Design of Cost Effective Lysimeters for Alternative Landfill Cover Demonstrations Projects

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Tarek Abichou,
Xiaoli Liu and Kamal Tawfiq
FAMU – FSU College of Engineering

State University System of Florida
Florida Center for Solid and Hazardous Waste Management
University of Florida
2207-D NW 13th Street
Gainesville, FL 32609
www.floridacenter.org

Executive Summary

Landfills are the most widely used facilities for solid waste disposal. Landfill covers are used to reduce the quantity of water that infiltrates into solid waste landfills, isolate solid waste from the environment and control gas migration. Resource Conservation and Recovery Act (RCRA) regulations prescribe that the covers employ layers which have low saturated hydraulic conductivity as hydraulic barriers. Those barriers can limit flow into underlying solid wastes, and consequently, reduce the rate of leachate generation and risk of additional groundwater contamination.

Experience has shown that the prescribed clay barrier layers are susceptible to failure caused by desiccation and cracking damage by freeze – thaw actions, and are expensive to build. An effective alternative cover design is evapotranspiration (ET) cover. ET covers possess many advantages over prescribed covers such as working with nature, long life time, easy maintenance and lower cost.

Once the feasibility of an ET cover is verified in a region, an evaluation of hydraulic equivalency is required for alternative cover to be approved by regulatory authorities. The hydraulic equivalency requires that percolation from the base of the alternative cover is less than or equal to percolation rate from the prescriptive cover. Lysimeters was suggested to be used in facilities measuring the percolation rate. There are some concerns about the precision with which percolation rate can be measured with lysimeters.

A series of numerical simulations were performed in this study to investigate the performance of lysimeters of various geometries and develop the optimal lysimeters dimensions for percolation rate measurement. The simulations consist of inputting data for lysimeter geometry, soil hydraulic property, weather condition, boundary condition, vegetation distribution and density. The output cumulative flux data was used to evaluate the performance of lysimeters.

The study shows at the specific weather condition used during this study, the lysimeters without sidewalls underestimate percolation rate by at least 25%. Installation of full sidewalls remarkably improved the lysimeter performance. The lysimeter with full scale sidewalls still underestimate by at least 10%. Lateral diversion and no-flow boundary at the bottom of lysimeter and the drainage layer right above the bottom pan caused the decrement of lysimeter performance. To measure percolation rate accurately, soil - specific and site - specific coefficients have to be determined.

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Xiaoli Liu	FAMU-FSU COE
Kamal Tawfiq	FAMU- FSU COE

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CHAPTER ONE

INTRODUCTION

Final covers are constructed for solid and hazardous waste landfills to reduce the amount of water infiltrating into the waste deposit, isolate waste and control gas migration. Resource Conservation and Recovery Act (RCRA) regulations require that final covers be constructed with clayey soils or with geosynthetic clay liners (GCLs), with or without geomembrane. These types of covers are susceptible to failure caused by desiccation and cracking damage, expensive to construct and maintain. Evapotranspiration (ET) covers can be an alternative approach to the traditional covers. ET covers exploit the water storage capacity of finer textured soils and the water removal capability of vegetation to reduce infiltration into the underlying waste. ET covers work with nature rather than attempting to control them.

Before the acceptance of ET landfill covers by the regulatory agencies, and the full-scale implementation of ET covers can be conducted, field studies are needed to verify the effectiveness of the designs. RCRA regulations require that percolation from any alternative covers must be equivalent to the prescriptive cover.

Five methods are typically considered to assess the field performance of ET cover test sections: 1) Water balance methods, 2) Trend evaluation, 3) Tracer experiments, 4) Darcy's Law method, 5) Lysimetry. Only lysimetry provides a direct measurement of percolation rate from an alternative cover. However, the following disadvantages of lysimeters are being challenged by the engineering community:

• The artificial no-flow boundary induced by the lysimeter at the base of the profile prevents upward and downward flow of vapor and liquid across the base of the lysimeter.

• Most lysimeters also include a drainage layer directly on top of the lower boundary for directing percolation to a measuring point. The larger pores associated with drainage layers induce a capillary break at the base of the cover profile that might not exist under natural conditions. As a result, an artificial increase in the storage capacity of the cover profile may be incurred relative to natural conditions, as well as an artificial reduction in percolation rate.

• Lateral diversion can be a significant problem with lysimetry. Lysimeters that are too small collect too little water and underestimate the percolation rate.

This study is a numerical study that investigates the influence of the above three factors on the lysimeter performance, how lysimeter geometry and boundary conditions affect lysimeter performance. Section Two describes five available methods for percolation rate measurement, and review different concerns about lysimeter application. Section Three describes the properties of HYDRUS - 2D, its application and validation, parameters used in this study. Section Four encapsulates the results from simulations using HYDRUS - 2D. A summary of results, along with recommendations based on this study is provided in Section Five. Section 6 includes a list of references used in this study.

CHAPTER TWO
BACKGROUND

2.1 Conventional Landfill Covers

Landfills are the most commonly used facilities for disposal of industrial, municipal, and low-level radioactive waste. Once a landfill is closed, final covers are required. Final covers are used to reduce the amount of water infiltrating into the waste deposit. They also act to isolate waste, and control gas migration. The Resource Conservation and Recovery Act (RCRA) Subtitle 'C' and 'D' prescribes the requirements of landfill covers. Under Subtitle D of RCRA, the United States Environmental Protection Agency (USEPA) provides the minimum criteria for covers and liner designs of municipal solid waste landfills. The regulations provide four types of cover designs based on the liner system at the base of the landfills (Table 2.1). Those cover designs are referred to as prescribed covers.

The prescribed covers make use of resistive principles, i.e., layers with low saturated hydraulic conductivity (compacted clay barriers, or geosynthetic clay liners with or without a geomembrane) to minimize the infiltration into the landfill by maximizing runoff and evaporation. The primary components of the prescriptive cover include a layer of vegetative cover underlain by drainage composite and a 60-mil HDPE geomembrane. Underneath the geomembrane is the low - permeability layer and a foundation layer. The prescriptive final cover overlays an interim native soil typically used to cover the waste on a daily basis (Fig. 2.1). Thickness of each layer varies from one state to another. Native vegetation is applied to the top

Table 2.1 Prescribed Regulatory Landfill Cover Designs (After SAIC, 2000).

Category	Existing Liner	Cover Requirement
A	No Liner	6 in. erosion layer, 18 in. barrier layer with K_{sat} <10^{-5} cm/s or Ksat of underlying soils, whichever is smaller
B	Soil Liner with K_{sat} < 10^{-6} cm/s	6 in. erosion layer, 18 in. barrier layer with K_{sat} <10^{-6} cm/s
C	Soil Liner with K_{sat} < 10^{-6} cm/s	6 in. erosion layer, 18 in. barrier layer with K_{sat} <10^{-7} cm/s
D	Composite liner (soil overlain by Geomembrane) having a K_{sat} <10^{-7} cm/s	6 in. erosion layer, 18 in. barrier layer with K_{sat} < 10^{-5} cm/s

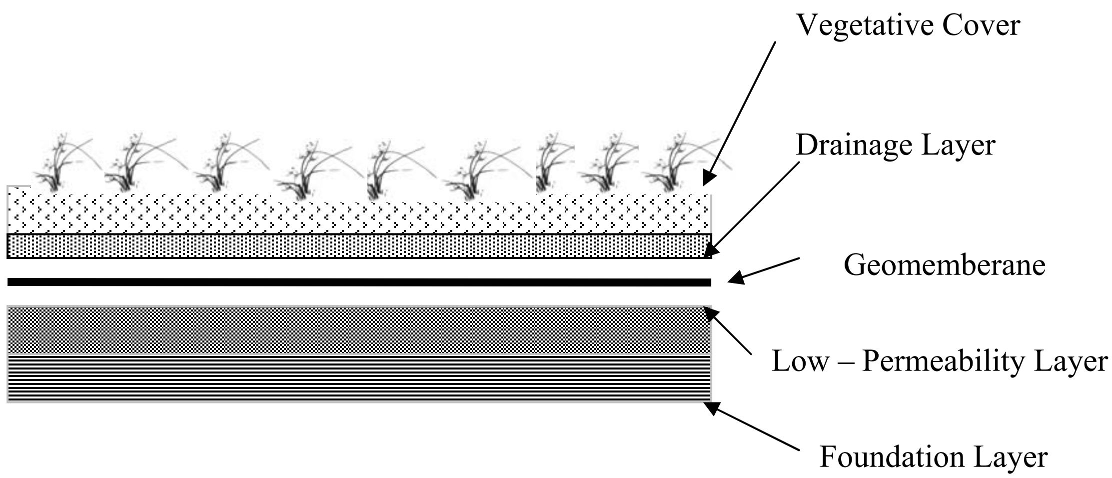

Fig. 2.1 Prescriptive Cover Profile (After SAIC, 2000).

layer for erosion control. Experience has shown that the prescribed clay barrier layers have several disadvantages, such as susceptible to failure caused by desiccation and cracking (Landreth et al., 1991) damage. These types of cover are also expensive to construct and maintain. In addition, the performance of these covers decreases with time and degradation due to erosion.

2.2 Introduction to Evapo – Transpiration (ET) Covers

The environment performance limitations and high cost of prescriptive cover designs and the requirements for long - term protection of human health stimulate the interest in alternative cover designs. In 1998, the USEPA initiated the Alternative Cover Assessment Program (ACAP) to promote innovative alternatives to the conventional landfill final cover designs. An effective alternative cover design is the "evapotranspiration cover" (ET cover) which exploits the water storage capacity of finer - textured soils and the water removal capability of vegetation (Licht, 1993; Wing and Gee, 1994; Benson and Khire, 1995; Stormont and Morris, 1998; Nyhan et. al., 1997; Ward and Gee, 1997; Benson et al., 2001). In ET cover design, the role of vegetation is critical, because root water uptake is the key means in removing water stored in the cover (Benson et. al., 2001). The general profile of ET cover is shown in Fig. 2.2. ET cover consists of a layer of vegetation designed to enhance evapotranspiration during growing season, and a compacted support layer which provides storage during seasons of low evapotranspiration. Underneath the compacted layer is the foundation layer. The ET cover seats on an interim cover layer which is used to cover the waste on the daily basis (SAIC, 2000).

The water balance of ET cover can be represented in Equation (2.1):

$$Pt = P - R - S - T - E - L \qquad (2.1)$$

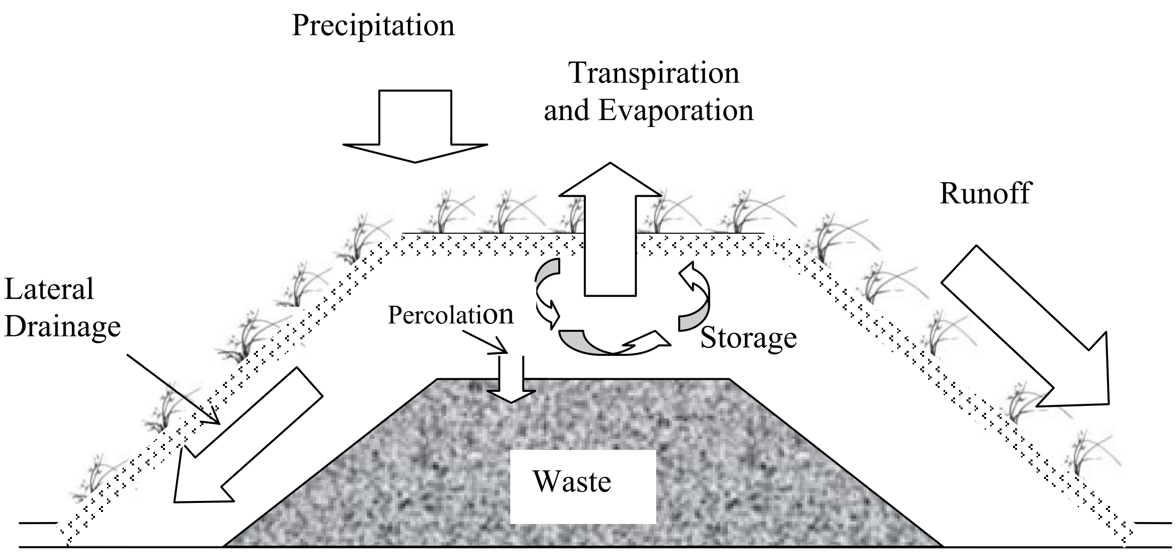

Fig. 2.2 Profile of Evapotranspiration Cover.

where Pt is percolation, P is precipitation, R is runoff, S is storage of fine – texture soil layer, T is transpiration of vegetation, E is evaporation, and L is lateral drainage (Khire 1997; Langoni, 2002). ET covers make use of the water uptake capabilities of vegetation roots, and the storage capacity of fine – texture soils to reduce the amount of percolation into landfill. By maximizing transpiration of vegetation, evaporation, and storage of soils, ET covers reduce the percolation in the water balance equation.

The performance of ET cover designs are determined by: (1) water retention characteristics of soil, (2) meteorological conditions, and 3) type of vegetation. Sufficient storage capacity is required to retain water that accumulates during winter when evapotranspiration is limited, and the storage capacity is a function of the soil texture and thickness. The soil type and thickness is influenced by the meteorological conditions. Vegetation with sufficient rooting depth, root density is also required.

Two basic designs of alternative covers were developed: monolithic covers and capillary barriers. Monolithic covers are composed of only one thick earthen layer of low hydraulic conductivity and high storage capacity, which increase the storage capacity and evaporation of monolithic cover and limit the percolation through the cover. The thickness of the cover is determined by the precipitation and the storage capacity of the soil. Monolithic covers work well when water is readily stored near the surface. Capillary barriers utilize two layer designs, fine grained layer seating above coarse grained layer. The capillary force generated between fine layer and coarse layer prevents water infiltrating into the coarse layer, which forces water to be stored in finer surface layer and thus contributes to higher evaporation.

The design of ET cover possesses theoretical and technical advantages over that of traditional prescribed cover. ET cover is based on the idea of working with nature to create better landfill covers (Benson et. al., 2000). Water accumulating in the fine – grained soil layer is pumped up by vegetation during plant growing season via evapotranspiration. Vegetation improves slope stability for ET covers and slope failure has been a technical problem for prescriptive covers especially in areas of heavy rainfall (Langoni, 2002). While the performance of prescribed covers decreases with time because of the desiccation and erosion, the performance of ET cover improves with time as the root system of vegetation develops vertically and horizontally. Expected life of evapotranspiration covers is thousands of years because they work with nature, while the life of prescribed covers is often uncertain (Langoni, 2002).

ET covers also have remarkable economic advantage over prescribed covers. Prescriptive covers can be costly, and especially if the required low permeability soil materials are not available locally and have to be transported over long distances to the landfill site. The ET covers are built with soils easily acquired locally and $50,000 to $75,000 per acre can be saved when using alternative covers (Benson et. al., 2000).

2.3. Hydraulic Equivalency

The hydraulic performance of ET covers, however, is the most important concern when comparing ET covers and prescriptive covers. Once the feasibility of an alternative earthen final cover is verified in a region, an evaluation of hydraulic equivalency is required for alternative cover to be approved by regulatory authorities. Hydraulic equivalency is generally defined as the situation when the percolation from the bottom of the alternative cover is less than or equal to percolation from the prescribed cover (Benson et. al., 2001). RCRA USEPA final cover regulations permit alternative covers provided the infiltration layer of the alternative cover achieves an equivalent reduction in infiltration as the infiltration layer of the prescribed cover, e.g. hydraulic equivalency. The demonstration of hydraulic equivalency can be conducted by comparing the percolation rate at the bottom of the ET cover to a predefined equivalency criterion for the prescriptive cover, or by comparing between percolation rates for the ET covers and prescriptive covers under identical climate conditions(e.g., SAIC, 2000; Benson, 2000; Benson et. al., 2001).

The percolation rate of a prescriptive cover is generally site specific, and the regulation in Subtitle C and D of RCRA did not set percolation rate criterion for prescriptive covers. To perform the assessment of alternative covers hydraulic equivalency, ACAP provided some guidance on typical equivalent percolation rate evaluations. Benson et al. (2001) provided a summary of the evaluation of those methods: "In lieu of a site – specific equivalency criterion, an alternative cover is equivalent to a soil cover (e.g., a resistive cover design employing compacted clay) if the percolation rate is less than 10mm/yr in semiarid and drier climates or 30 mm/yr in humid climates. For composite prescriptive covers (i.e., resistive cover designs employing a compacted clay layer overlain by a geomembrane), the percolation rate criterion is 3 mm/yr regardless of climate conditions". More stringent criteria have been adopted at other sites (Wing and Gee, 1994; Boehm et al., 1998; Chadwick et al., 1999; Benson et al., 2001).

2.3.1 Indirect Methods of Field Evaluation of Percolation Rate

To demonstrate the hydraulic equivalency of an alternative cover to prescriptive covers, field evaluation is necessary. Several methods (trend analysis, tracer methods, water balance method, Darcy's Law calculation, and lysimetry) have been used to estimate the percolation rate through a soil profile. The following is a brief summary of each method. Trend analysis, water balance method and Darcy's Law calculations are based on the monitoring of the water content profile with depth.

2.3.1.1 Trend Analysis.

Trend analysis assumes that the absence of a trend or variation in water content at depth means no flow is occurring and percolation is not transmitted at that depth. Darcy's law indicated that the flow of liquid water is caused by a gradient in total hydraulic head (comprised of pressure and gravitational heads) rather than a gradient in water content. In addition, water may also flow in the form of vapor as a result of gradients in vapor pressure and temperature (Scanlon and Milly, 1994). So trend analysis is not based on a sound assumption.

Another obvious flaw of trend analysis is that the percolation rate is calculated from water content and pore water pressure data which are collected by using nests of probes. It is assumed that soils are homogeneous and no cracks or holes made by worms or plant roots developing in the soils. Cracks and holes of worms or plant root, however, are common in landfill covers, especially for those several years old. This phenomenon can be illustrated from the water content data collected from a test section constructed by the ACAP research team in Albany Georgia (Fig. 2.3).

Fig 2.3 is a plot of soil water content and total water applied over the period April, 2000 to October, 2002. During the first eight months, the response to the amount of total applied was similar in shallow and deep soil. After January, 2001, the soil water content at depth 48 inches was more sensitive to total water applied than that in shallow soil. It is suggested that water migrated through cracks or holes and reached deep soil and bypassed shallow soils. In addition, water content is also affected by the position of the water content probes with respect to roots.

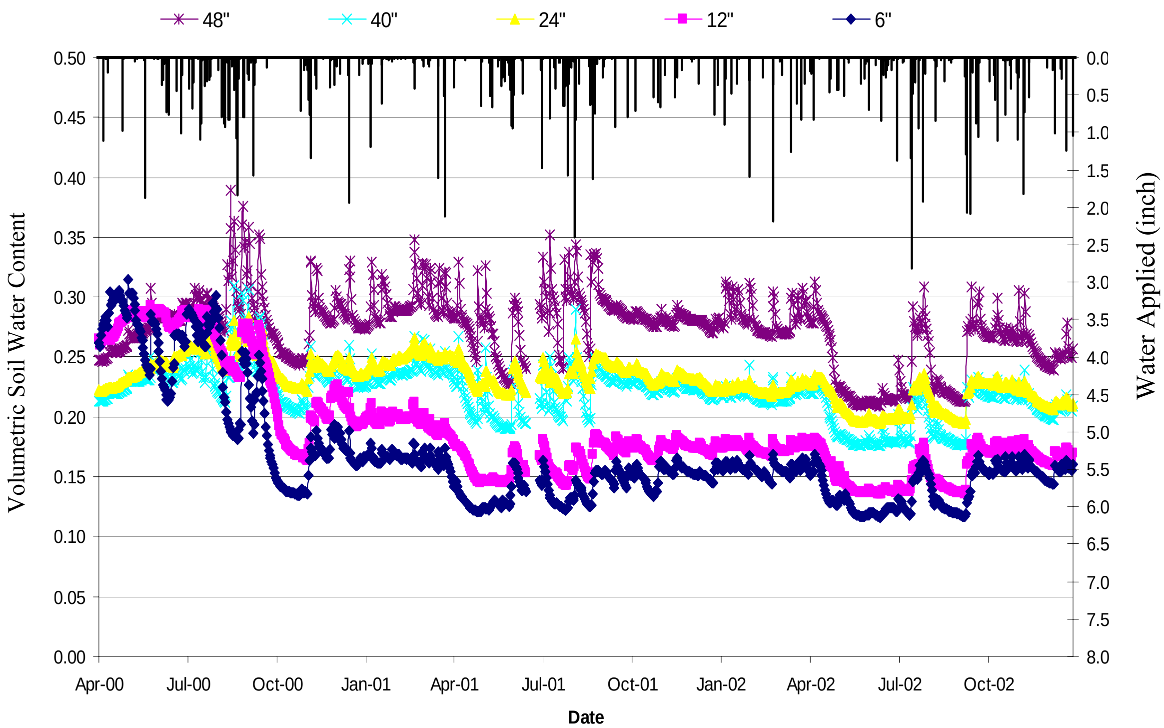

Fig. 2.3 A Plot of Soil Water Content and Total Water Applied in Albany Georgia.

2.3.1.2 Water Balance Method

The water balance method can be expressed in equation (2.2):

$$Pr = P - ET - R - \Delta S \tag{2.2}$$

where Pr is percolation rate, P is precipitation, R is runoff, ET is evapotranspiration, and ΔS is the change in soil water storage during a fixed period of time (Benson et al., 2001). The precision of percolation rate measurement depends on the measurement precision with which all the parameters on the right side of the above equation can be measured.

Precision with which precipitation is measured is influenced by such factors as the method used to make the measurements, the form of precipitation (solid, liquid or gas), the amount of spatial variability existing in the precipitation, and the location of measurements (Smith, 1992; Benson, et. al., 2001). Radiation and high wind velocity are two of the main sources of measurement error. Inadequate wind shielding of rain gauges can also bias the precipitation measurement by 50% or more (Larson and Peck, 1974; Benson, et. al., 2001). With appropriate shielding, up to 30% error still might exist at high wind velocity (> 8m/s). Even under ideal conditions, precipitation measurements have a precision less than 10% (Gee and Hillel, 1988; Benson et. al., 2001).

Measurement of evapotranpiration consists of measuring potential evapotranspiration and actual evapotranspiration. Potential Evapotranspiration (PET) is the amount of water that evaporates from land, water, and plant surfaces if soil water were in unlimited supply. Actual Evapotranspiration (AET) is the amount of water that is actually removed from a surface due to the processes of evaporation and transpiration. It is influenced by climate conditions, water availability, soil characteristics and vegetation conditions. In some portion of the year, AET is less than PET at most sites due to the existence of water stress caused by vegetation root water uptake. PET can be estimated with reasonable accuracy, and AET can be calculated from PET and the ratio of available soil moisture to available water capacity. Errors up to 20% of the estimated AET are common (Gee and Hillel, 1988; Benson, et. al., 2001).

Surface runoff from AEFCs can be measured with a precision of 2 to 3% of precipitation if the catchment being monitored is well defined and the outflow monitoring points are limited (Winter, 1981). Delineation of the catchment area and direct run off for measurement is critical for reasonable definition of the catchment. And it's required that drainage from the catchment not be impeded by the measurement system. If impediments exist, infiltration into the cover will be unrealistically large and runoff will be underestimated.

The best water content measurement devices (those employing nuclear or dielectric techniques) can provide water contents within ± 2% (Topp et al, 1980; Gee and Ward, 1999; Benson et al, 2001). Similarly, the cracks in soil might be a source of error of the measurement. Calibration bias also result in errors in water content on the order of 5% (Benson and Bosscher, 1999; Benson et al., 2001), especially for fine – textured soils often used for earthen covers. Thus, for a 1m thick cover, measured soil water storage can be determined with a precision of 20 mm at best (Benson, et. al., 2001).

The precision with which percolation rate is measured is determined by the measurement precisions of the variables described previously. The reported precision of percolation rate measuring with this method is 100 mm/year in humid area (Abichou, 2003).

2.3.1.3 Darcy's Law Method

If the unsaturated hydraulic properties of the cover soils are known (soil water characteristic curve [SWCC] and hydraulic conductivity), the percolation rate can be calculated with Darcy's law method, which can be expressed as:

$$Pr = K_{\Psi} i \tag{2.3}$$

where Pr is percolation rate, K_{Ψ} is the hydraulic conductivity at suction Ψ and i is the hydraulic gradient (Allison et. al., 1983; Stephens and Knowlton, 1986; Boehm et. al., 1998; Benson et. al., 2001). The value of suctions Ψ can be determined from SWCC provided the corresponding water content data have already been measured in the cover soils. The hydraulic gradient can be calculated from suctions (Ψ) and the elevations at which the water contents are measured. The hydraulic conductivity is estimated from the average suction at the depths where the gradient is calculated and the unsaturated hydraulic conductivity curve.

The water content measurement, as in trend analysis and water balance method, is the most significant potential source of error because of preferential flow through such macroscopic features as cracks, holes made by animals or plant roots or lateral flow due to fine variations in textures or anisotropy in hydraulic properties (McCord and Stephens, 1987; Benson et. al., 2001). In most cases, the probes used to measure water content yield data characteristic of conditions within the soil matrix and not along cracks, fissures, or macropores which are preferential flow paths.

Hysteresis in the SWCC is another source of error (i. e., the suction corresponding to a given water content depends on whether the soil is wetting, drying, or is in transition between wetting and drying). Most calculations made using the Darcy's law method employ a single SWCC (typically a drying curve) and ignore hysteresis. This error can be avoided by monitoring suctions (using devices such as tensiometers, psychrometers, or heat dissipation units) at the same depths at which the water content probes are placed. However, suctions measured with these devices are also subject to error (Benson et al., 2001).

Errors in estimation of K_Ψ also have a significant effect on the precision of percolation rate calculation. K_Ψ is estimated from the saturated hydraulic conductivity (K_{sat}) and the shape of the SWCC using equations based on capillary tube models (e.g., the van Genuchten – Mualem model [van Genuchten 1980]). Capillary tube models provide reasonable estimates of unsaturated hydraulic conductivity for coarse – grained soils, but often underestimate the unsaturated hydraulic conductivity of fine – textured soils such as those used for AEFCs (Fredlund et al., 1994; Meerdink et al., 1995; Chiu and Shackelford, 1998; Benson, et al., 2001). Measurements of the unsaturated hydraulic conductivity can be made to reduce this error, but they are tedious, time consuming, and expensive. These measurements can also be subject to errors as large as those present in capillary tube models (Stephens, 1996; Benson and Gribb, 1997; Benson et al., 2001).

If preferential flow is ignored, the precision with which percolation rate can be measured using Darcy's law method can be estimated. Errors in Ψ due to hysteresis can be as large as an order of magnitude as are errors in K_Ψ. Thus, estimates of percolation rate using the "Darcy's law method" have a precision of one to two orders of magnitude. In addition, spatial variability in the SWCC and K_Ψ may increase the precision by an order of magnitude. This relatively poor precision may be acceptable if the calculated percolation rate is very low (e.g., 0.0001 mm/yr), but is unacceptable if the calculated percolation rate is close to the equivalent percolation rate (Benson et al., 2001).

2.3.1.4 Tracer Method

Tracer method is conducted by spiking soils to be tested with a conservative solute which does not exist in pore water with detectable amount (e.g., bromide or deuterium oxide). The assumption behind tracer method is percolation only occur to the depth at which the tracer can be detected. Soil samples are collected from various depths in tested soils for chemical analysis.

The precision of percolation measured with tracer method is influenced by quite a few factors such as the concentration of the solute when it is spiked into the soils, the amount of uptake of the solute by plant roots, the accuracy of chemical analysis, the amount of water flowing through the cover during the monitoring period, the presence of preferential flow paths, and the quality of the mass balance achieved. Given the number of factors that can affect the precision of testing results, a quantitative assessment of precision is not possible (Benson et al., 2001).

2.3.2 Direct Method of Field Evaluation of Percolation Rate (Lysimeter)

2.3.2.1 Introduction to Lysimeter

Lysimeters are devices used to measure percolation of water infiltrating through soils and to sample soil water for chemical analysis. The main components of lysimetry are the buried containers with open tops which collect and measure soil water. Water infiltrating through soils reaches those buried containers and accumulates, and then is conduced into a measuring facility. There are two types of lysimeters: weighing and volumetric. Volumetric lysimeters are generally employed to monitor the percolation rate of an ET cover. A volumetric lysimeter consists of a pan for collecting water infiltrating through soils monitored, and sidewalls in most cases to prevent water from losing around the bottom pan.

2.3.2.2 Design of Lysimeters

Lysimeter consists mainly of a base pan with or without sidewalls. The pan acts as a collector of percolation. The pans of most lysimeters used to monitor landfill cover sections are rectangular while circle pans are used in some agricultural research. The depth of lysimeter is a critical design parameter and varies with the intended purposes of the tests. Because of the critical role of plants in removing water from landfill cover, the depth, distribution and density of plant roots have to be taken into account in determining depth of a lysimeter under a landfill cover. It was suggested that lysimeter depth should permit the development of normal rooting density and rooting depth and provide similar "available" water profiles to the field profile (Van Bavel, et al., 1961). The areal extent of lysimeters depends on the spatial variability in the properties of cover soils and vegetation. The length and width are usually 5 times larger than depth to ensure that preferential flow processes (e.g., rapid flow in such features as cracks, fissures, root channels, and worm holes) are captured in the test and that the construction process would mimic full – scale conditions (Bews et. al., 1999; Benson et al., 2001).

Some lysimeters have sidewalls along the side of pans while some don't. The sidewalls are used to prevent moisture lateral diversion. The height of sidewalls varies from zero (without sidewalls) to the depth of lysimeter. Flat lysimeters are used on the top of landfill cover while the inclined lysimeters are usually used on the slopes of landfill covers. The lysimeter construction generally employs linear low – density polyethylene a synthetic geomembrane which is highly puncture resistant and readily welded in the field. A geocomposite drainage layer containing nonwoven geotextiles heatbounded to each side of a geonet is placed directly on the geomembrane to function as a drainage layer and as a cushion during placement of soils (Benson et al., 2001).

2.3.2.3 Advantages and Concerns of Lysimeters

The key advantage of lysimetry over the four methods described is section 2.3.1 is its direct measurement of the percolation rate and higher precision. It was shown that percolation rates can be measured with a precision of 0.5 mm/yr or better using lysimeters (Gee and Hillel, 1988; Benson et al., 1994; Ward and Gee, 1997; Benson et al., 2001). The installation of lysimeters measurement system into soil, however, would introduce disturbance on the soils inside as well as outside lysimeters, which is thought to affect the percolation rate through the soil cover, and consequently affect the precision with which percolation rate is measured with lysimeter. The following concerns have been raised about using lysimeters as percolation measuring facility:

(1) Lateral diversion can be one of the primary sources of error with lysimetry if the areal extent of the lysimeter is insufficient and the lysimeter does not have vertical sidewalls. Lysimeters that are too small and collect too little water underestimate the percolation rate (Benson et al., 2001).

(2) Most lysimeters also include an earthen or geosynthetic drainage layer directly on top of the lower boundary for directing percolation to a measuring point. The larger pores associated with drainage layers induce a capillary break at the base of the cover profile that might not exist under natural conditions (Khire et al. 1997). As a result, an artificial increase in the storage

capacity of the cover profile may be incurred relative to natural conditions, as well as a possible reduction in percolation rate (Benson et al., 2001).

(3) The artificial no-flow boundary induced by the lysimeter at the base of the profile. This boundary, which does not exist in the actual field setting, prevents upward and downward flow of vapor and liquid and heat flux across the base of the lysimeter. In effect, the lysimeter acts as a rectifier. All water that migrates downward to the base of the profile is collected and routed out of the system. Consequently, the collected water can never move upward as a result of natural upward gradients induced by evapotranspiration. And moisture under the lysimeter could not be moved up either. Heat flux, an important parameter in soil moisture migration, is also intercepted by the insertion of the base of lysimeter (Benson et al., 2001). The other problem is disturbance of void space connection between soil under and above the lysimeter base, which might pose some problems on the measurement precision of lysimeter (Grebet and Cuenca, 1991).

(4) For the lysimeters with side walls, the side walls intercept the lateral flow of water and heat flux inside as well as outside lysimeters while bottom restricts vertical water movement, the phenomenon is more obvious on the slope of landfill cover. As a result, vertical flow is increased at the interface between the soil and the lysimeter side walls. The magnitude of this boundary effect is a function of the soil type and texture and the geometry of the side walls (Grebet and Cuenca, 1991). The side walls may also interrupt the development of vegetation roots which uptake water out of soil.

CHAPTER THREE
MATERIALS AND METHODS

The objectives of this study were to investigate performance of lysimeters in measuring percolations and to develop optimal lysimetry designs for ET covers. A numerical model, HYDRUS-2D, which can accurately simulate water balance through soils under variably saturated conditions, was used to assess the performance of lysimeters. HYDRUS-2D is one of the models developed for water balance simulation in variably saturated soils, and it can simulate flow in response to meteorological forcing and plant root water uptake. It is fairly well documented, has been widely used and tested, and it is in public domain (Scanlon.et. al., 2002). The following sections describe the HYDRUS-2D code.

3.1 HYDRUS-2D

3.1.1 HYDRUS-2D (version 1.0) Code Description

HYDRUS-2D was developed by J. Simunek, M. Sejna, and M. Th. Van Genuchten in 1996. It is a computer program used for analysis of water flow and solute transport in variably saturated porous media. Two forms of HYDRUS-2D are available:

Option A includes the HYDRUS-2D executable code and a graphics – based user interface. A mesh generator is available for a relatively simple rectangle domain geometry in this version. Users can either create the input files describing the domain geometry and associated finite element mesh by themselves or use the internal mesh generator to make a simple rectangular structured transport domain.

Option B consists of version A and a CAD program MESHGEN2D for designing a more general domain geometry, and its discretization into an unstructured finite element mesh for a variety of problems involving variably – saturated subsurface flow and transport. Version B is used in this study.

HYDRUS-2D is derived from the variably flow codes SWMS-2D of Simunek et al. (1992) and CHAIN-2D of Simunek and van Gneuchten (1994). A complete HYDRUS-2D package consists of seven main modules: HYDRUS2D, PROJECT MANAGER, MESHGEN2D, H2D_BERC (boundary), H2D_CALC (HYDRUS2), H2D_CLCI (HYDRUS2) and H2D_GRAF (Graphics).

HYDRUS2D is the main program which controls execution of the program and determines which other modules need to be run for a particular simulation. HYDRUS2D contains a project manager and both the pre-processing and post – processing units.

MESHGEN2D is a mesh generator for unstructured finite element grids. This program, based on Delaunay triangulation, is seamlessly integrated in the HYDRUS-2D environment. MESHGEN2D is used to define virtually any two – dimensional geometric transport domain and subsequently to design a finite element discretization for that domain.

BOUNDAY module helps user to specify boundary and initial conditions for both water flow and solute transport, and define the spatial distribution of other parameters characterizing the flow domain (e.g., spatial distribution of soil materials, hydraulic scaling factors, root – water uptake parameters, and possible hydraulic anisotropy) and/or observation nodes. Three types of boundary conditions are possible with Richards' equation – based models: Dirichlet is prescribed head, Cauchy is prescribed flux, and Neumann is a prescribed hydraulic gradient. All the three types can be used in HYDRUS-2D. Nine options are available in HYDRUS-2D to specify boundary condition (BC): no flux, constant pressure, constant flux, variable pressure, variable flux, free drainage, seepage face, and atmospheric. Free drainage BC is a Neumann – type, in which a unit vertical hydraulic gradient is imposed at the boundary. The atmospheric BC is a Cauchy type BC, in which the precipitation, potential evaporation, and potential transpiration rates must be specified. In the landfill cover simulations, free drainage BC is recommended for the bottom BC, seepage face BC is selected when drainage layer is installed above lysimeter bottom pan. Atmospheric boundary condition is for the surface condition, although one may wish to specify the infiltration rate as a constant or variable flux BC when testing landfill cover performance for an individual precipitation event. HYDRUS-2D cannot simulate erosion.

HYDRUS2 (H2D_CALC, H2D_CLCI) implements the primary data analysis and calculations for HYDRUS-2D. The HYDRUS2 program is a finite element model for simulating movement of water, heat, and multiple solutes in variably saturated media. The program numerically solves the Richards' equation for saturated-unsaturated water flow and the Fickian-based advection-dispersion equations for heat and solute transport. The governing flow equation was modified from Richard's equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x_i}\left[K(K_{ij}{}^{A}\frac{\partial h}{\partial x_j} + K_{iz}{}^{A}) \right] - S \tag{3.1}$$

where θ is volumetric water content [L^3L^{-3}], h is pressure head [L], x_i are the spatial coordinates [L], t is time [T], K_{ij}^A are components of a dimensionless anisotropy tensor K^A, K is unsaturated hydraulic conductivity function [L/T^{-1}] given by:

$$K(h,x,z) = Ks(x,z)Kr(h,x,z) \tag{3.2}$$

s is the sink term to account for water uptake by plant roots. It is defined as

$$S(h) = a(h)(LsTp)/(LxLz) \tag{3.3}$$

where, a(h) is the plant water stress function, Tp is the potential transpiration rate, Ls is the width of the surface, Lx is the width of the root zone, and Lz is the depth of the root zone.

A Galerkin type linear finite element method was used to solve the governing equations. An implicit (backwards) finite difference scheme is used to achieve integration in time for both saturated and unsaturated conditions. The resulting equations are solved in an iterative fashion, by linearization and subsequent Gaussian elimination for banded matrices, a conjugate gradient method for symmetric matrices, or the ORTHOMIN method for asymmetric matrices. Additional measures are taken to improve solution efficiency in transient problems, including automatic time step adjustment and checking if the Courant and Peclet numbers do not exceed preset levels. The mass-conservative method proposed by Celia et al. (1990) is used to evaluate the water content term. Upstream weighting is included as an option for solving the transport equation to minimize numerical oscillations.

The ability of HYDRUS-2D to converge to a stable solution depends upon the discretization and temporal iteration schemes. The finite element mesh was recommended by Simunek et al. (1996) to be constructed with close nodal spacing where the hydraulic gradient is expected to be large, such as the soil surface for atmospheric BCs, and near internal source/sinks like tile drains. A closely spaced mesh is particularly needed for coarse-textured soil with high n-values and small alpha values. This principle is also true for layer interfaces where hydraulic properties change sharply and further applies to the time iteration criteria for minimum time steps.

The unsaturated soil hydraulic properties are defined by a set of closed-form equations resembling the 1980 van Genuchten equations. To improve the description of hydraulic properties near saturation, certain modifications were made. This improvement included the incorporation of the ability to prescribe an air-entry pressure head, ha, and a pressure head, h_k, for matching the relative hydraulic conductivity function to a measured value below saturation, K_k, such that:

$$\theta(h) = \theta_r + \frac{\theta_m - \theta_r}{\left[1 + (\alpha h)^n\right]^m} \qquad \text{for } h < h_s \qquad (3.4)$$

$$\theta(h) = \theta_s \qquad \text{for } h \geq h_s \qquad (3.5)$$

and

$$K(h) = K_s K_r(h) \qquad \text{for } h < h_k \qquad (3.6)$$

$$K(h) = K_r + (K_S - K_k)\left[\frac{(h - h_k)}{(h_s - h_k)}\right] \qquad \text{for } h_k < h < h_s \qquad (3.7)$$

$$K(h) = K_s \qquad \text{for } h \geq h_s \qquad (3.8)$$

The effect of the prescribed heads, h_k and h_s, allows the use of a field-saturated water content (θ_s in Eq. 19), which is commonly found to be 10-15% lower than the laboratory measured saturated water content (θ_m in Eq. 18). It further provides a means of incorporating the effect of macropore flow on the hydraulic properties by making K(h) a two-region function (Wilson et al., 1992; Mohanty et al., 1997), whereby K_s represents the hydraulic conductivity when all pores are contributing and K_k is the hydraulic conductivity after the macropores empty.

GRAPHICS manages the geographical, hydrogeologic and physical inputs required to run HYDRUS2D and present results of a simulation by means of contour maps, isolines, spectral maps, and velocity vectors, and /or by animation using both contour and spectral maps. Output graphics include 2D contours (isolines or color spectra) in areal or cross-sectional view for heads, water contents, velocities, and concentrations. Areas of interest can be zoomed into, and vertical scale can be enlarged for cross-sectional views. The mesh can be displayed with boundaries, and numbering of triangles, edges and points. Observation points can be added anywhere in the grid. Viewing of grid and/or spatially distributed results (pressure head, water content, velocity, or concentration) is facilitated using high resolution color or gray scales.

HYDRUS – 2D can handle flow regions delineated by irregular boundaries. The flow region itself may be composed of nonuniform soils with an arbitrary degree of local anisotropy. Flow and transport can occur in the vertical plane, the horizontal plane, or in a three dimensional region exhibiting radial symmetry about the vertical axis.

HYDRUS - 2D also implements a scaling procedure to approximate hydraulic variability in a given soil profile by means of a set of linear scaling transformations which relate the individual soil hydraulic characteristics to those of a reference soil. A small catalog of soil hydraulic properties is included in the program. While the soil property catalog was derived from Carsel and Parrish (1988), it should be used with care, as some of the key parameters do not appear to be realistic.

3.1.2 Verification

Verification of the HYDRUS-2D code was accomplished by the developers by comparing simulations with both the UNSAT2 (Neuman, 1973) and SWATRE (Belmans et al., 1983) codes. The transport portion of HYDRUS-2D was verified by comparison with an analytical solution for a two-dimensional steady-state groundwater flow problem (Simunek et al., 1996). The comparison with UNSAT2 was made for a one-dimensional infiltration experiment modeled by UNSAT2 (Davis and Neuman, 1983). A homogenous soil column at an initial pressure head of -150 cm was subjected to ponded infiltration at the surface (a constant head BC). The open bottom boundary was modeled as seepage face BC, and the column sides as no flux BC. Good agreement between UNSAT2 and HYDRUS-2D was observed to demonstrate verification. A more rigorous verification test was made by comparing HYDRUS-2D to SWATRE (Feddes et al., 1978) results for a one-dimensional field profile. The soil profile consisted of two layers with a 30-cm thick root zone. Actual precipitation and potential transpiration rates were used for the atmospheric BC at the surface. The bottom BC was a deep drainage BC with the groundwater level set to 55 cm below the surface and the initial condition was taken to be in equilibrium with the groundwater level. Pressure heads, transpiration rates, and bottom discharge rates showed excellent agreement with SWATRE results to show verification. Gribb and Sewell (1998) further verified the parent code (SWMS_2D) by making comparisons to a general purpose partial differential equation solver, PDE2D. They found that water volumes in the flow domain were consistent for the four scenarios tested.

3.1.3 Validation

Pohll et al. (1996) coupled SWMS_2D with an overland flow model to simulate recharge below nuclear subsidence craters. They calibrated the overland flow model by adjusting the catchment area to match field measurements of run-on into the crater and calibrated the crater topography to match the measured pond depths in the crater. Since only the boundary condition on the subsurface flow model was calibrated, comparisons of the simulated to measured moisture profiles serve as a validation test for HYDRUS-2D. They found that the simulated water contents were slightly lower (4%) than measured values and with considerably less variability. They considered the model to be in good agreement with measurements given the apparent vertical heterogeneity of the single vertical profile within a three-dimensional flow field and the approach of simulating the profile as homogenous.

Although water balance models are not able to fully investigate the hydrology of capillary barriers, a Richards' equation-based model can be utilized. Kampf et al. (1998) used HYDRUS-2D to simulate the capillary barrier system of an engineered landfill cover. They investigated the process known as capillary diversion, or the breakthrough point of a capillary barrier where the downward vertical flow through the capillary layer equals the infiltration rate, q, from the top of the cover. The field measurements of two landfill facilities in Germany were used to compare the simulation results of the HYDRUS-2D model. The HYDRUS-2D model was calibrated using a number of flumes prior to the larger, field-scale experiment. The authors determined that the HYDRUS-2D model could effectively model capillary barriers with fair precision, as long as the model hydraulic parameters are calibrated to the specific site. The authors stress that soil properties taken from cores alone may not be sufficient to accurately characterize the performance of a capillary barrier at a site.

3.1.4 Sensitivity Analysis

Nofziger et al. (1994) performed sensitivity analyses on four widely used vadose zone transport models (RITZ, VIP, CMLS, and HYDRUS) to compare their behavior. HYDRUS is a predecessor of HYDRUS-2D and should behave similarly, since they are both founded upon the SWMS code. Nofziger et al. (1994) stated that of these four models, the HYDRUS model is most suited for detailed use by research scientists. The sensitivity analysis found that the HYDRUS model was particularly sensitive with respect to the amount of pollutant leached, to the partition coefficient, saturated water content, and the van Genuchten n parameters. For travel time, the model was especially sensitive to the van Genuchten n parameters, saturated water content, partition coefficient, root water uptake potential, and bulk density. For the pulse width, the model was sensitive to the van Genuchten n coefficient, bulk density, saturated water content, and dispersivity. All three of these processes were insensitive to the residual water content and diffusion coefficient. Sensitivity of the flow predictions was not addressed.

3.1.5 Application

HYDRUS-2D and its parent code, SWMS_2D, have been used for a wide range of applications and conditions. Several studies have used HYDRUS-2D to estimate soil hydraulic parameters from multi-step extraction technique (Inoue et al., 1998), transient flow (Simunek et al., 1998), cone penetrometer data (Kodesova et al., 1998), and disc infiltrometer data (Simunek et al., 1998). Mohanty et al. (1998) used HYDRUS-2D to simulate preferential flow and transport of nitrate to tile drains. Davis et al. (1997) coupled SWMS_2D with MODFLOW and MT3D for risk-based remediation modeling of contaminated sites.

HYDRUS-2D has been used for risk analysis (Abbaspour et al., 1997) of landfill covers and performance evaluation of landfill covers (Wilson et al., 1998). Abbaspour et al. (1997) included parameter uncertainty in the risk assessment of a landfill in Switzerland using SWMS_2D to analyze two-dimensional flow and transport. Wilson et al. (1998) used HYDRUS-2D to compare the performance of a monolayer to a subtle-layered ET cover design with regard to the ability of layering to disrupt preferential flow paths. They ran compaction tests on various particle-size fractions of material from the borrow source for a low-level waste repository at the

Nevada test Site. They determined the saturated hydraulic conductivity, and water retention characteristics on each size fraction compacted to 83% and 90% maximum dry density. These data were incorporated into HYDRUS-2D to simulate infiltration for a 100-yr, 6-hour storm event for various cover designs. They simulated preferential flow fingering by assigning a K_s value in a vertical path of nodes that constituted 5% of the cross-sectional area to be four orders of magnitude higher than the remaining nodes. The location of the 5 percent cross-sectional area preferential flow finger was randomly selected for each layer. Based upon the HYDRUS-2D preferential flow analysis, they found that the monolayer cover would need to be 26 percent thicker on average to limit infiltration for the single storm event. However, if subtle layering was incorporated into the cover, the thickness could be reduced by 20 to 60% depending upon the number of layers and their arrangement.

3.2 Simulations

In this study, HYDRUS 2D was used to simulate water balance across lysimeters with varying geometries. The lysimeter geometry was varied based on the sizes of bottom pan, heights of sidewalls, and slope of the bottom pan. The geometry of the simulation domain is defined by entering the X-Y coordinates of each corner of the geometry, generated using the Geometry Generator Module already included in HYDRUS-2D. Fig. 3.1 shows a cross section of an example of simulation domain generated during this study. Once the domain geometry is defined, a finite element mesh is generated. The mesh was refined in all corners of the geometry to minimize the mass balance error. Fig.3.2 shows the same simulation domain after mesh generation.

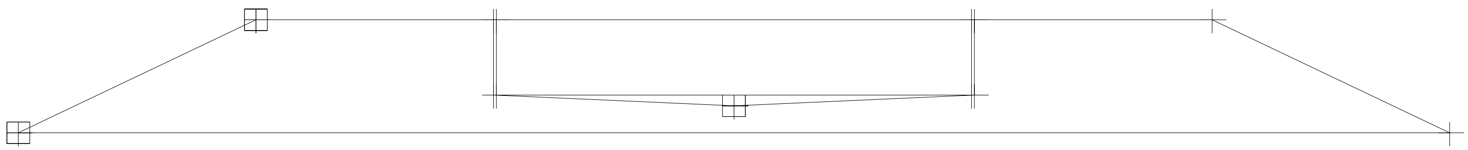

Fig. 3.1 A Cross Section of a Simulation Domain Generated During This Study.

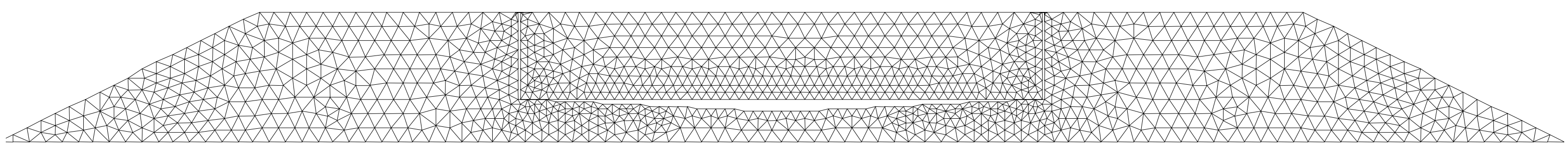

Fig 3.2 Mesh generated by HYDRUS 2D.

The simulations consisted of evaluating water balance across a soil profile that is 1.0 m thick. The top 0.75 m of the soil profile was assumed to be vegetated with grass and the root density was set to be 0.2. The bottom 0.25 m was assumed to have no roots. Daily precipitation, evapotranspiration, and transpiration data obtained from the Albany, GA ACAP site were used as the climatic input for the upper boundary conditions used at the soil surface. Three types of soils were simulated as landfill cover building materials, and those soils were loam, silt and clay loam. The water retention parameters and saturated hydraulic conductivity were defined in HYDRUS-2D. All simulations were performed for 730 days with the climatic data.

The bottom boundary of lysimeters typically consists of a layer of geocomposite overlaying a geomembrane. This layer is used to facilitate drainage and was simulated with Seepage Face boundary condition. Seepage Face boundary condition simulates the case when percolation occurs only after the boundary is saturated. Initial water contents across the profile were simulated to vary from 0.35 at the top of soil profile to 0.15 at the bottom of the soil profile. The same input was kept constant for all the simulations during the entire study.

3.2.1 Full Scale Landfill Covers

The main objective of using lysimeter is to measure the percolation through soil cover designs. As described in Section 2, several methods have been proposed to assess the performance of ET cover designs. Only lysimeters offer the opportunity to directly measure the percolation through the soil cover. However this requires the use of a pan and drainage collection layer at the bottom of the soil layer. This layer does not exist in the full-scale cover on top of a landfill, but is necessary for directly measuring the percolation through the cover soil. Another concern is the lateral diversion surrounding the bottom pan of lysimeters which might cause the underestimation of cover percolation rate. Sidewalls were constructed to improve the situation in some cases, the construction of sidewalls, however is expensive, and its efficiency has not be quantified. Critics of the lysimeter technique argue that the flow of water in a lysimeter may be different from that in the full-scale cover, and therefore, the measurement result may be different from the real percolation rate.

In order to investigate the effects of the presence of the bottom pan, simulations were first performed to simulate the full scale cover without lysimeter at the bottom. The flow domain of a full scale cover was simulated with a soil profile with a width of 50 m. Loam, silt and clay loam were simulated separately as cover building materials. The Free Drainage boundary condition was set as the cover bottom boundary. Free Drainage boundary condition simulates the case when water can drain out of the boundary as it reaches the boundary. Fig.3.3 shows a diagram of an example simulating full scale cover cross section. Results from these simulations were considered to represent the water balance which is likely to exist in the full scale cover under natural state. The results obtained from those simulations are referred to as the Full Size Cover. Criteria unit cumulative fluxes were obtained by dividing the values of cumulative flux from those simulations by the width of the cover, which is 50 m, and were used to evaluate the performance of lysimeters simulated in this study. These simulations provide criteria for evaluating the performance of lysimeters.

3.2.2 Effects of Lysimeter Geometry

Lateral diversion is thought to be one of the primary sources of error in percolation rate measurement using lysimeters. To investigate the existence of lateral diversion and its influence on the precision of percolation measurement as the lysimeter size increases, simulations of lysimeters without sidewalls were conducted. The size of lysimeters was varied from 5 m to 7

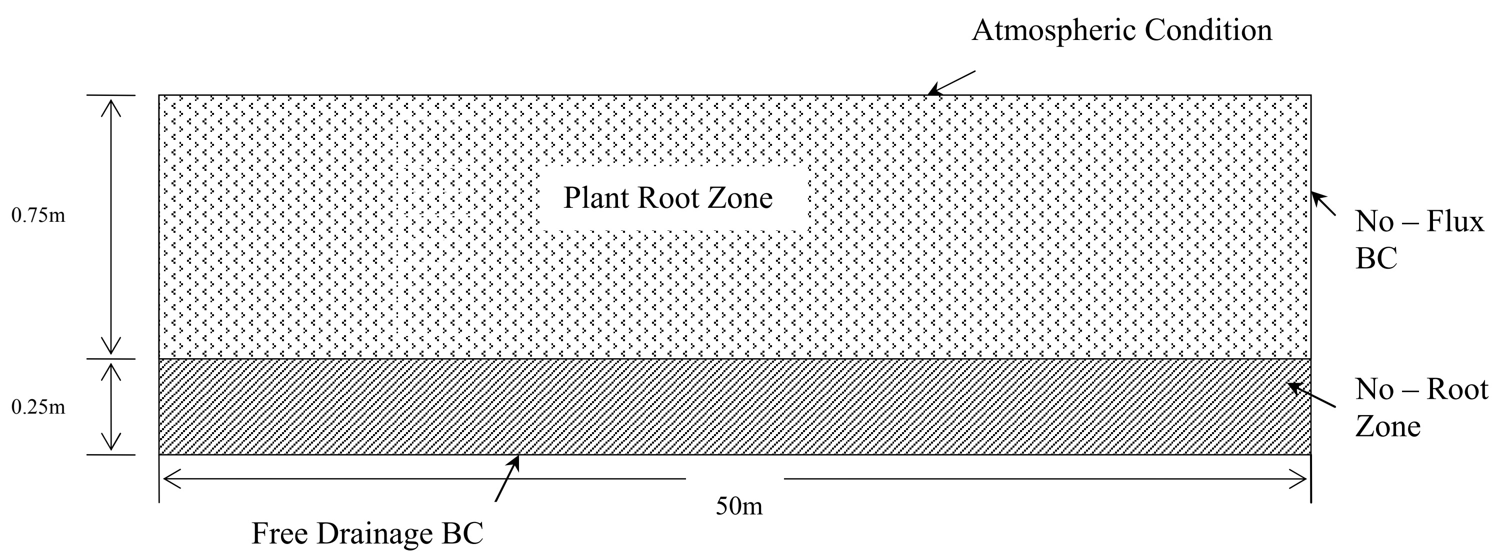

Fig. 3.3 Sketch of Simulation With Full Scale Cover.

m and 10 m. No lysimeter pan with a larger width was simulated because it was assumed that lysimeters with more than 10 m wide pan are not economical and are not likely to be constructed. Fig.3.4 shows a schematic of lysimeter without sidewalls. Since HYDRUS2D is two-dimensional, simulations are a cross section of the lysimeter.

Sidewalls were suggested for lysimeters to prevent lateral diversion. To address the effect of sidewalls on the lysimeter performance, a series of simulations were conducted. For each lysimeter size (5 m, to 7 m and 10 m) a sidewall was added. The height of sidewalls was varied from 25 cm, 50 cm, and 100 cm. The boundary condition of sidewalls was simulated as No Flow boundary. Fig.3.5 shows a profile of lysimeter with sidewalls.

To assess the performance of an ET cover on slopes, lysimeters are typically constructed on slopes. Simulations with inclined lysimeter cross sections were performed. The slope of landfill covers is one of the factors controlling the ratio of infiltration to runoff for a given precipitation. To investigate the effects of slope on percolation rate, simulations with sloped landfill covers and sloped lysimeters with the same gradients were performed. The slopes were varied from 1:3, 1:4, and 1:5. Only the 10 m wide lysimeter was used. The heights of sidewalls were 25 cm, 50 cm, and 100 cm. Fig. 3.6 shows a schematic of these simulations.

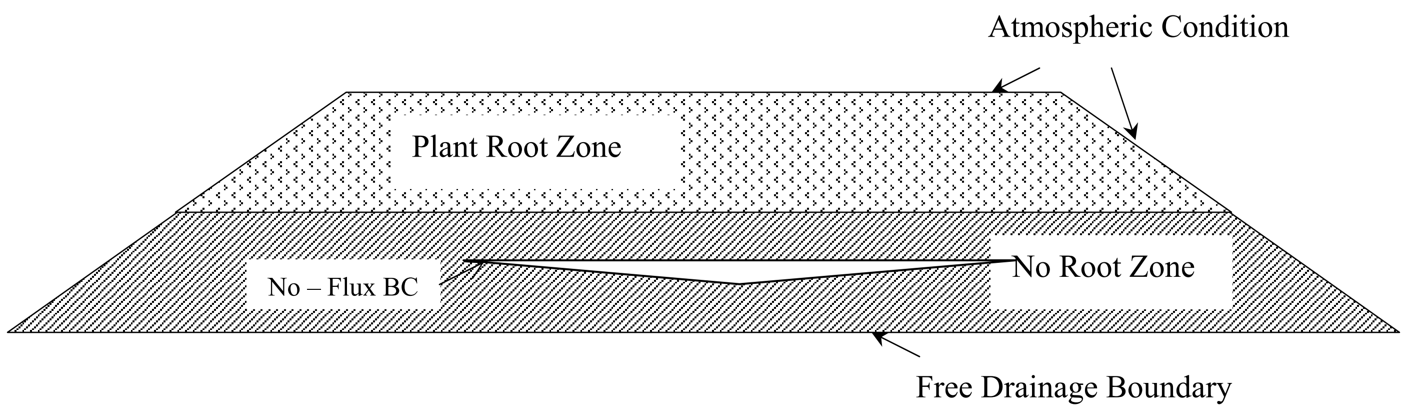

Fig.3.4 Profile of Lysimeter Without Sidewalls. The Upper Boundary of Lysimeter is Seepage Face Boundary Condition

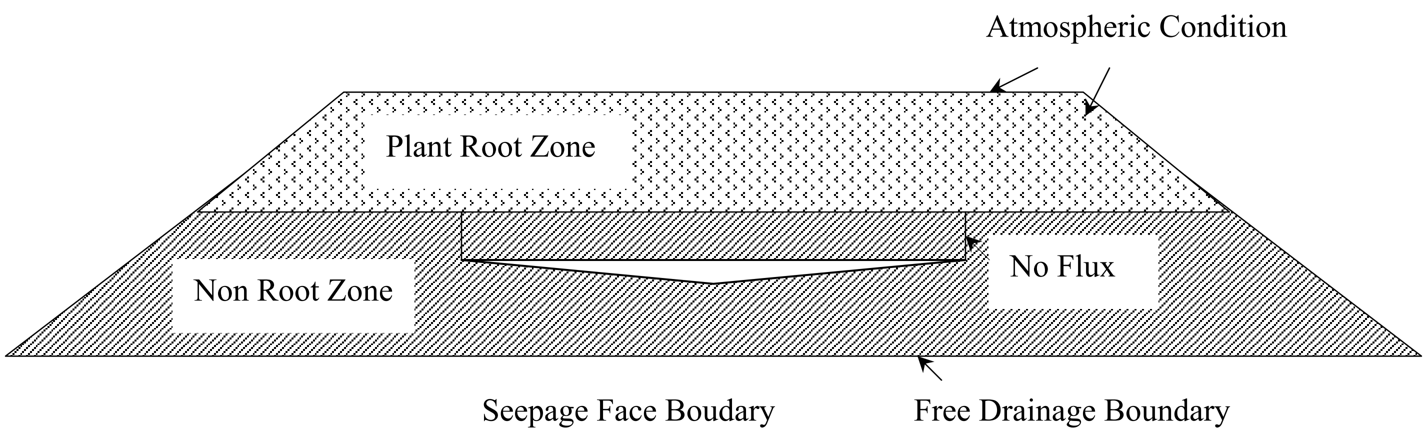

Fig. 3.5 Profile of Lysimeter With Short Sidewalls.

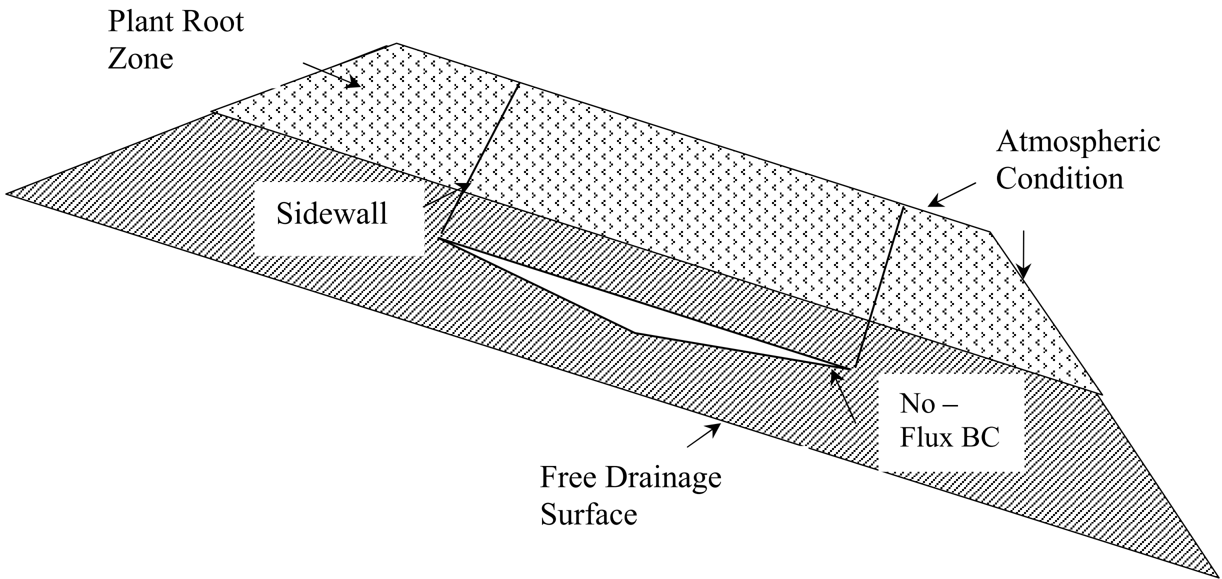

Fig. 3.6 Profile of Inclined Lysimeter. The Upper Boundary of Lysimeter is Seepage Face Boundary Condition.

CHAPTER FOUR

RESULTS AND ANALYSIS

All the simulations performed during this study are listed in Table 4.1. Baseline cover simulations were performed with Free Drainage boundary condition to approximate the natural situation. The bottom boundary of lysimeters was simulated with Seepage Face condition to approximate the drainage layer right above the lysimeter bottom pan. This layer typically consists of a geo-composite (Geonet – Geotextile) layer. The sizes of simulated lysimeters were 5 m, 7 m, and 10 m. The heights of sidewalls simulated were 25 cm, 50 cm, and 100 cm. The slopes of the inclined lysimeters were 1:3, 1:4 to 1:5. The soils in the simulated lysimeters were loam, silt and clay loams. The hydraulic properties of these soils are shown in Table 4.2, in which the θ_r is residual soil water content [L^3L^{-3}], θ_s is saturated soil water content [L^3L^{-3}], α is coefficient in the soil water retention function [L^{-1}], n is exponent in the soil water retention function, Ks is saturated soil conductivity. The values in Tab. 4.2 were default values in HYDRUS 2D. The data such as weather condition, soil thickness, soil hydraulic properties, vegetation distribution and depth were kept the same for each simulation.

4.1 BaseLine Cover Simulations

Lysimeters are used to assess the performance of the actual cover in the field. In order to study the performance of any lysimeter design, a baseline performance is needed, i.e., the percolation rate from any lysimeter design should be evaluated against the percolation rate from

Table 4.1 Simulations of Lysimeters in This Study.

Boundary	Condition	Size of Cover or Lysimeters(m)	Soil Type	Height of Sidewalls(cm)	Slope of Covers
BaseLine	Free Drainage	50	loam	N/A	0, 1:3, 1:4, 1:5
Full Scale		50	silt	N/A	0, 1:3, 1:4, 1:5
Cover		50	clay loam	N/A	0, 1:3, 1:4, 1:5
Lysimeter	Seepage Face	10 (large)	loam, silt, clay loam	0	0, 1:3, 1:4, 1:5
				25	0, 1:3, 1:4, 1:5
				50	0, 1:3, 1:4, 1:5
				100	0, 1:3, 1:4, 1:5
		7 (medium)	loam, silt, clay loam	0	0, 1:3, 1:4, 1:5
				25	0, 1:3, 1:4, 1:5
				50	0, 1:3, 1:4, 1:5
				100	0, 1:3, 1:4, 1:5
		5 (small)	loam, silt, clay loam	0	0, 1:3, 1:4, 1:5
				25	0, 1:3, 1:4, 1:5
				50	0, 1:3, 1:4, 1:5
				100	0, 1:3, 1:4, 1:5

Table 4.2 The Hydraulic Properties of Loam, Silt and Clay Loam.

	$\theta_r(cm^3 cm^{-3})$	$\theta_s(cm^3 cm^{-3})$	$Alpha(cm^{-1})$	n	Ks (cm/sec)
Loam	0.078	0.43	0.036	1.56	2.87×10^{-4}
Silt	0.034	0.46	0.016	1.37	6.9×10^{-5}
Clay Loam	0.095	0.41	0.019	1.31	7.15×10^{-5}

actual cover. To obtain a percolation rate through an actual cover, baseline cover simulations were performed to obtain such a criterion. The criterion was developed by performing simulations on full scale landfill covers and studying the cumulative flux through the lower boundary of the covers. The width of the full scale covers was 50 m. Boundary conditions used for these simulations were Free Drainage, which allowed moisture to seep through once it reaches the boundary. All other inputs (soil thickness, root distribution, and initial soil water content) were constant. A unit percolation rate was calculated by dividing cumulative flux by the size of lysimeter in each simulation and is referred to from hereon as the Baseline Unit Cumulative Flux.

Baseline simulation was performed with three types of soils. These soils are loam, silt, and clay loam, all of which have low plasticity and are less susceptible to desiccation cracking during and after installation (Jorge G., et. al, 2003). The unit cumulative fluxes across the bottom of the full scale flat loam, silt and clay loam covers are presented in Fig 4.1. The unit cumulative flux is 144.4 cm across the cover with loam, 128.2 cm across the cover with silt loam, and 133.6 cm for the clay loam cover.

Fig 4.1 also shows the unit cumulative flux across sloped covers with Free Drainage boundary condition. The slopes of the inclined covers were 1:3, 1:4, and 1:5. Loam, silt and clay loam were input as soil types in all the three inclined covers. When cover was simulated with loam, the unit cumulative flux was 145.6 cm for slopes 1:3, 1:4, and it was 147 cm for slope 1:5. The unit cumulative flux across the inclined silt covers was 132.2 cm for slope 1:3, 126.8 cm for slope 1:4, and 134.4 cm for slope 1:5. The unit cumulative flux across the inclined clay loam covers was 123.4 cm for slope 1:3, 128.8 for slope 1:4, and 129.8 cm for slope 1:5 while the value was 133.6 cm across the flat clay loam cover. Less percolation was observed through the

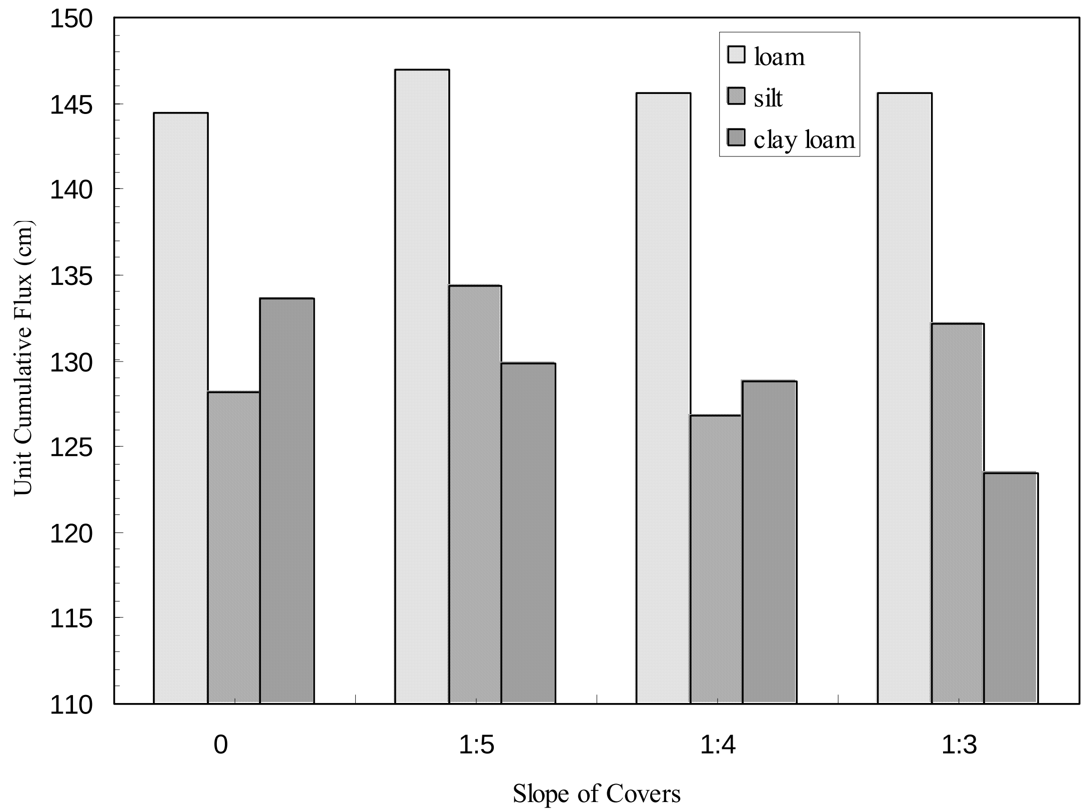

Fig 4.1 BaseLine Unit Cumulative Flux of Full Scale Covers
After Two Years Simulations.

inclined clay loam covers than the flat covers simulated of clay loam. The unit cumulative fluxes through those covers were used as the criterion to evaluate the accuracy of lysimeters of various geometries.

In the covers with loam, the change of slopes has little effect on the percolation rate across the cover bottom. For the clay loam covers, the percolation rates decreased as the slopes became steeper. The difference of unit cumulative flux between flat clay loam cover and inclined cover with 1:3 slope is 10.2 cm after two years simulation. In the covers simulated with silt, the percolation rate across 1:3 cover and 1:5 cover is higher than that of flat cover, and percolation rate from 1:4 cover is lower than that of flat cover.

4.2 Simulations with Flat Lysimeters

4.2.1 The Effect of Size on the Performance of Flat Lysimeters

It was suggested that lysimeters that are too small or narrow collect too little water and thus underestimate the percolation rate, therefore, to ensure that preferential flow processes (e.g., rapid flow in such features as cracks, fissures, root channels, and worm holes) are captured, the size of lysimeters is five times larger than depth (Chiu and Shackelford , 1994, 2000). The effect of size on actual percolation rate was never examined. In order to investigate the effect of size on the performance of lysimeters, simulations were performed using three lysimeter sizes. The thickness of the cover in all the simulation was 1 m, and the size of lysimeters simulated in this study varied from 5 m, to 7 m and 10 m, all of which are greater than five times of the cover thickness. The drainage layer installed above most lysimeters bottom pans was simulated with the Seepage Face boundary condition, which allows moisture to seep down only once the soils at the boundary are saturated. Theses lysimeters did not have vertical sidewalls.

The ratios of unit cumulative fluxes across lysimeters to the BaseLine Unit Cumulative Fluxes are shown in Fig. 4.2.

The performance ratios of lysimeters increase as the size of lysimeters increases. The ratios in loam covers were 49%, 58.37% and 66.16% when the lysimeter sizes were 5 m, 7 m, and 10 m, respectively. The difference between the ratios of large lysimeter (10 m) and the small lysimeter (5 m) was 16.24%. The Performance ratios in clay loam covers were 68.7 % for small lysimeter (5 m), 64.15 % for the medium lysimeter (7 m), and 74.4 % for the large lysimeter (10 m). The difference between ratios of large and small lysimeters was 5.7%. In the silt covers, the performance ratios were 65.8 %, 70 %, and 76 % for small lysimeter, medium lysimeter and large lysimeter, respectively.

While the performance of lysimeter improves as the size increase, Fig 4.2 indicated the performance ratios of the lysimeters without sidewalls are below 80% for all the three soils types for all sizes. Lateral diversion is thought to be the main reason for this phenomenon. Fig. 4.3 shows the existence of lateral diversion at the edge of lysimeters when sidewall is not implemented. Fig. 3b shows the water velocity vectors at the bottom of the lysimeter. Water does not flow vertically at the edges of the lysimeter. It’s impractical to improve performance ratio by increasing the size of lysimeters.

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4.2.2 Effect of Sidewalls on the Performance of Flat Lysimeters

It is believed that sidewalls can prevent lateral diversion (Benson et. al., 2001), although no data was available to exactly determine that the extended sidewalls improve the performance of lysimeters. Construction of sidewalls onto lysimeters, however, is proved to be expensive, and the costs increase with the height of sidewalls. The full scale sidewalls can cost up to 50 % of

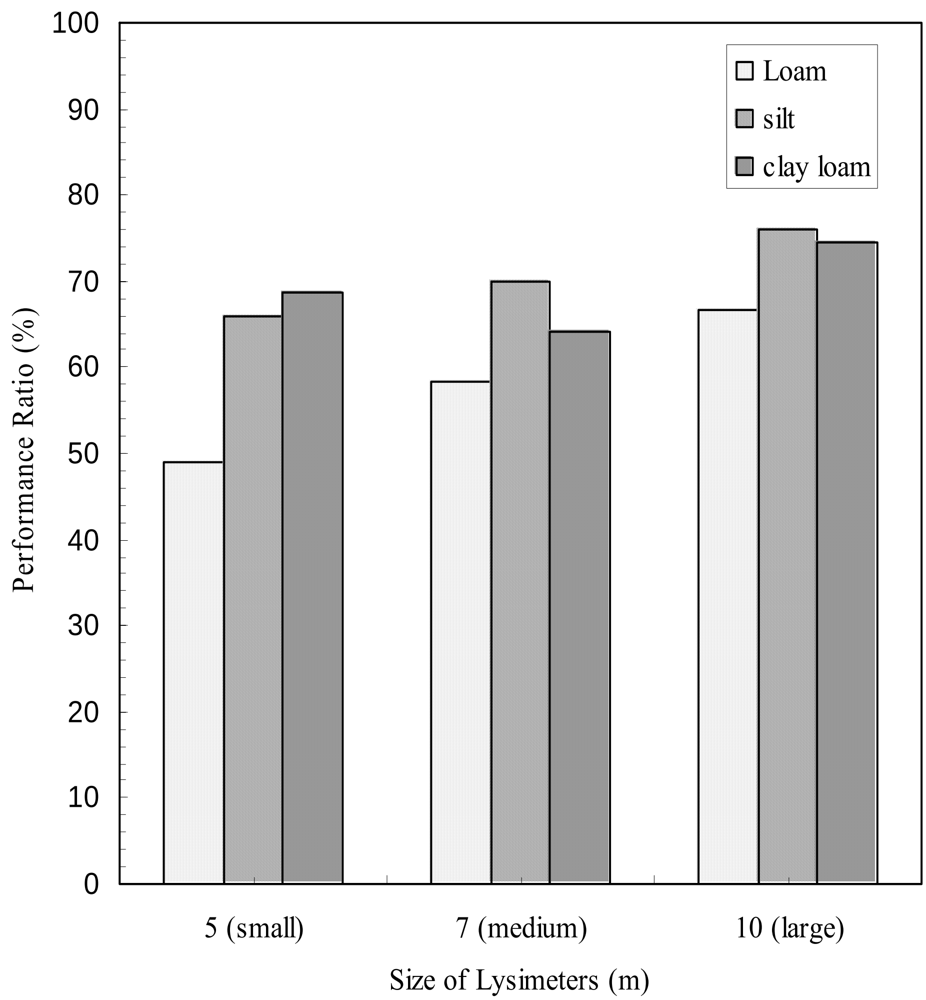
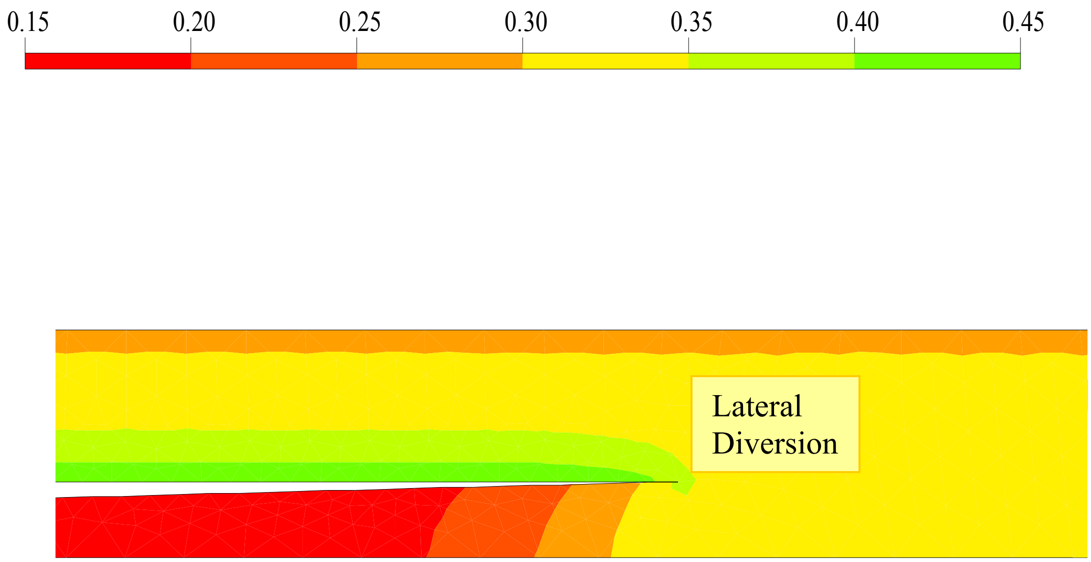
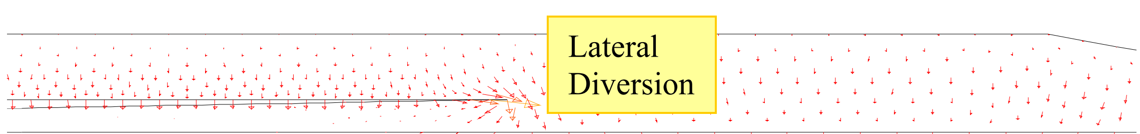


Fig.4.2 Performance Ratio of Lysimeters Without Sidewall
After Two Years Simulation.



(a)



(b)

Fig. 4.3 Illustration of Lateral Diversion of Lysimeters Without Sidewall: Water Content Profile (a), Velocity Vector Profile (b) the total cost of lysimeter (Abichou, 2003). To develop lysimeters with maximum performance ratio and least cost, small (5 m), medium (7 m) and large (10 m) lysimeters with sidewalls were simulated. Three typical heights of sidewalls simulated were 25 cm, 50 cm, to 100 cm. When the sidewall is 100 cm, it is equal to the thickness of cover. Loam, silt and clay loam were used to simulate the cover soils of all the geometries of lysimeters simulated in this study. Seepage Face boundary condition was selected as the lysimeter bottom boundary.

Fig.4.4 shows the performance ratio of unit cumulative fluxes across small lysimeters (5 m) to the Baseline Unit Cumulative Fluxes. For the lysimeters in loam, installation of 25 cm sidewalls improves the performance of lysimeters by 21%, from 49% to 71%. The performance ratio increased to 82.8% when 50 cm sidewalls were installed. As the height of sidewalls increased from 50 cm to 100 cm, the performance ratio of lysimeters increased to 87.4%, which was 38% higher than that of small lysimeter without sidewalls in loam covers.

In clay loam, installation of 25 cm sidewalls improves the performance of lysimeter from 68.7% to 74.25%, and increment of the height of sidewalls from 25 cm to 50 cm increased the performance ratio to 82.5%. As the height of sidewalls increased from 50 cm to 100 cm, no improvement of performance ratio was achieved.

Simulations with silt showed that installing 25 cm sidewalls increased the performance ratio from 65.8% to 79%, 9% more increment in performance was observed by increasing sidewalls from 25 cm to 50 cm. Little improvement (1.7%) was achieved by changing the sidewall from 50 cm to 100 cm.

Simulations of medium lysimeters (7 m) were also conducted with sidewalls in ET covers simulated with clay loam, silt and loam, respectively. Fig. 4.5 shows the performance ratio of

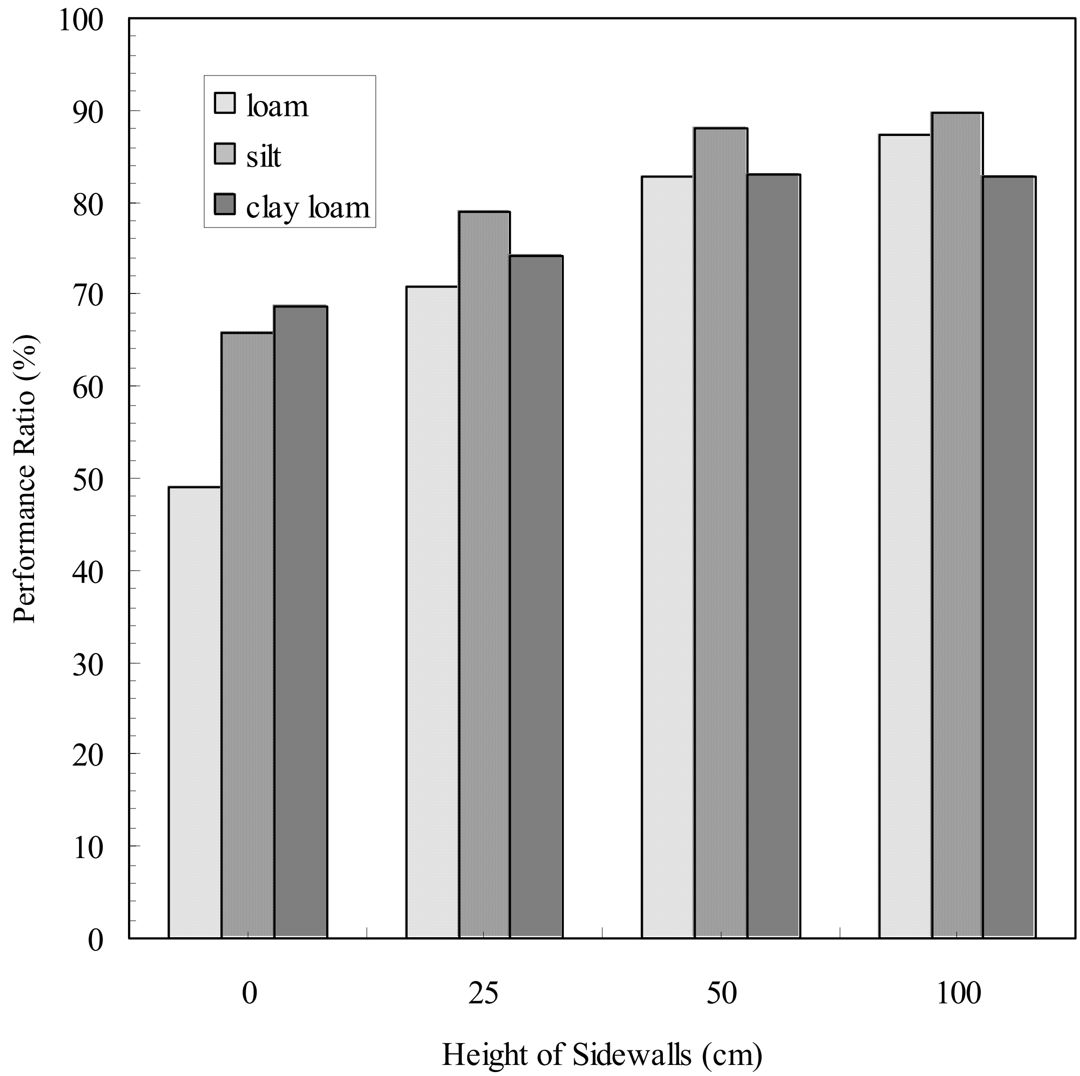


Fig. 4.4 Performance Ratio of Small Lysimeters With Sidewall After Two Years Simulation.

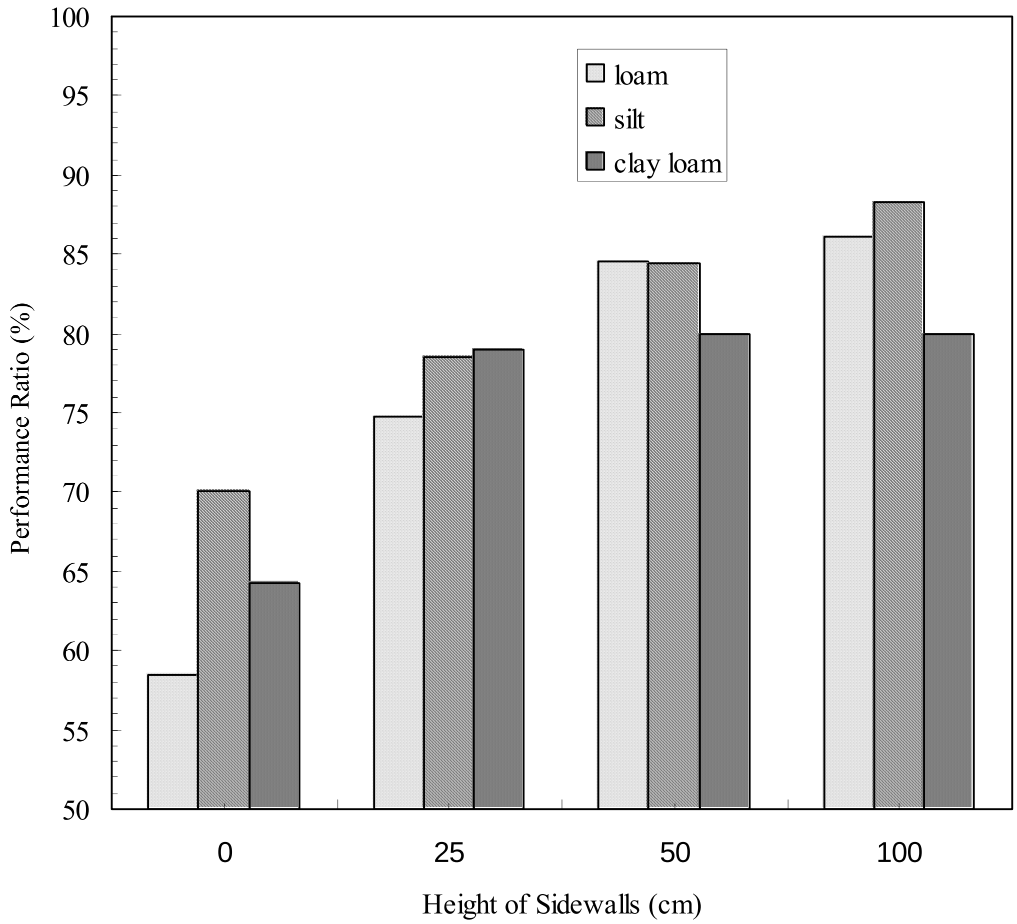


Fig 4.5 The Performance Ratio of Medium Lysimeters With Sidewalls After Two Years Simulation.

medium lysimeters (7 m) with 25 cm, 50 cm, and 100 cm sidewalls and in loam, silt and clay loam ET covers. In loam covers, installing 25 cm sidewalls increased the performance from 58.37% to 74.8%, and the performance ratio increased to 84.5% when 50 cm sidewalls were installed. Little improvement (2%) of the lysimeter accuracy was acquired when the sidewall height was increased from 50 cm to 100 cm in the loam cover. The ratio of medium lysimeter with 100 cm sidewalls in loam cover was 86.15%, which is similar to that of large lysimeter with 100 cm sidewalls (85.9%) in the same cover.

For the silt lysimeter, the performance ratio was increased from 70% to 78.5% by installing 25 cm sidewalls, and 84.4% performance ratio was achieved when 50 cm sidewall was installed. 88.25% was observed after increasing sidewalls from 50 cm to 100 cm.

In the covers simulated with clay loam, 15% promotion was obtained after 25 cm sidewalls were installed, from 64.15% to 79%. 1% more improvement was achieved by increasing sidewalls from 25 cm to 50 cm. No obvious improvement was observed when the height of sidewalls increased from 25 cm to 50 cm and then to 100 cm.

The performance ratios of large lysimeters with sidewalls were presented in Fig.4.6. Eleven and a half percent improvements were achieved after 25 cm sidewall was installed onto the large lysimeter in loam cover, from 66.76% to 78.25%. The performance ratio was 83.8% when the sidewall height was increased to 50 cm. The performance ratio was 85.87% when 100 cm sidewall was installed onto the large lysimeter in loam cover.

For the lysimeters in silt covers, the installation of 25 cm sidewall increased the performance ratio from 76% to 85%. When the height of sidewall was increased to 50 cm, the ratio was 88.14%. When sidewall height was increased to 100 cm, the performance ratio was 91.26%.

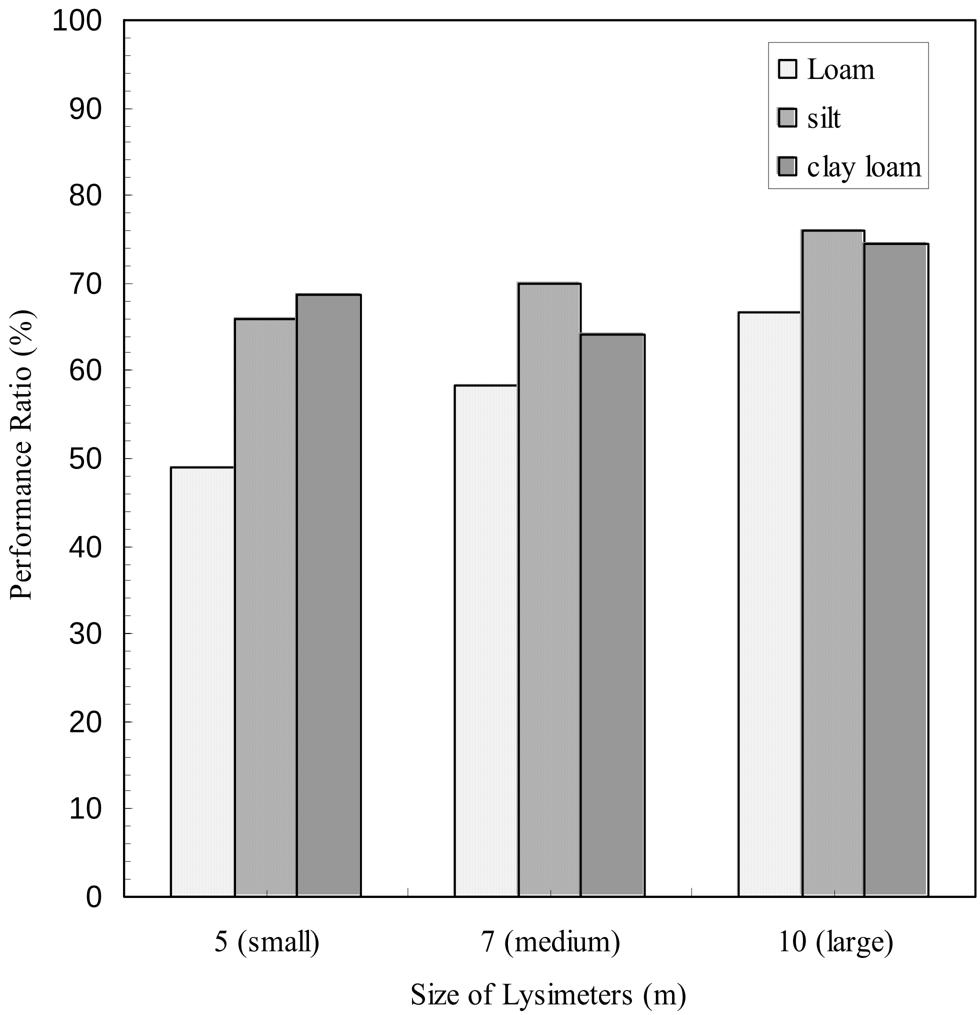


Fig. 4.6 The Performance Ratio of Large Lysimeters With Sidewalls After Two Years Simulation.

The performance ratio increased to 82.33% after 25 cm sidewalls were installed onto the large lysimeter in clay loam. Slight performance improvement of lysimeters was made by increasing sidewall height from 25 cm to 50 cm and then to 100 cm in the clay loam covers.

The simulations in this group indicate that sidewalls can improve the performance of lysimeters for different soils, and large lysimeters have better performance than medium and small lysimeters. With 25 cm sidewalls, the performance ratio increased to 78.25% for loam, 85% for silt and 82.3% for clay loam covers. Increasing the heights of sidewalls from 25 cm to 50 cm improved the performance of lysimeters by 4 to 5%. Increasing sidewalls from 50 cm to 100 cm in loam and silt covers increased the performance by 2 to 3%. For the lysimeters simulated with loam and silt covers respectively, large lysimeters had better performance than small and medium ones with the same sidewall heights, and the large lysimeters with full scale sidewalls (100 cm) have the best performance. These lysimeters, however, have performance ratio less than 91%.

4.3 Lysimeters for Sloped ET Covers

A large portion of a landfill cover is on slopes. The performance of lysimeters is a concern when percolation rate is measured with sloped lysimeters. The lysimeter performance is expected to be influenced by both the gradient of slopes and the height of sidewalls. To explore optimal lysimeter geometries for various landfill slopes, simulations were conducted with three typical landfill slopes 1:3, 1:4, and 1:5. The size of lysimeters was set to 10 m. The height of sidewalls varied from 0 cm (without sidewalls) to 25 cm, 50 cm and 100 cm. The input of the thickness of soils, vegetation distribution, and root depth was the same as the tests run for flat covers described in Section 4.2.

The performance ratios of lysimeters on slope 1:5 are shown in Fig. 4.7. In the silt covers, the performance of lysimeters increased with the height of sidewalls. The performance ratios are 72.8% for lysimeter with no – sidewall, 73.4% for lysimeter with 25 cm sidewalls, 79.6% for lysimeter with 50 cm sidewalls, and 83.3% for lysimeter with 100 cm sidewalls. In the clay loam covers, the performance ratios are 71.5% for lysimeters with no – sidewalls, 76.7% for lysimeters with 25 cm sidewalls, 79.4% for lysimeters with 50 cm sidewalls, and 80.9% for lysimeter with full scale sidewalls. In the covers simulated with loam, the performance ratios are 77.6%, 70%, 86.4%, and 79.6% for lysimeters without sidewalls, with 25 cm sidewalls, 50 cm sidewalls, and 100 cm sidewalls, respectively.

Fig 4.8 shows the performance ratios of lysimeters on slope 1:4. For lysimeters without sidewalls, the ratio is 77% for loam, 68.5% for silt, and 73% for clay loam. As much as 23 % underestimation was observed in those tests. Lateral diversion was thought to be one of the primary sources of underestimation. Installation of 25 cm sidewalls changes the lysimeter performance ratios to 73% in loam cover, 69% in silt cover, and 84.6% in clay loam cover. Installing 50 cm sidewalls helped to promote the lysimeter performance to 80 % in landfill covers simulated with loam, silt, and clay loam. With full scale sidewalls, 89 % performance can be achieved in lysimeter in silt covers, 85.6 % in lysimeter in clay loam covers, and 83 % in lysimeter in loam covers. More than 10 % underestimation still exists.

Fig. 4.9 illustrated the performance of lysimeters of slope 1:3. For lysimeters without sidewalls, the ratio is 82.4% for loam, 74% for silt, and 73% for clay loam. Up to 18% underestimation was observed in those tests. Installing 25 cm sidewalls on lysimeter changed the performance ratios to 68.4% in loam cover, 85.5% in silt cover, 89% in clay loam covers. The

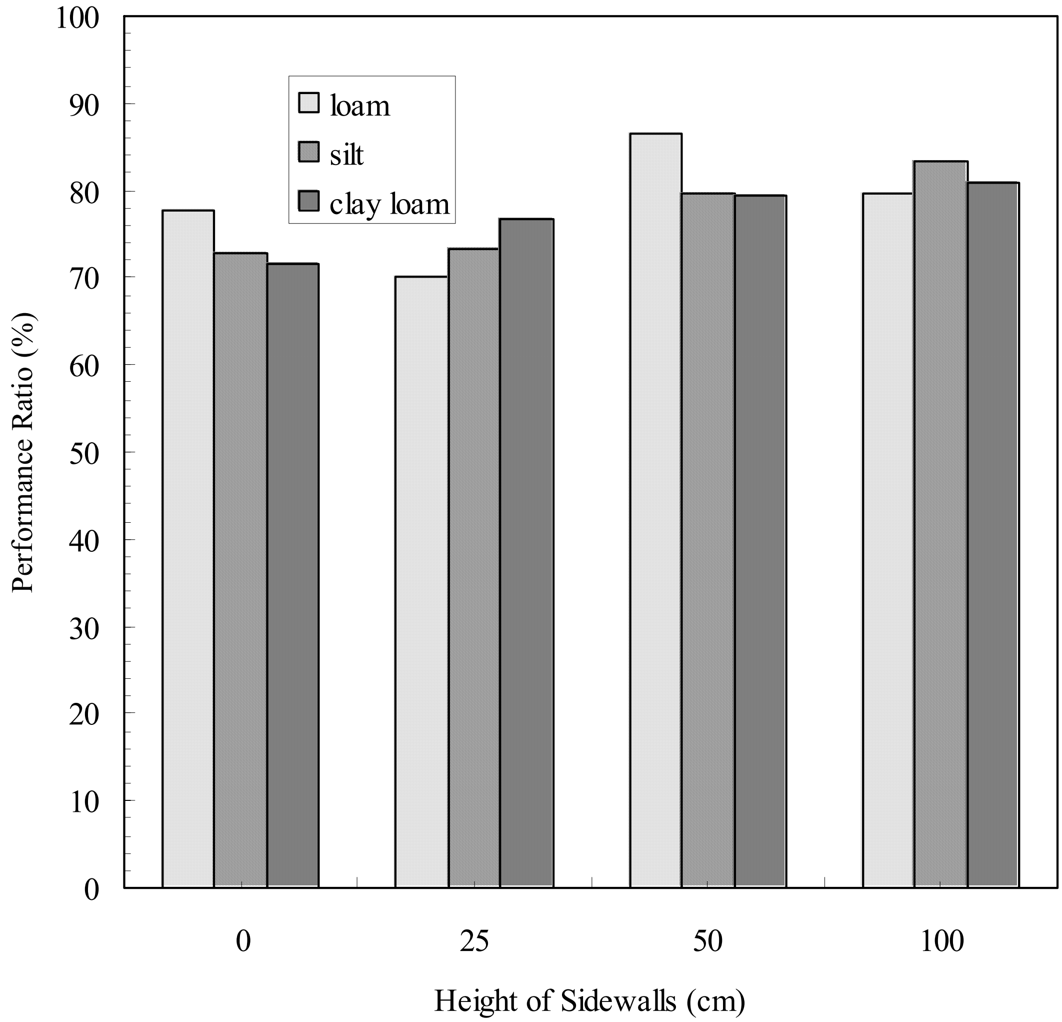


Fig. 4.7 Performance of Large Lysimeters With Sidewalls on Slopes 1:5 After Two Years Simulation.

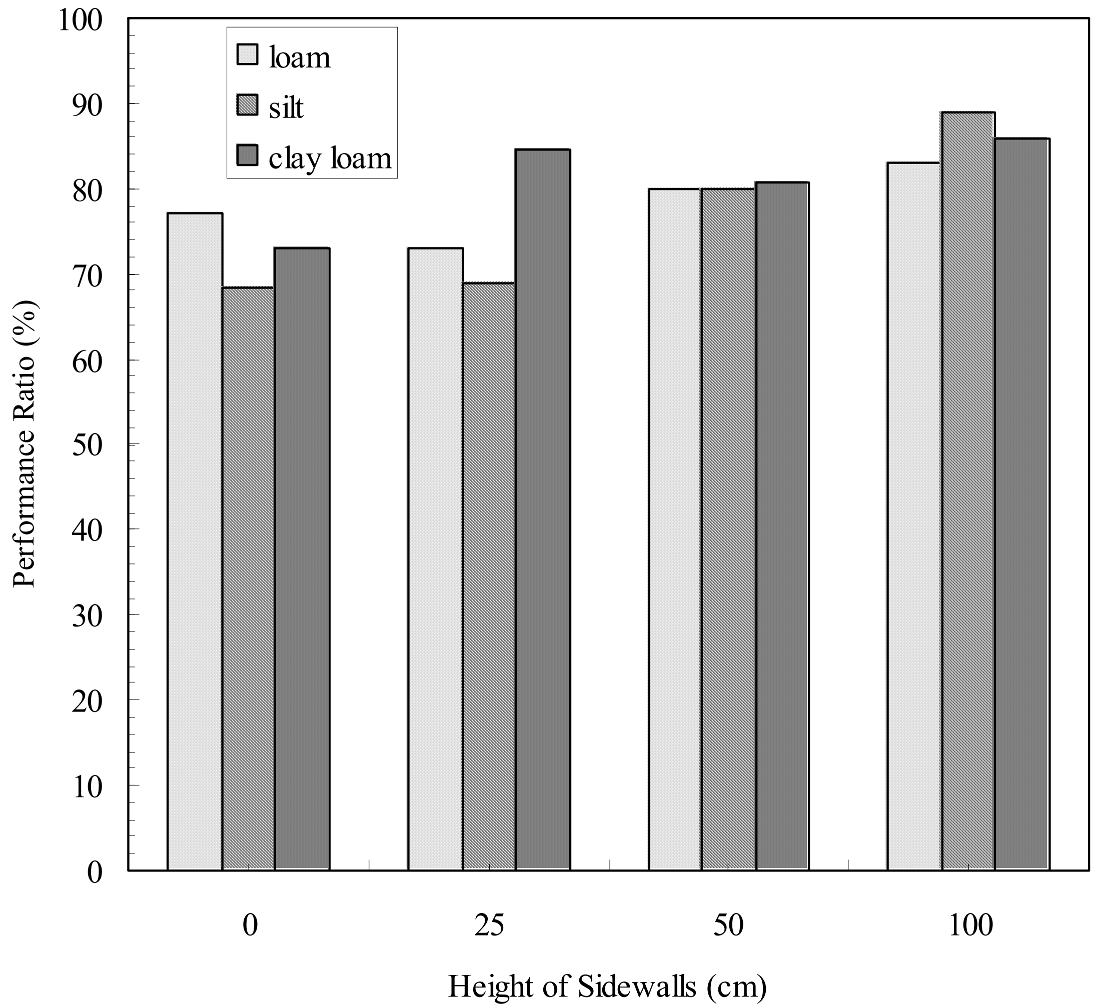


Fig. 4.8 Performance Ratio of Large Lysimeters With Sidewalls on Slopes 1:4 After Two Years Simulations.

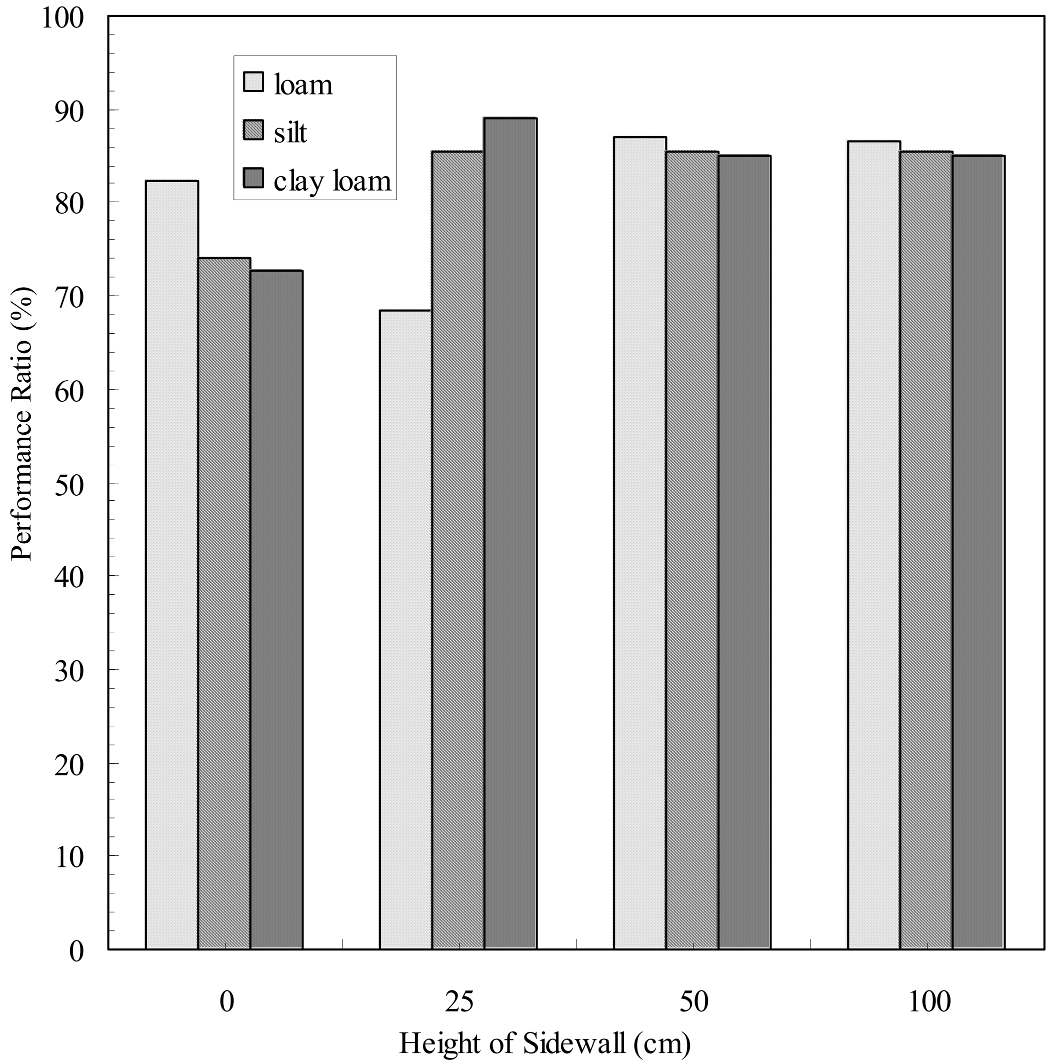


Fig.4.9 Performance Ratio of Large Lysimeters With Sidewalls on Slopes 1:3 After Two Years Simulations.

performance ratios were 87 % in loam cover, 85.5% in silt cover, and 85% in clay loam when 50 cm sidewalls were installed. Increasing the height of sidewalls from 50 cm to 100 cm had little effect on lysimeter performance.

On slope 1:5, in silt covers and clay loam covers, lysimeter with 100 cm sidewalls have best performance; in loam cover, lysimeter with 50 cm sidewalls has best performance. On slope 1:4, lysimeters with 100 cm sidewalls have best performance for all three types of soils. On slope 1:3, lysimeters with 50 cm sidewalls have the same performance as those with 100 cm sidewalls.

4.3 Synthesis

Comparison of unit cumulative flux across lysimeters and that of the criterion full scale covers suggested that lysimeters without sidewalls underestimate the amount of percolations across ET covers by as least 25%, when loam or silt or clay loam is used to simulate the covers. Analysis showed that lateral diversion is one of the primary causes which decrease the performance of lysimeters. Installation of sidewalls can improve the performance of lysimeters to certain extent. In the flat covers, full-scale (100 cm) sidewalls improved the performance of large lysimeters to 85.9% for loam, 91.26% for silt and 84.5% for clay loam. On the inclined covers, lysimeters with 100 cm sidewall on the slope 1:4 in silt cover showed the highest performance ratio, which is 89%, and the underestimation of percolation rate is 11%.

At the base of lysimeters, an artificial no-flow boundary was selected. All water that percolates downward to the base of lysimeters is collected and routed out of the system. As a result, the water collected in the lysimeters can not move upward due to capillary force induced by evapotranspiration and temperature gradients, which might occur under natural conditions. This artificial no – flow boundary, which does not exist in the actual field setting, prevents upward and downward flow of vapor and liquid across the base of the lysimeter, and consequently reduces the accuracy of lysimeters.

An earthen or geosynthetic drainage layer is installed in most lysimeters directly on top of the lower boundary for directing percolation to a measuring point. In this study, this layer was simulated with Seepage Face boundary condition which allows moisture to seep through only when the soils are saturated. The larger pores associated with the drainage layers induce a capillary break at the base of the cover profile that might not exist in actual settings (Khire et al. 1999; Benson et al, 2002). Consequently, an artificial increase in the storage capacity of the cover profile and an artificial reduction in percolation rate may be incurred relative to natural conditions.

The combined effects of no-flow boundary at the base and the drainage layer on top of the lower boundary of lysimeters are thought to underestimate the percolation rate tested using lysimeters. To correct the deviations caused by those artificial boundary conditions, coefficients need to be apply to the lysimeter test results. These coefficients are soil dependent and should be evaluated for each design.

CHAPTER FIVE

SUMMARY AND CONCLUSION

A numerical study was performed to investigate the performance of lysimeters in measuring percolation rate through ET covers and to develop an optimum geometry of lysimeters. HYDRUS - 2D, which can accurately simulate water balance through soils under variably saturated conditions, was used to assess the performance of lysimeters. The simulations consisted of evaluating water balance across a soil profile that is 1.0 m thick. The soils simulated included loam, silt and clay loam. The top 0.75 m of the soil profile was assumed to be vegetated with grass. The root density was set to be 0.2. The bottom 0.25 m was assumed to have no roots. Daily precipitation, evapotranspiration, and transpiration data obtained from the Albany, GA ACAP site were used as the climatic input for the upper boundary conditions used at the soil surface. All simulations were performed for 730 days with the climatic data.

The bottom boundary of lysimeters typically consists of a layer of geocomposite overlaying a geonet, which functions as a drainage layer. This layer is simulated with Seepage Face boundary condition. Initial water contents across the profile were simulated to vary from 0.35 at the top of soil profile to 0.15 at the bottom of the soil profile. The above input parameters were kept constant for all the simulations during the entire study.

The simulation started by building criteria against which performance of lysimeters is evaluated. The criteria were developed by performing simulations on full scale landfill covers and determining the cumulative flux through the lower boundary of the covers. The width of the full scale covers was 50 m, and the bottom boundary of the baseline cover simulations was approximated with Free Drainage boundary condition. Both flat and inclined cover criteria were developed. Baseline Unit Cumulative Flux was defined by dividing the cumulative flux from Baseline Covers simulations by the width of full scale covers, which is 50 m. The percolation rates from all lysimeter designs in this study were evaluated against the percolation rates of the corresponding Baseline Unit Cumulative Flux.

5.1 The Effect of Size on the Performance of Flat Lysimeters

In order to investigate the effect of size on the performance of lysimeters, simulations were performed using three sizes: small (5 m), medium (7 m) and large (10 m). The drainage layer installed above the lysimeter bottom pans was simulated with the Seepage Face boundary condition. The types of covers were simulated: loam, silt and clay loam.

The performance ratio of lysimeters increases with the size of lysimeters in all three types of covers. In the loam covers, the ratios are 49%, 58.3% and 66.16% for the small, medium, and large lysimeters, respectively. The performance ratios in clay loam covers are 68.7% for small lysimeter, 64.15% for the medium lysimeters, and 74.4% for large lysimeters. In the silt covers, the performance ratio of small lysimeter is 65.8%; the value of medium lysimeter is 70%, and 76% for large lysimeter.

The relationship between lysimeter performance and geometry is also influenced by the type of soils implemented in the covers. The performance ratio across large lysimeter is 76% in clay loam, 74.48% in silt and 66.16% in loam.

While 10 m is the maximum size of lysimeter in the field, all the simulated lysimeters without sidewalls underestimate the cumulative flux by at least 24%. Lateral diversion is thought to be the one of the primary sources of error.

5.2 Effect of Sidewalls on the Performance of Flat Lysimeters

Sidewalls were suggested to prevent lysimeter lateral diversion and are installed on many lysimeters (Benson, et. al., 2001). On the other hand, installing sidewalls onto lysimeters is proved to be expensive (Abichou, 2003). To evaluate the performance of lysimeters with sidewalls and develop cost effective – optimal performance lysimeters, small, medium and large lysimeters with sidewalls were simulated. The heights of sidewalls vary from 25 cm, to 50 cm and 100 cm.

The performance ratios of small, medium and large lysimeters are listed in Table 5.1, Table 5.2 and Table 5.3, respectively. Those simulations indicate that:

- For small lysimeters, the sidewalls have to be 50 cm to have performance higher than 80%.
- For medium lysimeters, the sidewalls have to be 50 cm to have performance higher than 80%.
- For large lysimeters, the sidewalls can be 25 cm to have performance higher than 80%.

The performance ratios also depend on the type of soils to some extent. In the loam covers, small lysimeter with 100 cm sidewall has best performance, which is 87.4%. In silt covers and clay loam covers, large lysimeters with 100 cm sidewalls have best performance, and ratios are 91.26% in silt cover and 84.5% in clay loam cover.

The simulations in this group indicate that sidewalls can improve the performance of lysimeters, and the increment of lysimeter performance was different for different soils and

Table 5.1 Performance Ratio of Small Lysimeters With Sidewalls.

Height of Sidewalls (cm)	Types of Soils		
	Loam	Silt	Clay Loam
25	70.9%	79%	74.25%
50	82.8%	88%	82.9%
100	87.4%	89.7%	82.8%

Table 5.2 Performance Ratio of Medium Lysimeters With Sidewalls.

Height of Sidewalls (cm)	Types of Soils		
	Loam	Silt	Clay Loam
25	74.8%	78.5%	79%
50	84.5%	84.35%	80%
100	86.15%	88.25%	80%

Table 5.3 Performance Ratio of Large Lysimeters With Sidewalls.

Height of Sidewalls (cm)	Types of Soils		
	Loam	Silt	Clay Loam
25	78.25%	85%	82.33%
50	83.8%	88.14%	83%
100	85.87%	91.26%	84.58%

different lysimeter geometries. For the lysimeters with 25 cm sidewalls large lysimeters have the best performance, medium lysimeters are the next. The performance difference among small, medium and large lysimeters with 25 cm is smaller than that of lysimeters without sidewalls. After 50 cm sidewalls are installed, the performances of the lysimeters of different sizes are similar. The performance ratios are between 82.8% to 84.5% in loam covers, between 84.35% and 88% in silt covers, and between 80% and 83% in clay loam covers. The size has little influence on the performance of lysimeters with 100 cm sidewalls, and ratio is between 85.87 and 87.4% in loam covers, between 88.28% and 91.26% in silt covers, and between 80% and 84.6% in clay loam covers. More than 9% underestimation was observed in all the simulations. No – flux condition at the lower boundary of lysimeter bottom pan and the drainage layer are thought to be reasons for that underestimation.

5.3. Lysimeters for Sloped ET Landfill Covers

To test the performance of lysimeters and explore optimal lysimeter geometries for various landfill slopes, simulations were conducted with three typical landfill cover slopes 1:3, 1:4, and 1:5. Full scale simulations were performed with sloped covers. The height of sidewalls varied from 0 cm (without sidewall), to 25 cm, 50 cm, and 100cm. The boundary condition was simulated with Seepage Face condition. The performance ratios lysimeters on slopes 1:5, 1:4, 1:3 are listed in Table 5.4, Table 5.5 and Table 5.6, respectively.

On the landfill covers with slope 1:3, the performance ratio of lysimeters without sidewalls is 82.4% for loam, 74% for silt, and 73% for clay loam. Installation of 50 cm sidewalls improves the ratio to 87% in loam cover, 85.5% in silt cover and 85% in clay loam cover. Little improvement is achieved by changing sidewall from 50 cm to 100 cm.

Table 5.4 Performance Ratio of Large Lysimeters on Slope 1:5.

Height of Sidewalls (cm)	Types of Soils		
	Loam	Silt	Clay Loam
0	77.6%	72.8%	71.5%
25	70%	73.4%	76.7%
50	86.4%	79.6%	79.4%
100	79.6%	83.3%	80.9%

Table 5.5 Performance Ratio of Large Lysimeters on Slope 1:4.

Height of Sidewalls (cm)	Types of Soils		
	Loam	Silt	Clay Loam
0	77%	68.5%	73%
25	73%	69%	84.6%
50	80%	80%	80.7%
100	83.1%	89%	85.8%

Table 5.5 Performance Ratio of Large Lysimeters on Slope 1:3.

Height of Sidewalls (cm)	Types of Soils		
	Loam	Silt	Clay Loam
0	82.4%	74%	72.8%
25	68.4%	85.5%	89%
50	87%	85.5%	85%
100	86.5%	85.5%	85%

When the slope is 1:4, the performance ratio of lysimeters without sidewalls is 77% for loam, 68.5% for silt, and 73% for clay loam. Installation of 50 cm sidewalls improves the ratio to 80% in loam cover, silt cover and clay loam cover. The lysimeters with 100 cm sidewalls have best performances; the ratio is 83.1% for loam, 89% for silt and 85.8% for clay loam.

On the landfill covers with slope 1:5, the lysimeters without sidewalls has the lowest performance ratios, the values increase as the heights of sidewalls increase. The lysimeters with 100 cm sidewalls have the best performances; the ratios are 79.6% in loam cover, 83.3% in silt cover and 80.9% in clay loam cover.

On the sloped landfill covers, underestimation of the percolation rate is common when lysimeters are used as measuring facilities. The performance ratio of all the lysimeters is below 86%.

5.4 Conclusions

Both flat and inclined lysimeters without sidewalls underestimate the percolation rate across landfill covers by at least 25% when loam or silt or clay loam is used for the cover. Installation of sidewalls can improve the performance of lysimeter to certain extent. Large lysimeters with full scale sidewalls achieve best performance in silt or clay loam covers. The performance ratio of large flat lysimeter with full scale sidewall is 91.26% in silt cover, 84.6% in clay loam cover. The small lysimeter with full scale sidewall achieve best performance in loam cover, which is 87.4%. Over 9% underestimation was observed in all the flat lysimeters. In the inclined covers, the lysimeters with best performance underestimate percolation rate by at least 14%.

Two factors are thought to be responsible for the inaccuracy: 1) the artificial no – flow boundary induced by lysimeter bottom pan; 2) drainage layer installed on top of the lysimeter bottom pan. Both no-flow boundary and the drainage layer are necessary for lysimeters to serve their functions properly; therefore the performance of lysimeters can not be improved by removing either of the two implementations.

5.5 Recommendations for Future Work

The parameters governing the performance of ET covers include soil hydraulic properties, initial water content, cover thickness, vegetation properties and root distribution, site – specific weather conditions. The performance of lysimeters, inevitably, is influenced by those factors. This study has addressed the significant issues about how the lysimeter geometry affects measurement accuracy, and suggested that coefficients are needed to improve lysimeter performance. The determination of coefficients is complicated.

Percolation control of ET cover system relies on the storage of moisture within the cover soils during the rainy season and the subsequent release of the stored moisture by evapotranspiration during the dry season. The precipitation scale, frequency, duration of wet season and dry season influence the percolation rate. Percolation response of the stored moisture to cover design parameters such as rooting depth, cover thickness, and building soil saturated hydraulic conductivity is highly nonlinear (Jorge, 2003). To ensure performance of lysimeters in various situations, numerical simulations are necessary to determine coefficients for specific situations before measuring with lysimeters.

This study is primarily based on numerical simulations, although most of the input parameters were collected from field. Comparison between field measuring results and simulation results has to be conducted to test the reality of boundary parameters and other parameters selection.

Based on these simulations, we recommend that lysimeters should have a width of at least 5 meters. The performance of such lysimeters depends on the type of soil used and the local weather conditions. The performance can be improved by a sidewall that is 0.30 m high. Additional height will not improve the performance by much. Low sidewalls render the construction inexpensive and reduce the risk of over-compaction.

SECTION SIX

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SECTION 7

APPENDICES

(on CD)

A. Climate Data from Albany, GA ACAP site

B. Baseline Cover Simulations

C. Simulations of Flat Lysimeters Without Sidewalls

D. Simulations of Flat Lysimeters With Sidewalls

E. Simulations of Inclined Lysimeters With and Without Sidewalls