a, the sensor nest consists of the following three types of sensors: (1) an impedance moisture content sensor with a thermocouple; (2) a TDR moisture content sensor; and (3) a vibrating wire piezometer with a thermistor. At location E 9 m, the sensor nest consists of an impedance moisture content sensor and a TDR moisture content sensor. The use of different types of sensors at the same location was to calibrate and independently verify the data measured among sensors. A vertical pressure sensor was installed immediately outside the northern edge of the test section to monitor the weight (or vertical stress) of waste placed on the test section. The vertical pressure sensor also contained a thermistor which was used to monitor the temperature of waste adjacent to the blanket. All sensors except for the vertical pressure sensor were installed immediately below the GDL. Holes measuring 300 mm in diameter and about 300-mm-deep were excavated in the silty soil layer and waste below the GDL and sensor(s) was placed in drainage backfill consisting of coarse sand or crushed glass ($D_{50} = 12$ mm, hydraulic conductivity ~ 1 cm/s) as presented in Figure 2(b).

Monitoring System

Meteorological sensors including a rain gauge, an air temperature sensor, and a barometric pressure sensor were also installed at the site. All sensors including the leachate flow gauge and pressure gauge were connected to a data logger located at the site. The data logger was programmed to take readings at the desired frequency. Most of the data collected from the test section was collected at a 5-minute frequency to allow for a relatively precise monitoring of the injected leachate. From September 2003 to May 2004, about $1,800 \text{ m}^3$ of leachate was recirculated in the GDL blanket corresponding to approximately 27 leachate recirculation events. The leachate injection rate, Q , ranged

from 0.9 to 2.6 m³ per hour per meter length of the pipe perpendicular to the plane of the paper (m³/hr/m). The control valve schematically presented in Figure 2a was used to regulate the injection rate. The maximum leachate rate of 2.6 m³/hr/m corresponds to the maximum rate the pump at the site could deliver at the total head that exists for the system. During this monitoring period, the rain gauge recorded about 500 mm of cumulative precipitation at the site.

RESULTS

Leachate Recirculation Trials

After the GDL blanket was covered with about 2-m-thick waste, leachate recirculation was started in Sept. 2003. In Sept. 2003 the vertical stress recorded at the site was about 10 kPa. It rose to about 20 kPa in May 2004 due to waste filling.

Verification of Response of Moisture Content Sensors

At location E 9 m, data collected from the TDR moisture content sensor was compared to the impedance moisture content sensor. Data from this comparison is presented in Figure 3. In Figure 3, the negative values on the x-axis (-120 to 0) represent the time before the leachate injection started and the positive values on the x-axis (0 to 240) represent the time since the leachate injection began. The two arrows on the x-axis correspond to when the leachate injection was started and turned off.

Figure 3 indicates that about 40 minutes after the leachate injection began, at location E 9 m, the impedance started to drop and the TDR reading started to increase at the same time indicating an arrival of the wetting front of the injected leachate. The

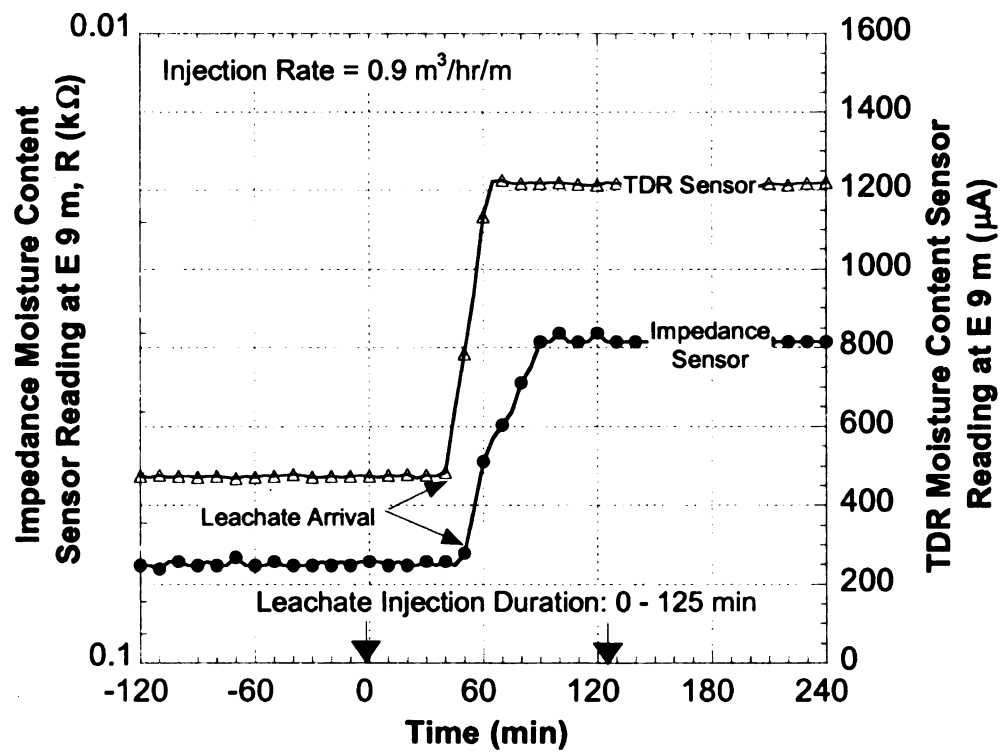


Figure 3. Verification of response of impedance moisture content sensor using TDR moisture content sensor at location E 9 m.

impedance dropped from about 0.07 k Ω to 0.03 k Ω and stabilized. Similarly, the TDR reading increased from about 500 to 1,200 μ A and stabilized. According to the lab calibration data, the stabilized high readings of the TDR and impedance moisture content sensors correspond to 100% saturation immediately below the blanket. This indicates temporary saturation of the blanket at Location E 9 m due to the leachate injection.

Verification of Response of Temperature and Pressure Transducer Sensors

Figure 4 presents the temperature and pressure head (h_p) measurements at location E 4.5 m. Before leachate injection began, the temperature measured by the thermistor was about 24°C and the pressure head measured by the transducer was about 10 cm. Leachate was injected at a rate equal to 2.6 m³/hr/m. The net leachate injection pressure head (h_i) in the blanket was estimated to be around 4 m. It was estimated by subtracting head loss in the segment of the leachate injection pipe between the blanket and the leachate pressure gauge located outside the blanket. Note that the leachate injection pressure is measured using a pressure gauge located approximately 40 m outside the blanket (Figure 2). The elevation of the leachate injection pressure measurement point is smaller than the average elevation of the blanket by about 100 cm. Moody's diagram (Moody 1944) was used to estimate the head loss.

The temperature of the injected leachate was around 19°C. About 10 to 15 minutes after the leachate injection began, in response to the arrival of the wetting front of the injected leachate, the temperature measured by the thermistor decreased and simultaneously the pressure head measured by the piezometer in the blanket increased.

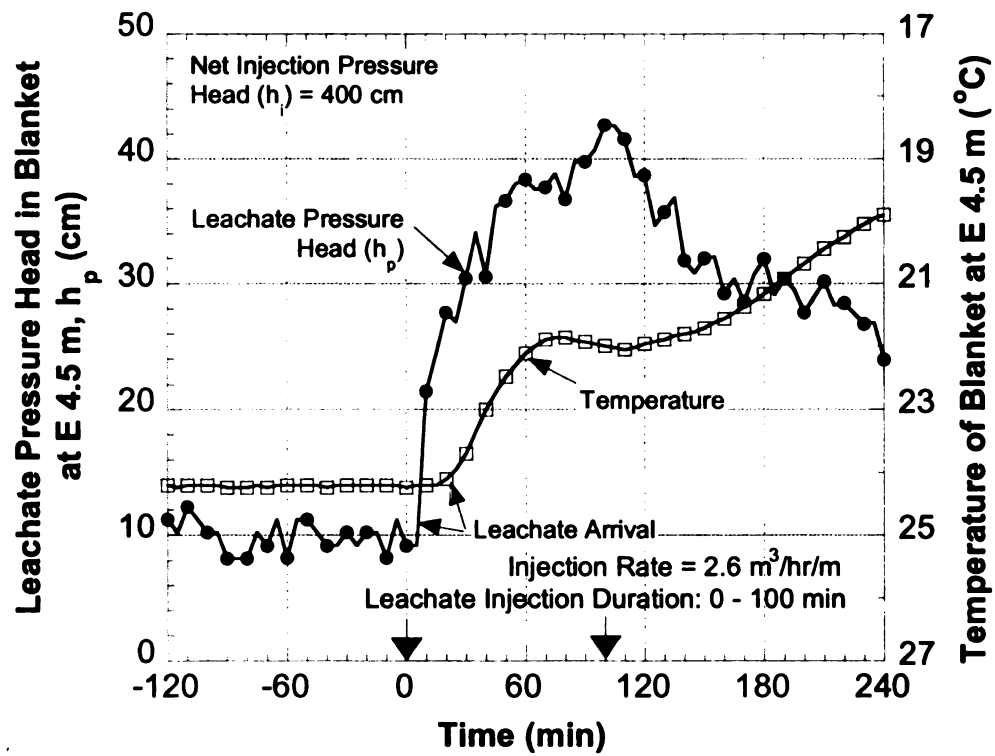


Figure 4. Migration of leachate in the GDL blanket evaluated by change in temperature and increase in pressure head measured by embedded sensor at location E 4.5 m.

Note that no precipitation was recorded during the time periods presented in Figures 3 and 4. Hence, the response of the sensors observed in Figures 3 and 4 is strictly due to the leachate injected in the blanket during those periods. Data presented in Figs. 3 and 4 indicate that moisture content, temperature, and pressure head, when measured simultaneously, can be used to monitor the migration of injected leachate in or immediately below the permeable blanket.

Flow of Leachate through the GDL Blanket

Figure 5 present the typical response of impedance moisture content sensors located in the eastern and western portion of the GDL blanket for leachate injection events corresponding to Q equal to $0.9 \text{ m}^3/\text{hr}/\text{m}$. Figure 5 shows that the impedance moisture content sensors that were initially partially saturated, experienced a decrease in impedance as the injected leachate reached the location of the sensor. However, those sensors that were initially completely saturated did not show any decrease in impedance. Figure 5 represents the response of the impedance moisture content sensors to a leachate injection event when about 20 m^3 of leachate was injected in the blanket over a 125-minute duration. Figure 5a shows that the injected leachate in the eastern portion of the GDL reached the E 4.5 m sensor in 10 minutes, the SE 9 m sensor in 20 minutes, the E 9 m sensor in 50 minutes, the SE 16 m sensor in 60 minutes, and the NE 16 m sensor within 120 minutes after the leachate injection began. Figure 5b shows that the injected leachate in the western portion of the GDL reached both the NW 14 m and W 18 m in 100 minutes after the leachate injection began. The rate of travel of injected leachate in the eastern and western portion of the blanket was not uniform. However, leachate did

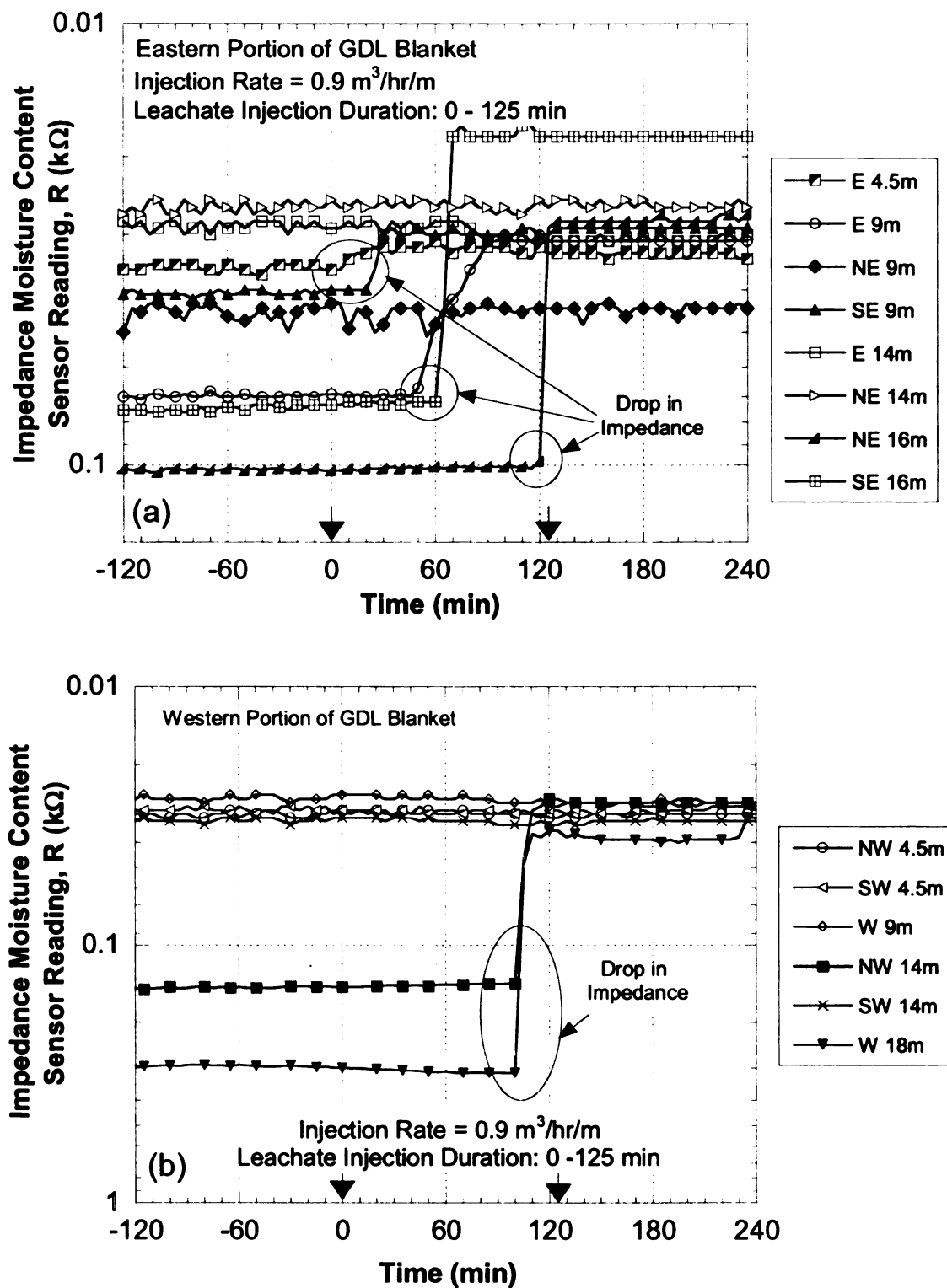


Figure 5. Response of impedance moisture content sensors located in the (a) eastern; and (b) western portions of the blanket to a leachate injection event at leachate injection rate equal to $0.9 \text{ m}^3/\text{hr}/\text{m}$.

reach the farthest sensors (SE 16 m, NE 16 m, and W 18 m) located in the eastern and western portions of the blanket.

Effect of Injection Rate on Leachate Travel

Figure 6 presents the arrival time of injected leachate at the locations of sensors in the eastern and western portion of the GDL for two leachate injection events at Q equal to 0.9 and 2.6 m³/hr/m. The arrival time was determined by the response of impedance moisture content sensors, located in the eastern and western portion of the GDL blanket, to the arrival of injected leachate.

Moisture content sensors that were initially saturated were not able to record the migration of injected leachate. Thus, only sensors that were partially saturated responded to the migration of injected leachate. In order to ease the observation of the response of sensors, sensors located in the same direction (e.g., NE, E, SE, etc.) were clustered and assigned the same symbol in Figure 6. Hollow and solid symbols represent the arrival times for leachate injection events at Q equal to 0.9 and 2.6 m³/hr/m, respectively. The rate of travel of injected leachate was greater for the higher Q . Note that the slope of dashed and solid lines in Figure 6 is the average rate of travel of injected leachate for Q equal to 0.9 and 2.6 m³/hr/m, respectively. Figure 6 also shows that the solid symbols are to the left side of alike hollow symbols, corresponding to the same cluster of sensors, indicating an earlier arrival of injected leachate for the higher Q . For Q equal to 0.9 m³/hr/m, the injected leachate did not travel uniformly within the eastern or western portions of the GDL blanket. For Q equal to 2.6 m³/hr/m, the travel of injected leachate was more uniform. However, response of additional sensors is needed to confirm such conclusion.

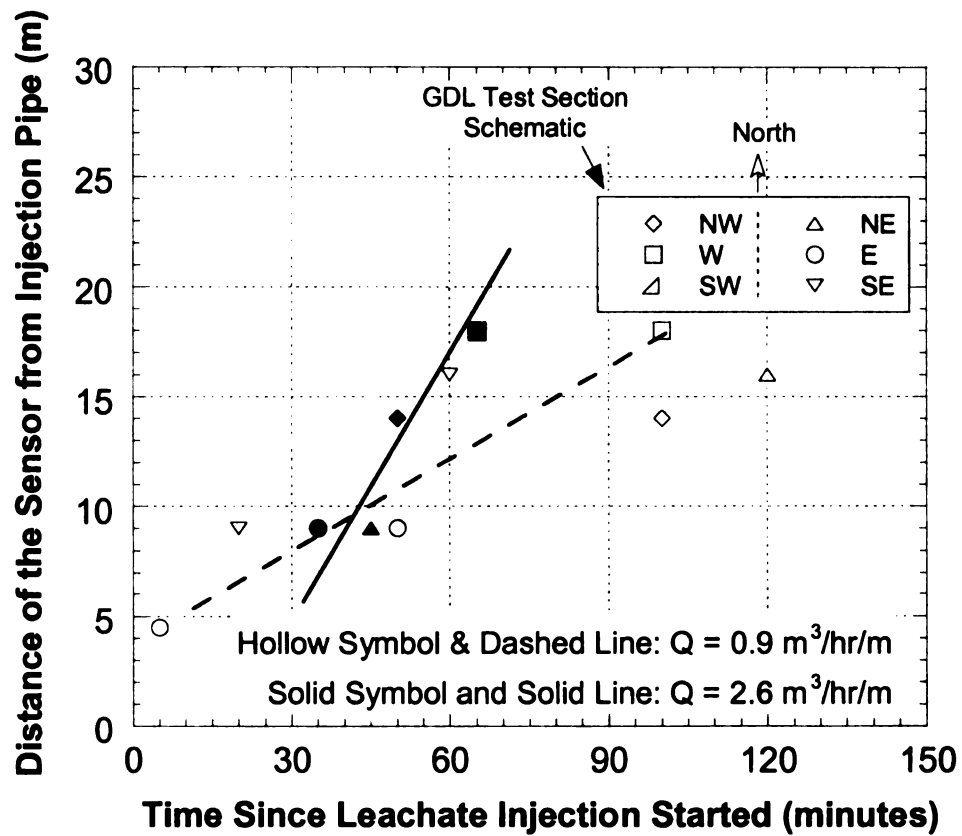


Figure 6. Effect of leachate injection rate on the rate of travel of leachate in the blanket for leachate injection events corresponding to injection rates equal to 0.9 and 2.6 $\text{m}^3/\text{hr}/\text{m}$.

Based on the arrival time of injected leachate at a given sensor, the injected leachate traveled at an average rate of 5 to 10 m/hr in the GDL blanket for Q equal to 0.9 m³/hr/m and at an average rate of 12 to 18 m/hr for Q equal to 2.6 m³/hr/m. We believe that the rate of travel of injected leachate for a given leachate injection rate was not uniform across the blanket due to these key factors: (1) preferential flow in the GDL due to wrinkles formed in the GDL during installation; (2) spatial variation of the hydraulic conductivity and moisture content of the underlying waste; and (3) the waste surface slightly sloped (~ 3.5%) towards east – southeast. Wrinkles were formed in the GDL because the waste surface on which the GDL was laid was uneven and due to the thermal stresses induced from a few days of sun exposure before the GDL was covered with waste.

Correlation of Modeling and Field Results

Haydar and Khire (2005b) have presented a numerical parametric study of design parameters influencing the rate of travel and pressure head of injected leachate in permeable blankets. The conceptual model used in the parametric study consisted of an LRS and a leachate collection system (LCS). The LRS consisted of a 60-m-wide and 0.15-m-deep PB made of pea gravel having a saturated hydraulic conductivity equal to 10^{-2} m/s. A 0.1-m-diameter perforated pipe was centrally placed in the blanket to inject liquid. The LCS consisted of two leachate collection pipes horizontally spaced at 60 m and embedded in a 0.3-m-deep drainage layer made of pea gravel.

Haydar and Khire (2005b) did not specifically simulate the GDL blanket presented in this manuscript due to the limited scope of the study and limitations of the modeling. For example, the GDL blanket having 10 mm thickness could not be accurately simulated

in HYDRUS-2D for the relatively large model domain (100-m wide by 22-m deep) represented in the field. The authors showed that if the thickness of the PB is reduced, for all other parameters kept constant, it results in an increase in the rate of travel of injected liquid. Both, the simulated blanket and the GDL blanket had an equal hydraulic transmissivity equal to $20 \text{ cm}^2/\text{s}$. Further details on the conceptual model and boundary conditions are presented in Haydar and Khire (2005b). The rate of travel in the blanket simulated by Haydar and Khire (2005b) (solid lines in Figure 7) and the measured rate of travel from the field data (hollow symbols in Figure 7) collected from the GDL blanket are superimposed in Figure 7 for Q equal to $0.9 \text{ m}^3/\text{hr}/\text{m}$. Because field-scale hydraulic conductivity of landfilled waste (k_w) is rarely measured, a range of k_w values (10^{-7} to 10^{-5} m/s) representing the typical range were simulated (refer to the solid lines in Figure 7).

The initial degree of saturation of the blanket (S_B) and the underlying waste (S_W) were assumed equal to 50% and 65%, respectively. In the field, the degree of saturation of the underlying waste was not measured. Haydar and Khire (2005b) showed as the degree of saturation of waste (or blanket) increases, the rate of travel of injected leachate in the blanket also increases. However, this increase is relatively small. Hence, the assumed values for the degrees of saturation, even though may not match the field values, are reasonable for the comparison sought here.

Figure 8 presents the simulated pressure head in the PB versus that measured in the field. The simulated pressure head in the PB was measured at a distance of 4.5 m from the injection pipe. This distance is equivalent to the distance between the embedded pressure transducer and the injection pipe in the GDL blanket. For the simulation, Q was assumed equal to $0.9 \text{ m}^3/\text{hr}/\text{m}$ and k_w values ranging from 10^{-6} to 10^{-5} m/s . S_B and S_W

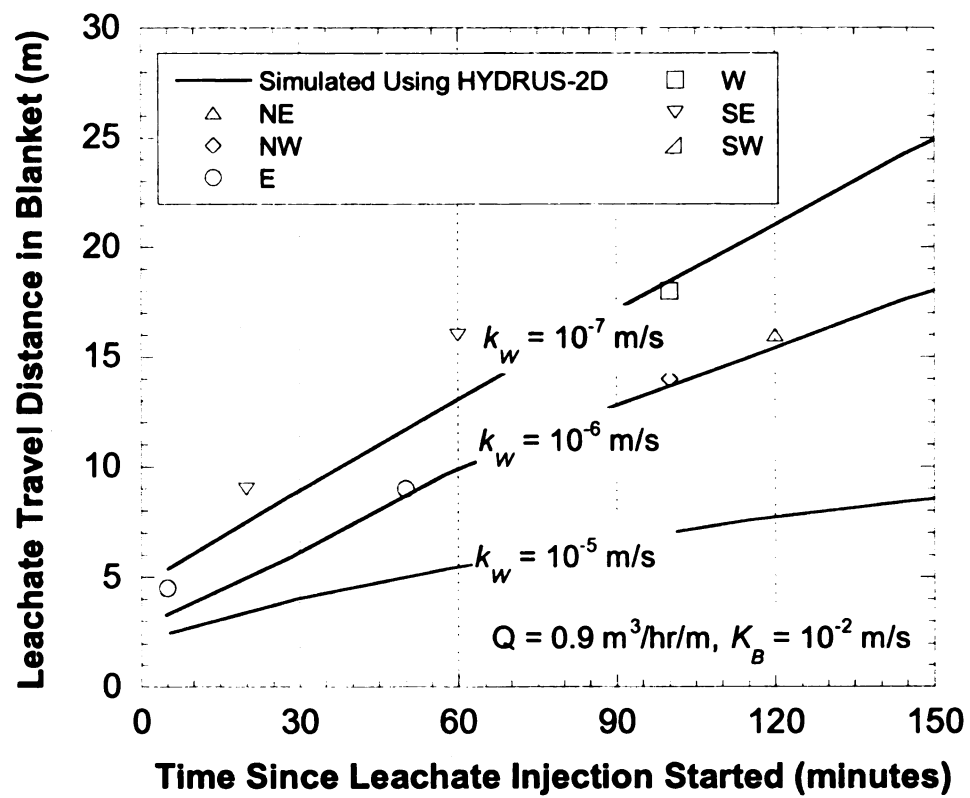


Figure 7. Correlation between simulated and measured rate of travel of injected leachate for leachate injection events corresponding to injection rates equal to $0.9 \text{ m}^3/\text{hr}/\text{m}$.

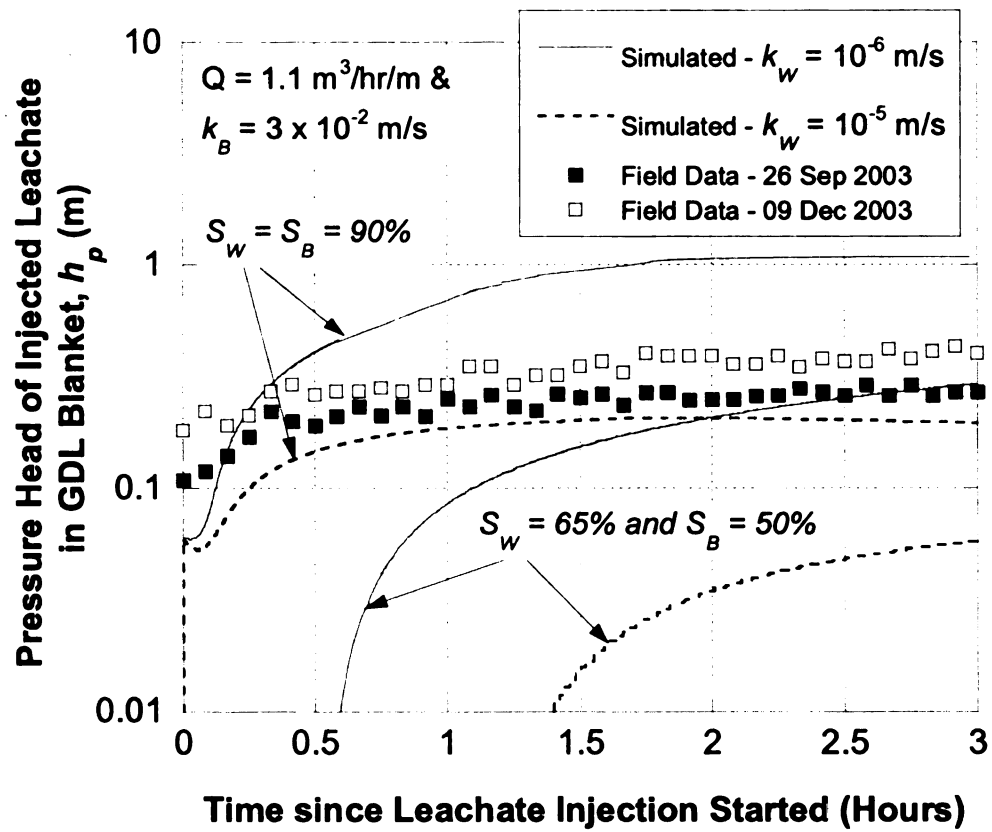


Figure 8. Measured and simulated pressure head of injected leachate in the GDL blanket for two leachate injection events corresponding to $Q = 0.9 \text{ m}^3/\text{hr}/\text{m}$.

ranged from 50 to 90%. The magnitude of simulated h_p was less for a greater k_w and for lower S_w and S_B . From Sep. to Dec. 2003, the degree of saturation of the GDL blanket and the waste beneath it increased due to the frequent leachate recirculation. This correlated well with an increase in the pressure head measured in Dec 2003 compared to that in Sep. 2003.

Because k_w , S_w , and SWCCs of the underlying waste are unknowns, the field data collected in this study cannot be simulated any more accurately. Figures 7 and 8 indicate that the data measured in the field is in the ball parks of simulated leachate travel for the assumed variables. Hence, we believe that designers can use the modeling approach presented by Haydar and Khire (2005b) to carry out preliminary design of field-scale PBs made up of GDLs or other permeable materials. However, we recommend comprehensive monitoring of the PB to obtain site-specific data to improve the design and operation of the PB.

Monitoring of Pressure Head and Temperature in the GDL Blanket

Potential clogging of the geotextiles in the GDL is one of the key operational concerns for permeable blanket made of GDL. Haydar and Khire (2005b) numerically simulated the clogging of the blanket by decreasing the hydraulic conductivity of the PB and maintaining the leachate injection rate constant. The simulated data indicate that, if the blanket partially clogs, the injection head needs to be increased to maintain the leachate injection rate. As the leachate injection head increases, the liquid pressure heads in the blanket and its immediate vicinity also increases. We evaluated potential clogging of the GDL blanket during the monitoring period by evaluating the monitored leachate injection

pressures and leachate pressure head measured immediately below the GDL blanket at E 4.5 m.

Figure 9 presents the leachate injection rates and injection pressures during the monitoring period. Figure 9 shows that the leachate injection pressures were about 200, 400, and 800 cm for leachate injection rates equal to 0.9, 1.4, and 2.6 m³/hr/m, respectively, used at the site. For a given injection rate, leachate injection pressure readings were constant and did not increase throughout the monitoring period. An increase in these readings would have indicated potential clogging of the blanket.

Total hydraulic friction loss in the non-perforated 40-m-long portion of the leachate injection pipe and the 12-m-long perforated portion of the leachate injection pipe was estimated using Moody's diagram (Moody 1944). For leachate injection rate ranging from 0.9 to 2.6 m³/hr/m, the total friction loss ranged from about 100 to 300 cm. Thus, the net leachate injection pressures (h_i) ranged from about 50 to 400 cm.

For each leachate injection event, both the pressure transducer and the thermistor located at E 4.5 m responded to the arrival of the injected leachate. Figure 10 presents the pressure head and the temperature measured at E 4.5 m during the monitoring period. The pressure transducer recorded an increase in leachate pressure head as the pore water pressure increased due to the arrival of injected leachate. The increase in the pressure head gradually dissipated after the leachate injection was stopped. The shorter peaks of h_p with a magnitude of about 30 cm in Figure 10 correspond to a leachate injection rate of 0.9 m³/hr/m and the taller peaks with a magnitude of about 80 cm correspond to a leachate injection rate of 2.6 m³/hr/m.

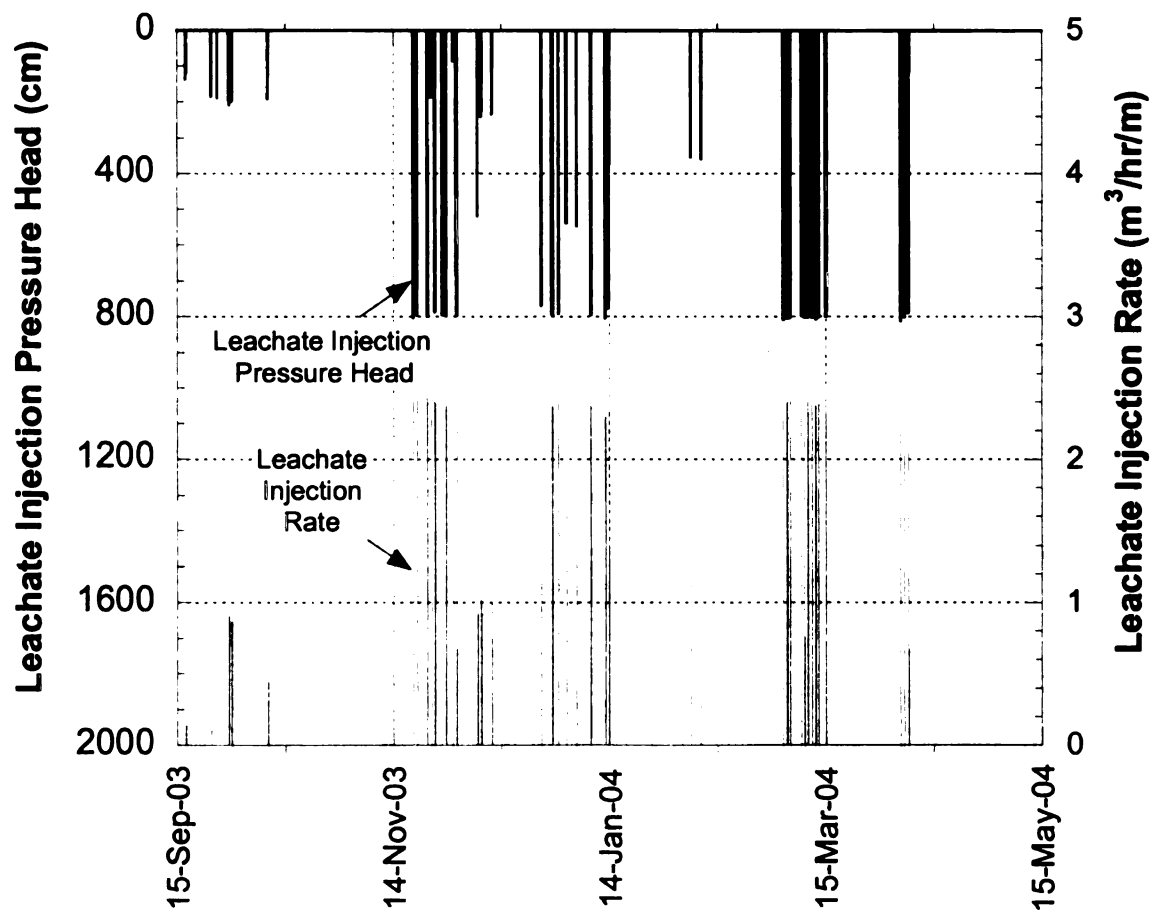


Figure 9. Leachate injection pressure and leachate injection rate measured at the site.

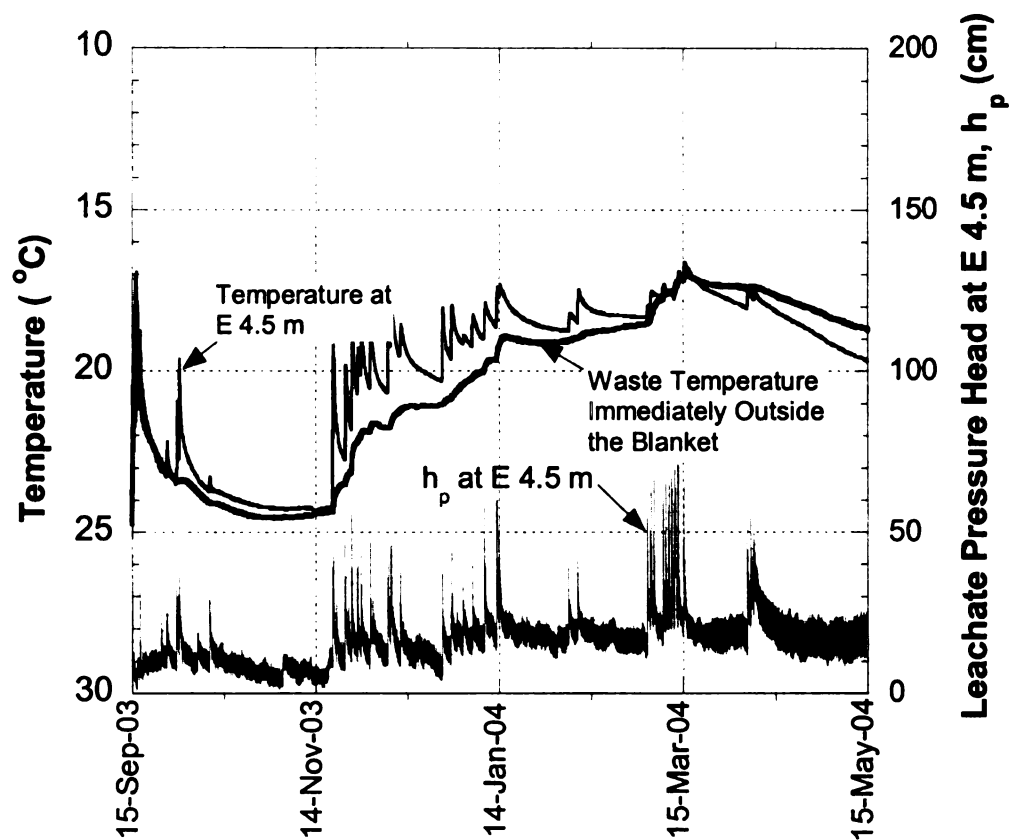


Figure 10. Leachate pressure heads and temperatures within the blanket and waste temperature outside the blanket measured at the site.

Comparison of the leachate injection pressure and the leachate pressure head below the blanket at E 4.5 m indicates that significant leachate pressure head loss occurred as the injected leachate traveled through the GDL blanket. The pressure head measured at E 4.5 m never exceeded the injection pressure head.

The temperature of the GDL blanket was also affected by leachate recirculation. The temperature in the blanket temporarily decreased due to the arrival of injected leachate. This occurred because the temperature of the injected leachate was almost always less than the temperature of the blanket. The temperature of waste monitored using the vertical stress sensor located immediately outside the northern edge of the blanket was close to or greater than the temperature recorded at E 4.5 m (Figure 10). The variation of the seasonal air temperature had a relatively small effect on the temperature of the blanket due to the thermal insulation provided by the waste mass.

SUMMARY AND CONCLUSIONS

A 34-m-long by 12-m-wide permeable blanket constructed using a GDL was tested in the field to recirculate leachate in an active MSW landfill. Leachate was injected at rates ranging from 0.9 to 2.6 m³/hr per meter length of the injection pipe. Moisture content, temperature and pressure sensors were embedded immediately below the blanket to monitor the rate of migration, temperature, and pressure of injected leachate in the blanket.

Our major conclusions are: (1) the GDL blanket is a possible option to recirculate leachate in MSW landfills; (2) the rate flow of injected leachate in the GDL blanket is a function of the leachate injection rate, extent of wrinkles present in the GDL before it is covered, the slope of the blanket, and the degree heterogeneity in the hydraulic properties

of underlying waste; (3) excess pressures were not developed in the vicinity of the blanket indicating that the GDL blanket provided hydraulic continuity; (4) the moisture content sensors embedded immediately below the blanket became saturated during leachate injection demonstrating that the blanket transported the leachate; and (5) in the long term, clogging of GDL blanket is a possibility, however, clogging at the site was not indicated by the data during the 20-month-monitoring-period.

We recommend that designers consider the following when implementing this design in the field: (1) carry out numerical modeling of the blanket design using site-specific design variables; (2) evaluate the effect of increase in waste moisture content and leachate pressure heads on the slope stability of the landfill; (3) instrument at least a portion of the blanket in the field to collect data on site-specific performance; and (4) maintain sufficient distance between the edges of the blanket and the side slopes of the landfill to minimize the potential for leachate breakouts. Long-term monitoring of pressure buildup and potential clogging still needs to be investigated to assess long-term hydraulic efficiency of permeable blankets made up of GDL.

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SUMMARY AND PRACTICAL IMPLICATIONS

The key objectives of this dissertation were to: (1) perform a parametric study for leachate recirculation or liquid injection using horizontal trenches (HTs) and permeable blankets (PBs); and (2) evaluate the use of PBs for leachate recirculation in MSW landfills. To achieve these objectives, numerical modeling followed by field-scale testing of three instrumented PBs was carried out at an active MSW landfill located in Jackson, Michigan.

The key installation related advantages of PBs over conventional systems are: (1) excavation of waste is not needed during the construction of the blanket resulting in less odor problems; and (2) a PB can substitute multiple horizontal trenches or vertical wells. The key operational advantages of PBs are: (1) PB acts as an engineered heterogeneity and reduces the effect of spatial variation of waste properties on wetting the waste resulting in a relatively uniform distribution of injected leachate in the waste; and (2) PBs made up of granular materials can provide an ideal platform to embed sensors for monitoring the pressure, temperature, and migration of injected liquid to evaluate long-term performance of the system.

The key findings of the numerical modeling of PBs and HTs and field-scale testing of PBs are presented below.

HORIZONTAL TRENCHES

The key findings of numerical modeling of HTs are:

- An increase in the width of an HT results in a greater wetted width compared to when the depth is increased.

- When the hydraulic conductivity of an HT backfill is equal to or greater than that of the surrounding waste, any further increase in the hydraulic conductivity of the HT has negligible impact on the wetted area of waste.
- For a given injection pressure head, the wetted width is independent of the saturated hydraulic conductivity of the waste.
- When two or more rows of HTs are designed, HTs in these rows should be vertically staggered to reduce dry zones. HTs should be placed at about 10 m horizontal spacing for formations consisting of HTs in a single row for injection pressure head ranging from 3 to 5 m. HTs should be placed at about 20 m horizontal spacing for formations consisting of HTs in multiple rows where HTs are staggered and operated at injection pressure head ranging from 3 to 5 m.
- The pattern of wetted area of injected leachate was greatly affected when heterogeneity and anisotropy of the waste was considered. Introduction of heterogeneity and anisotropy resulted in non-uniform leachate wetting. Increase in the horizontal correlation length of hydraulic conductivity of waste resulted in a greater wetting in the horizontal direction with a greater potential for leachate breakouts.

PERMEABLE BLANKETS

Numerical Modeling

The key findings from the numerical modeling of PBs are as follows.

- Greater the leachate injection rate, hydraulic conductivity of the PB, or degree of saturation of the waste and PB, faster the rate of travel of the injected leachate in

the PB. Similarly, lower the hydraulic conductivity of the underlying waste, faster the rate of travel of the injected leachate in the PB

- The pressure head of injected leachate in a PB is inversely proportional to the hydraulic conductivities of the PB and waste. Hence, in order to maintain lower pressure heads in the landfill resulting from the leachate injection, it is preferable to select a material having relatively high hydraulic conductivity to construct the PB.
- Increase in the depth of a PB increases the storage capacity of the blanket and hence decreases pressure head buildup of leachate in the blanket. Thus, a thicker PB is preferable if slope stability of the landfill dictates lower leachate injection pressure heads.
- When leachate is injected periodically, the greater the ratio of on to off duration of leachate injection, the greater the wetted width at steady-state. In addition, when leachate is injected periodically, the average degree of saturation of the PB and the underlying waste increases resulting in a faster travel of injected leachate until a steady-state is reached.

Field-Scale Testing

The key findings from the field-scale testing of the PBs are:

- The migration of injected leachate in PBs can be monitored using an automated sensing system designed to measure moisture content, temperature, and liquid pressure within the PBs. However, unlike water content, pressure heads and

temperatures do not max out and hence can be used to detect the migration of injected leachate in the PBs irrespective of the degree of saturation of the PBs.

- The data collected from the sensors embedded in the three field-scale permeable blankets during the period from September 2003 to May 2005 indicated that the injected leachate traveled across the entire width (~ 30 m) of the blankets. The rate of travel of injected leachate was a function of leachate injection rate, hydraulic conductivity or transmissivity of the PB, and degree of saturation of the waste and PB. For a leachate injection rate of $3.6 \text{ m}^3/\text{hr/m}$, injected leachate traveled at an average rate of 18 m/hr in the glass blanket and at an average rate of 45 m/hr in the tires blankets. For a leachate injection rate equal to $2.6 \text{ m}^3/\text{hr/m}$, injected leachate traveled at an average rate of 15 m/hr in the GDL blanket.
- Injected leachate traveled more uniformly in the glass PB compared to the other two blankets. This was due to the uniform particle size distribution of crushed glass used for the blanket. The migration of injected leachate in the GDL blanket was not uniform possibly because of wrinkles in the GDL before it was covered and slight slope of the surface on which it was laid. In the shredded tires PB, the flow was not uniform due to the heterogeneous nature of the shredded tires.
- The pressure head measured in the GDL blanket was greater than that measured in the glass PB, at the same distance from the injection pipe. This was most likely due to lower storage capacity in the GDL blanket compared to the glass PB.
- The pore water pressure in none of the three PBs exceeded the leachate injection pressure head. The maximum pressure head measured in the three PBs during the monitoring period was 1.5 m.

- The hydraulic efficiency of the blanket for long-term performance needs to be investigated by further monitoring of the test sections.

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