SW-869

Revised Edition

LANDFILL AND SURFACE IMPOUNDMENT PERFORMANCE EVALUATION MANUAL

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Project Officer

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FOREWORD

The Environmental Protection Agency was created because of increasing public and governmental concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay of its components require a concentrated and integrated attack on the problem.

Research and development is the first necessary step in problem solution; it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater and solid and hazardous waste pollutant discharges from municipal and community sources; to preserve and treat public drinking water supplies; and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research -- a vital communications link between the researcher and the user community.

This document describes a method for evaluating designs for landfills and surface impoundments to predict the amount of liquid collected in leachate collection systems and the amount seeping through the liner into underlying soils. The method takes into account the slope, thickness, and permeability of the soil or clay liner, the thickness and permeability of sand or gravel drainage layers, and the spacing of pipes in the leachate collection system.

Francis T. Mayo
Director, Municipal Environmental
Research Laboratory

AUTHOR'S FOREWORD

This evaluation procedures manual updates an identically titled document published by the U.S. EPA Office of Water and Waste Management in September 1980 as publication No. SW-869. The principal modifications are:

(1) Material referring to partially saturated flow and prediction of time of first arrival of leachate at the base of the landfill has been moved to an Appendix. This material was removed from the body because proven methods are not currently available for measuring the required soil properties in the laboratory. Readers who are interested in current research being conducted on this topic are referred to Messuri (1982).

(2) More example problems have been included.

(3) A section has been added that discusses the effects that changes in design parameters have on the performance of liner/drain systems.

I would like to summarize the philosophy upon which this Evaluation Procedures Manual is based. The mathematical principles that describe the transport of liquids through hazardous waste landfills and surface impoundments are technically complex. Faced with this situation, it is tempting to circumvent these difficulties by reverting to empiricism or rules of thumb. I have avoided doing so, however, by using linearized versions of complicated mathematical equations and by using simplified boundary conditions. Thus, the evaluator will be able to assess the performance of a design using algebraic equations.

This approach has three important benefits:

(1) As better analytical techniques are developed, it will be possible to modify the evaluation procedure in a rational and consistent manner. Thus, at the design level, acceptable configurations for landfills and surface impoundments will change gradually rather than abruptly. The evaluator will not be placed in the awkward position of having to explain to the engineer that a design that was acceptable last year is seriously out of compliance this year.

(2) Engineering firms that design hazardous waste landfills and surface impoundments will be able to use the more sophisticated analytical techniques if they desire. For example, they may wish to use nonlinear versions of equations or more comprehensive boundary conditions for equations, thereby introducing more realism into the analysis. Because such analytical approaches are compatible with the approach being used by the the evaluator, the engineer will be able to explain the reason for differences in the results of the two analyses and be able to more easily convince the evaluator that the more progressive analytical

approach yields an acceptable, and hopefully more economical, design.

(3) The analytical approaches presented in this manual provide a quantitative basis upon which the evaluator and engineer can discuss possible modifications so that an unacceptable design configuration can be transformed into one that is acceptable. This approach avoids the dilemma that the engineer sometimes faces of (a) being told that a design violates a rule of thumb criterion, but (b) being given no guidance on how to modify the design to comply with the intent of the requirements.

In addition to providing an evaluation procedure, this manual provides design techniques that can be used by the engineer. A logical choice for the designer to make would be to use the same analytical procedures to arrive at the proposed design that the evaluator will be using to determine the acceptability of the design. Engineers will be able to approach liquid routing through landfills and surface impoundments as a discrete analytical task, and they will be able to substantiate their designs quantitatively.

Chapter 1 describes the purpose of this manual and establishes its relationship to other U.S. EPA manuals. Chapter 2 describes the physical attributes of the hazardous waste disposal facilities for which this evaluation procedure has been developed. Chapter 3 provides the analytical basis for the evaluation procedure. The fundamental physical and mathematical principles are presented and the relevant equations are given. Chapter 4 presents the detailed evaluation procedure and serves as a checklist; the experienced evaluator will use this chapter only. Chapter 5 presents example evaluations. Chapter 6 contains references, and the Appendix discusses principles of partially saturated flow.

In conclusion, I hope that this Evaluation Procedures Manual provides a straightforward, analytically sound basis for the rational design of hazardous waste landfills and surface impoundments with respect to their ability to provide containment of liquids.

I would like to especially acknowledge the assistance of Mike Roulier, Dirk Brunner, Chris Donaldson, and Susan DeHart.

Charles A. Moore
November 1, 1982

PREFACE

Subtitle C of the Resource Conservation and Recovery Act (RCRA) requires the Environmental Protection Agency (EPA) to establish a Federal hazardous waste management program. This program must ensure that hazardous wastes are handled safely from generation until final disposition. EPA issued a series of hazardous waste regulations under Subtitle C of RCRA that is published in 40 Code of Federal Regulations (CFR) 260 through 265 and 122 through 124.

Parts 264 and 265 of 40 CFR contain standards applicable to owners and operators of all facilities that treat, store, or dispose of hazardous wastes. Wastes are identified or listed as hazardous under 40 CFR Part 261. The Part 264 standards are implemented through permits issued by authorized States or the EPA in accordance with 40 CFR Part 122 and Part 124 regulations. Land treatment, storage, and disposal (LTSD) regulations in 40 CFR Part 264 issued on July 26, 1982, establish performance standards for hazardous waste landfills, surface impoundments, land treatment units, and waste piles.

The Environmental Protection Agency is developing three types of documents for preparers and reviewers of permit applications for hazardous waste LTSD facilities. These types include RCRA Technical Guidance Documents, Permit Guidance Manuals, and Technical Resource Documents (TRDs). The RCRA Technical Guidance Doucments present design and operating specifications or design evaluation techniques that generally comply with or demonstrate compilance with the Design and Operating Requirements and the Closure and Post-Closure Requirements of Part 264. The Permit Guidance Manuals are being developed to describe the permit application information the Agency seeks and to provide guidance to applicants and permit writers in addressing the information requirements. These manuals will include a discussion of each step in the permitting process, and a description of each set of specifications that must be considered for inclusion in the permit.

The Technical Resource Documents present state-of-the-art summaries of technologies and evaluation techniques determined by the Agency to constitute good engineering designs, practices, and procedures. They support the RCRA Technical Guidance Documents and Permit Guidance Manuals in certain areas (i.e., liners, leachate management, closure, covers, water balance) by describing current technologies and methods for designing hazardous waste facilities or for evaluating the performance of a facility design. Although emphasis is given to hazardous waste facilities, the information presented in these TRDs may be used in designing and operating non-hazardous waste LTSD facilities as well. Whereas the RCRA Technical Guidance Documents and Permit Guidance Manuals in certain areas (i.e., liners, leachate management, closure, covers, water balance) by describing current technologies and methods for designing hazardous waste facilities or for evaluating the performance of a facility design. Although emphasis is given to hazardous waste facilities, the information presented in these TRDs may be used in designing and operating non-hazardous waste LTSD facilities as well. Whereas the RCRA Technical Guidance Documents and Permit Guidance Manuals are directly related to the regulations, the information in these TRDs covers a broader perspective and should not be used to interpret the requirements of the regulations.

A previous version of this document dated September 1980 was announced in the Federal Register for public comment on December 17, 1980. The new edition incorporates changes as a result of the public comments, and supersedes the September 1980 version. Comments on this revised publication will be accepted at any time. The Agency intends to update these TRDs periodically based on comments received and/or the development of new information. Comments on any of the current TRDs should be addressed to Docket Clerk, Room S-269(c), Office of Solid Waste (WH-562), U.S. Environmental Protection Agency, 401 M Street, S.W., Washington, D.C. 20460. Communications should identify the document by title and number (e.g., "Landfill and Surface Impoundment Performance Evaluation, (SW-869).

ABSTRACT

This technical resource document provides recommended procedures for evaluating the effectiveness of liquid transmission control systems for hazardous waste landfill and surface impoundments. The procedures described allow an evaluator to determine the performance of (1) compacted clay liners intended to impede the vertical flow of liquids, (2) sand or gravel drainage layers used to convey liquids laterally into collection systems, (3) slopes on such liner/drain layers, and (4) spacings of collector drain pipes.

The mathematical principles that describe the transport of liquids through hazardous waste landfills and surface impoundments are technically complex. Faced with this situation, it is tempting to circumvent these difficulties by reverting to empiricism or rules of thumb. In this manual, however, this has been avoided by using linearized versions of complicated mathematical equations and by using simplified boundary conditions. Thus, the evaluator is able to assess the performance of a design using algebraic equations.

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1. INTRODUCTION

1.1 Purpose

This Evaluation Procedures Manual has been developed to describe the technical approach and to present equations for determining how the design of hazardous waste surface impoundments and landfills will function in controlling the quantity of liquids entering the environment. This manual is not intended to provide a means of proving that a poor design will not work. Its purpose, rather, is to allow the evaluator to determine how the design will function. It is the responsibility of the design engineer to propose an adequate design initially. The procedures described herein should allow an evaluator to determine the performance of:

(1) compacted clay liners or synthetic liners intended to impede the vertical flow of liquids,

(2) sand or gravel drainage layers intended to convey liquids laterally into collection systems,

(3) slopes on such liner/drain systems, and

(4) spacings of collector drain pipes.

1.2 Relationship to Other Manuals

As shown in figure 1, this procedures manual relates to four other manuals in the following ways:

(1) SW-868, titled Hydrologic Simulation on Solid Waste Disposal Sites (Perrier and Gibson, 1982) and prepared by the U.S. Army Corps of Engineers, Waterways Experiment Station, provides the analytical basis for determining the partitioning of rainfall into surface runoff and infiltration. The water that infiltrates is, in turn, partitioned into that which returns to the atmosphere through evapotranspiration, that which is stored in the cover soil, and that which percolates downward into the landfill. The last of these components, percolation, becomes the principal input to the present manual because it is the inflow due to percolation that must be adequately controlled as it is routed through the landfill. The Hydrologic Simulation on Solid Waste Disposal Sites manual provides the inflow on a daily basis based upon the CREAMS model developed by the U.S. Department of Agriculture.

(2) SW-168, titled Use of the Water Balance Method for Predicting Leachate Generation from Solid Waste Disposal Sites (Fenn, Hanley and DeGeare, 1975), provides an alternative source for determining the quantity of liquid percolating through the cover. The method presented in this manual is based upon the principles developed by Thornthwaite and Mather (1955 and 1957).

(3) SW-870, titled Lining of Waste Impoundment and Disposal Facilities (Matrecon, Inc., 1980), relates to the present manual in that the outflow quantities to collector drain pipes from sand and gravel drainage layers determined according to procedures described in the present manual become input quantities to section 5.6 of SW-870.

(4) SW-871, titled Hazardous Waste Leachate Management Manual (Monsanto Research, 1980), uses the outflow quantities to collector drain pipes determined in the present manual as an indirect input.

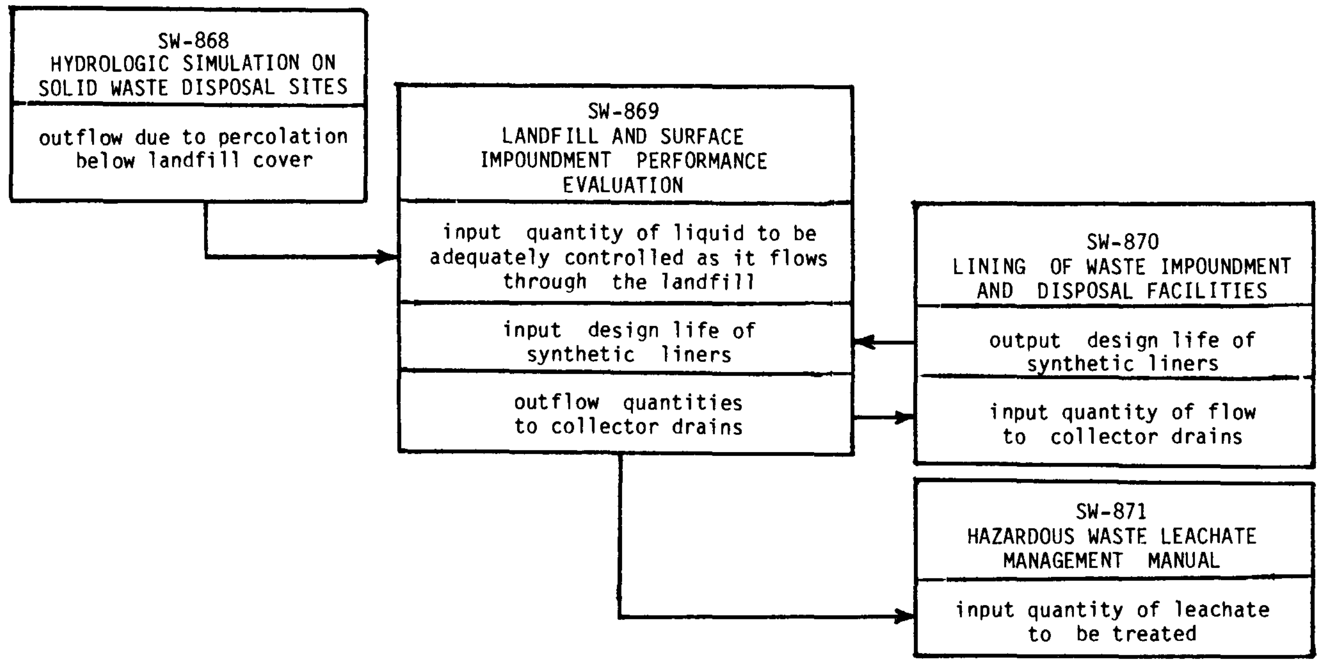


Figure 1 - Relationship of this manual to other manuals is the series.

2. DESIGN CONFIGURATIONS

It would not be practical or appropriate in this manual to specify exact configurations for hazardous waste landfill or surface impoundment designs. Rather, the approach followed here is to describe analytical procedures for evaluating the transport of liquids through simple modular configurations. With these analytical procedures at their disposal, evaluators can then interconnect several modules to represent the specific configuration being evaluated.

Figure 2 shows a hypothetical landfill cross section including final cover, waste cells, intermediate or daily cover, and a liner/drain system resting on undisturbed ground. Three separate modules can be delineated as follows:

(1) final cover with adjacent waste cells beneath,

(2) intermediate cover with adjacent waste cells above and below, and

(3) liner/drain system consisting from bottom to top of underlying undisturbed ground, clay liner, sand drain layer, and overlying waste cell.

2.1 Functional Characteristics of Design Modules

The modules shown in figure 2 will be examined in some detail to delineate the functional characteristics of each. This examination forms the basis for abstracting the physical characteristics to be included in the analytical techniques to be presented. The configuration described here is hypothetical only and does not necessarily constitute a recommended design.

The final cover shown in figure 2 is redrawn in more detail in figure 3a. It consists from bottom to top of:

(1) the waste,

(2) an undifferentiated leveling layer whose purpose is to provide an even, reasonably firm base and controlled slope upon which to construct the final cover,

(3) a low permeability compacted clay liner to retard the rate of downward movement of liquid,

(4) a high permeability sand or gravel drain layer to provide a horizontal pathway along which liquid collected on the clay liner can be transmitted to collector drain pipes for diversion away from the

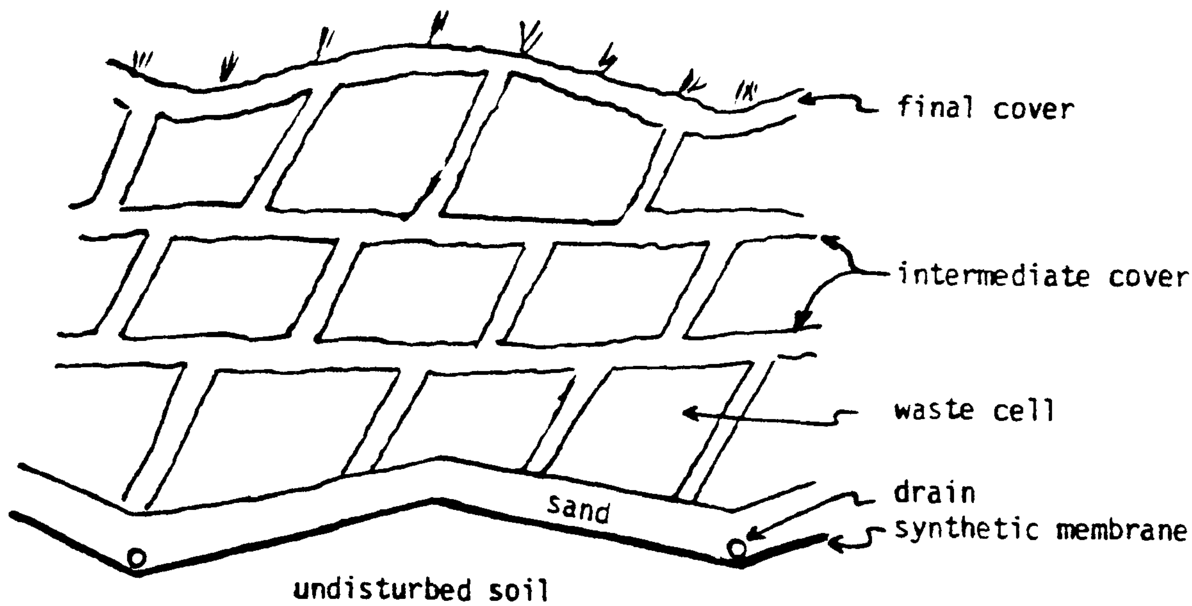
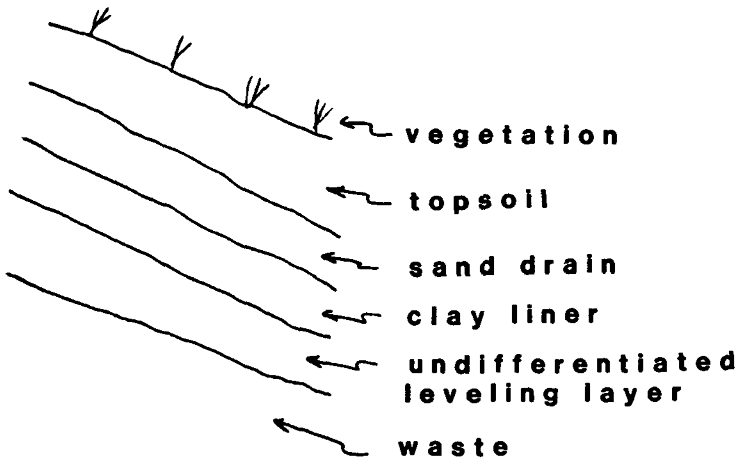
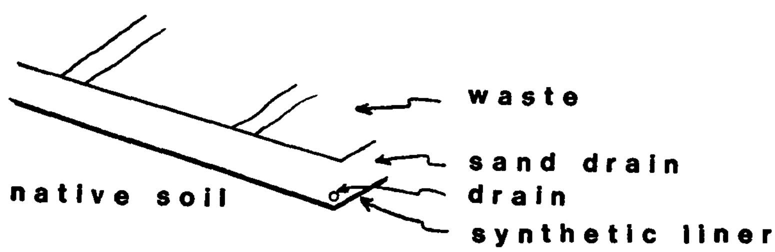


Figure 2 - Cross section of landfill showing typical containment cells.



(a) detail of cover

(b) detail of intermediate cover



(c) detail of drain and liner system

Figure 3 - Detailed views of modules constituting landfill cross section of figure 2.

landfill, and

(5) a vegetated topsoil layer to provide both an opportunity for evapotranspiration to return liquid to the atmosphere and to provide a trafficable, erosion resistant surface upon which precipitation can be encouraged to flow horizontally for collection in drain pipes and subsequent diversion away from or recirculation through the landfill.

The intermediate cover is drawn in more detail in figure 3b. It consists of:

(1) underlying waste,

(2) a somewhat controlled layer of soil whose purpose is to provide a trafficable working surface and temporary diversion of water, and

(3) overlying wastes.

The underlying liner/drain module is drawn in more detail in figure 3c. It consists from bottom to top of:

(1) the undisturbed native soil to which the transmission of contaminated liquid must be controlled,

(2) a very low permeability synthetic liner to restrict and control downward movement of liquids into the native soil,

(3) a high permeability sand or gravel drain layer whose purpose is to provide a horizontal pathway along which liquid that collects on the synthetic liner can be transmitted to the collector drain pipes for diversion away from the landfill, and

(4) the overlying waste.

2.2 Categorizing Functions of Design Units

The various layers described above perform differing functions with respect to the transmission of liquid through the landfill. The low permeability layers, such as the clay liner in the final cover and the synthetic membrane in the bottom liner, are included to retard the rate of vertical flow of liquids. The high permeability layers, such as the sand or gravel drain in the liner/drain module, are included to encourage the flow of leachate toward the collector drain pipes. Some layers, for example the topsoil, are included because they are able to reduce the quantity of liquid available for leachate formation due to their evapotranspiration properties. Finally, some layers serve functions not primarily concerned with their ability to control transmission of liquids. These include the undifferentiated leveling layer, the waste, and the intermediate cover.

2.3 Definition of Units to be Included in the Liquid Transmission Control System

The above observations form the basis for an important axiom in evaluating the adequacy of containment in a hazardous waste surface impoundment:

> Certain units within the design are included primarily to control liquid transmission. These units should be clearly delineated and their intended functions described by the designer in the design documents.

In preparing the facility plans the designer should:

(1) specifically designate those units that are intended to control liquid transmission;

(2) describe how each unit will function to achieve this control;

(3) quantitatively assess the control capabilities of each unit in a rational manner; and

(4) demonstrate that each unit can be reasonably expected to serve this function when constructed according to the specifications given in the design.

Units for which the designer has not provided this information should be considered only to provide a safety margin above the basic control requirements and should not be taken into consideration in evaluating the adequacy of the system to meet minimum control requirements.

2.4 Liquid Diversion Interfaces

From figure 3 it is evident that many of the units that serve to control liquid transmission occur as modules consisting of an interface between two layers. There exist several distinct interfaces above which liquids are usually transmitted rapidly and in a horizontal direction, and below which liquids are usually transmitted slowly and in a vertical direction. It is the contrast in hydraulic transmissibility from high to low that accomplishes the change in flow direction from predominantly vertical to predominantly horizontal, thus diverting the flowing liquids to collector systems, subsequently to be conducted from the site. Examples are:

(1) the interface between the atmosphere and the vegetative cover,

(2) the interface between the sand drain and the compacted clay membrane in the final cover, and

(3) the interface between the sand drain and the synthetic membrane in the bottom liner system.

2.5 Constructing Liquid Routing Diagrams

Figure 4 shows a liquid routing diagram that both describes the several units comprising a landfill, and clearly designates by the letters LTC those modules that are considered to be part of the Liquid Transmission Control system. Shown also is a series of lines and arrows that explain the routing of liquid on its course through the liquid transmission control system. The interfaces which are composed of high transmissibility units overlying low transmissibility units and which serve to divert flow direction from vertical to horizontal are designated by the symbol DI for Diversion Interface. This suggests the first step in the evaluation procedure:

> If the designer has not already done so, construct a liquid routing diagram for the landfill. Using the symbol LTC, designate the units that are considered to be part of the liquid transmission control system. Determine the location of diversion interfaces and label them DI. Use arrows to show the liquid transmission control mechanisms. If the designer has provided such a diagram, the evaluator should confirm that it represents an appropriate diagram for use in evaluating the proposed design.

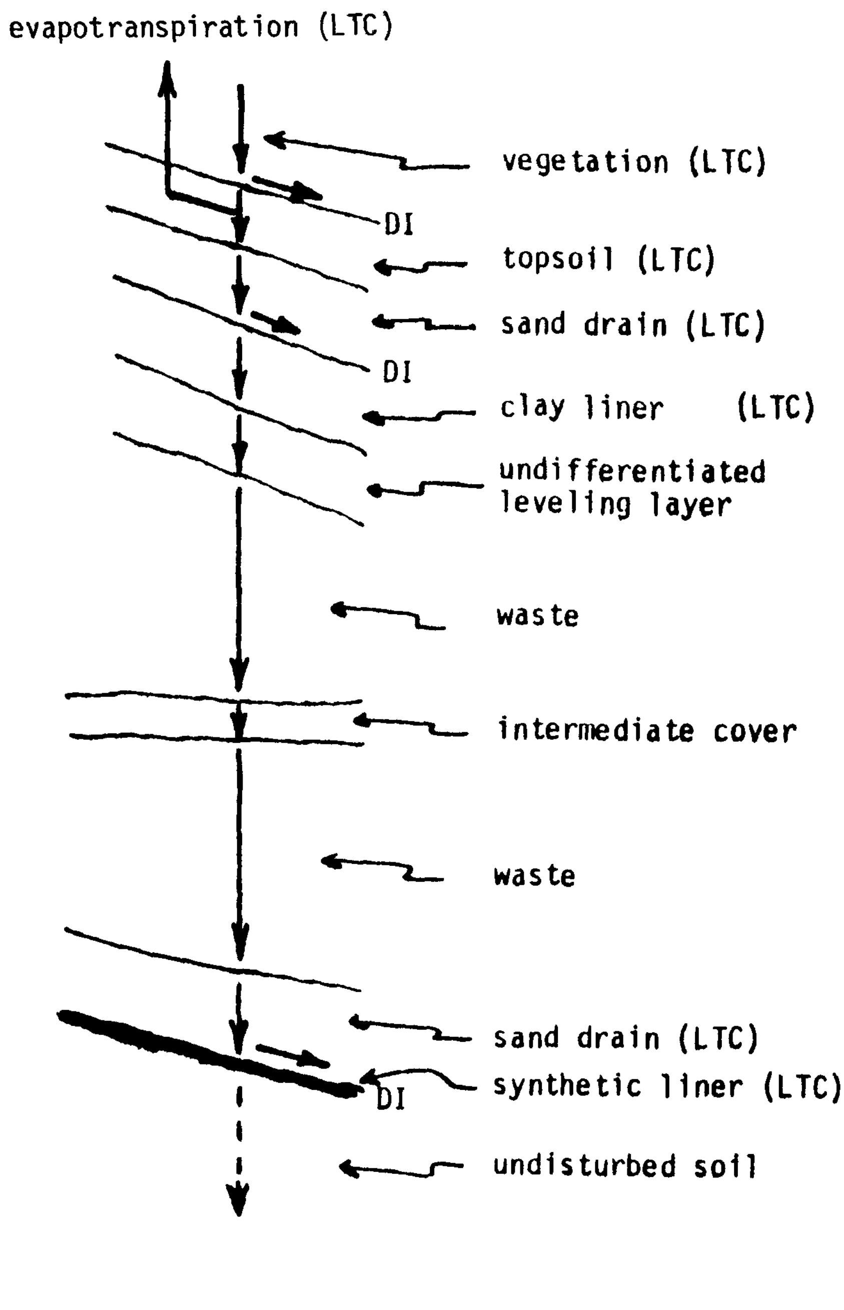


Figure 4 - Liquid routing diagram showing intended functions of components of leachate containment system.

3. ANALYTICAL METHODS

3.1 Introduction

Many landfill designs incorporate one or more liner/drain modules to limit the quantity of leachate that reaches the environment underlying the landfill. Modules located above the waste serve to intercept water before it can become contaminated, whereas modules located below the waste collect the leachate for treatment or for recirculation through the landfill.

The liner/drain system is one of the principal elements of hazardous waste landfills over which there can be a high degree of control during construction. The liner/drain system is constructed of select material and is emplaced using construction techniques that can be carefully supervised. Moreover, the finished liner/drain system can be inspected. Therefore, in designing and evaluating liner/drain systems, the engineer can use relatively exact analytical techniques and be assured that the design can be implemented in the field.

This chapter presents the equations that quantify leachate flow in individual liner/drain modules and in systems composed of multiple modules:

(1) Section 3.2 presents the equations used to calculate the maximum height of rise of leachate in a sand or gravel drain layer. The drain layer must be thick enough so that mounding liquid does not overtop it, thereby risking further contamination through additional contact with the waste.

(2) Section 3.3 presents the equations used to calculate the quantity of leachate flowing through compacted clay liners after they have become saturated. These equations determine how much leachate seeps through the liner to impinge on underlying liner/drain modules or to migrate into the underlying hydrogeologic regime.

(3) Section 3.4 presents the equations used to calculate the efficiency of liner/drain modules. These equations quantify the proportion of leachate that is diverted to horizontal flow, later to be collected, and the proportion that continues to seep downward.

These equations serve as the basis for the evaluation procedures to be presented in Chapter 4.

3.2 Analysis of Sand and Gravel Drain Layers

3.2.1 Calculating the Maximum Height to which Leachate Rises in a Drain Layer

Because of viscous resistance to horizontal flow, leachate tends to mound up in sand or gravel drain layers. This mounding could be great enough to cause the leachate to overtop the drain layer, resulting in the leachate becoming further contaminated. It is important to make certain that the thickness of the sand or gravel drain layer is greater than the anticipated height of mounding of the leachate.

The height of the mound does not increase without limit; rather, for a particular configuration of drain layer and for a given steady state impingement rate, leachate mounds to a certain maximum height. Figure 5 shows the conditions assumed for calculating the height of mounding in sand and gravel drain layers. Figure 5a shows a drain layer of thickness d (m) overlying a low permeability liner. The module slopes symmetrically at an angle α (exaggerated in this drawing) down to drain pipes spaced a distance L (m) apart. The saturated permeability of the drain layer is k_{s1} (m/sec), and its porosity is n. Liquid impinges upon the module at a rate of e (m/sec). The source of this liquid could be rainfall, recirculated leachate, or liquid generated by the waste itself.

In the limiting case of $\alpha = 0$ (shown in figure 5b), the shape of the water mound that accumulates in the drain layer is given by Harr (1962) as:

$$h = \frac{1}{n}\left(\frac{e}{k_{s1}}(L - x)x\right)^{1/2} \tag{1}$$

For a horizontal module, the maximum value of h occurs at x = L/2 and is given by:

$$h_{max} = \frac{L}{2n}\left(\frac{e}{k_{s1}}\right)^{1/2} \tag{2}$$

As an example, consider a flat module having drain pipes placed 30 m (approximately 100 feet) apart in a sand having $k_{s1} = 1x10^{-3}$ cm/sec and n = 0.5. Assume an annual rainfall of 100 cm/yr (39 in/yr) equally

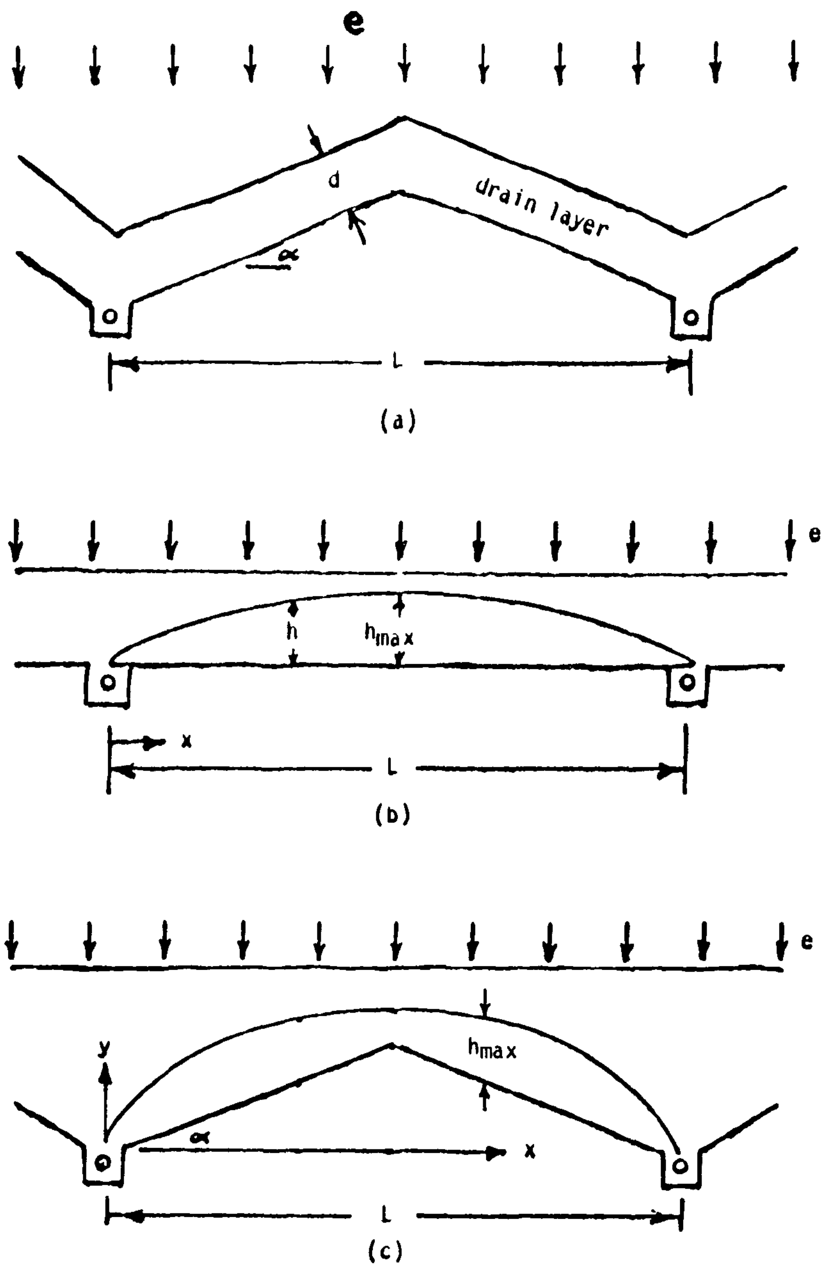


Figure 5 - Geometry assumed for bounding solution for effectiveness of sand drains.

distributed in time so that e = 3.2×10^{-6} cm/sec. Thus from equation (2):

$$h_{max} = \frac{30m}{2(0.5)} \left(\frac{3.2 \times 10^{-6} \text{ cm sec}}{1 \times 10^{-3} \text{ sec cm}} \right)^{1/2} = 1.7 \text{ m}$$

The high value for h_{max} obtained in this example demonstrates that designing an open-topped, flat-bottomed landfill is impractical. Returning to figure 5a, it can be seen that putting the drain module on a slope α not equal to zero tends to accelerate the flow of water toward the collector pipes. Figure 5c shows the accumulation profile. It is very much like that of figure 5b, except that h_{max} does not occur at x = L/2. The configuration with α not equal to zero has some convenient properties when compared with α equal to zero. The obvious one is that the hydraulic gradient toward the drain pipe is higher. Another significant advantage is that if the liquid were to cease impinging on the drain layer, the mound would completely drain out into the collector drain pipes in a finite amount of time if α is not equal to zero; whereas, the drainage time for α equal to zero is infinitely long.

As shown in figure 5c, there is a value for h_{max} that is given by an expression similar to equation (2):

$$h_{max} = \frac{L}{2n} \left[\sqrt{\frac{e}{k_{s1}} + \tan^2 \alpha} - \tan \alpha \right] \qquad (3)$$

For the example presented above, but with $\alpha = 10^\circ$ rather than zero, we can use equation (3) to give:

$$h_{max} = \frac{30m}{2(.5)} \left[\left(\frac{3.2 \times 10^{-6} \text{ cm sec}}{1 \times 10^{-3} \text{ sec cm}} + \tan^2(10) \right)^{1/2} - \tan(10) \right] = 0.26 \text{ m}$$

Thus, placing the module at this incline reduces the height of mounding by a factor of 6.5.

3.2.2 Comments on the Height of Rise

Figure 6 presents h_{max}/L as a function of α for several values of e/k_{s1}. The graph holds for all values of α because equation (3) reduces to equation (2) for $\alpha = 0$. It can be seen that for higher e/k_{s1} ratios, increasing the slope of the liner reduces h_{max} significantly. For lower e/k_{s1} ratios, increasing the slope of the liner has some effect on h_{max} for small α; however, further increases in α produce little additional benefit.

Equations (2) and (3) were derived on the assumption that saturated Darcy flow occurs within the drain layer. This presumes that the wetted volume of soil is large relative to the diameter of the soil particles. The h_{max} to grain diameter ratio should be perhaps 10 or more for the equations to be valid. For example, if 1 inch gravel is being used for the drain layer, and equation (2) or equation (3) predicts h_{max} = 0.5 inch, the value of h_{max} is not likely to be valid.

These equations also assume that the liner/drain module is constructed as a perfectly flat plane oriented at an angle α to the horizontal. In practice there will be undulations in the surface of the compacted clay liner that can provide an opportunity for ponding to occur over relatively short distances to relatively shallow depths. This is not likely to affect h_{max} appreciably; however, it may significantly affect the calculations to be performed in section 3.4. Thus, when evaluating the slope on a liner/drain module, the designer and evaluator should not rely on extremely shallow slopes functioning in accordance with the equations presented.

Both equations (2) and (3) include the soil porosity, n, in the relationship. The reason for this is as follows. Impingement rates are given in units of meters per second based upon the assumption that the depth of accumulation is measured by a device such as a rain gage. However, when one meter of water is introduced into a sand or gravel layer, the water can only occupy the soil voids. It cannot occupy the volume devoted to the soil solids. Thus, one meter of water will mound to a height equal to the impingement quantity divided by the soil porosity; hence, the division by n.

Finally, the analytical solution represented by equation (3) was obtained by neglecting a small differential term that would tend to reduce the value determined for h_{max}. The error involved is relatively small, and it is on the conservative side (i.e. use of equation (3) will result in drain layers being designed somewhat thicker than necessary). McBean et al. (1982) present a numerical method that approximates the exact solution for the case of a sloped liner/drain module.

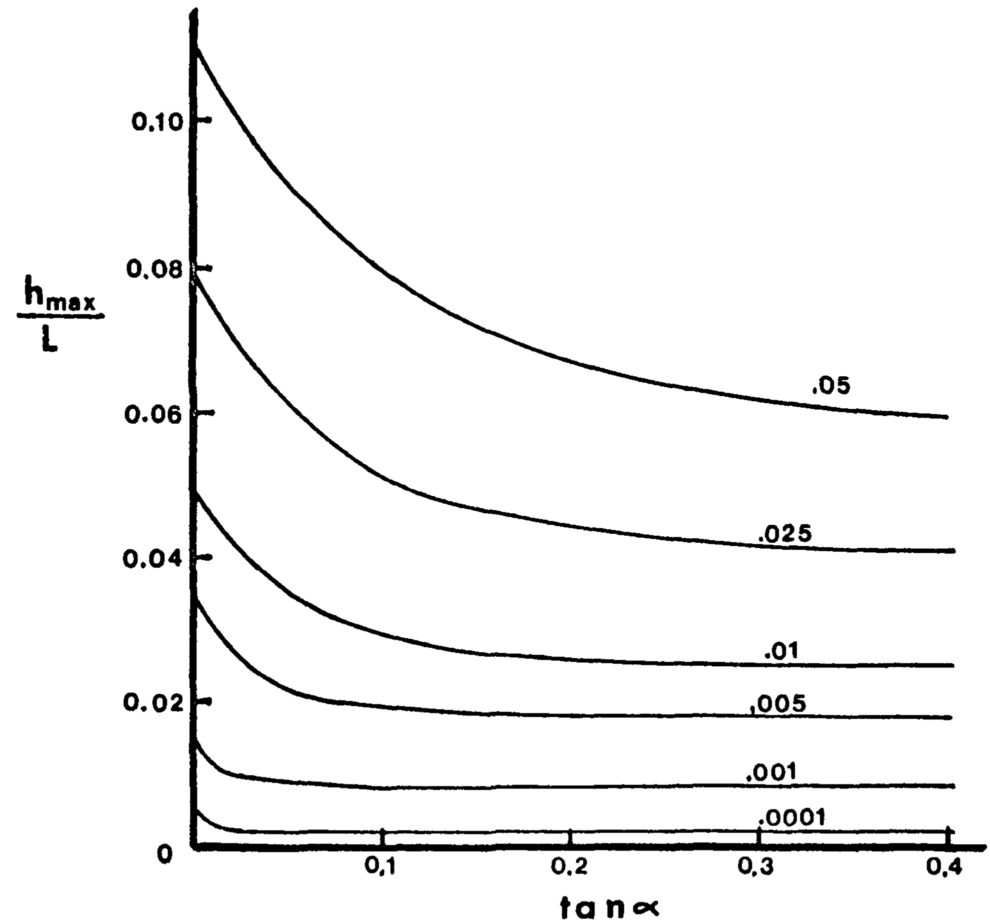


Figure 6 - Relationship between h_{max}/L and tan α for various values of k_s/e.

3.3 Analysis of Flow through Saturated Clay Liners

3.3.1 Calculating Vertical Seepage Quantities through a Liner

After the clay liner has become saturated, gravitational forces dominate the flow process. The total quantity, Q, of liquid passing through the clay liner in time, Δt, is given by:

$$Q = k_{s2} \frac{dh}{dz} (A) \Delta t \qquad (4)$$

where

k_{s2} = the saturated hydraulic conductivity of the clay liner, more commonly referred to as the Darcy coefficient of permeability,
dh = the change in total hydraulic head,
dz = distance over which the head change occurs, and
A = cross sectional area through which flow occurs.

The quantity of liquid seeping through the liner, e, per unit cross-sectional area and per unit time can be determined by setting A and Δt in equation (4) equal to 1.0. Thus, for a saturated liner of thickness, d, with no leachate standing on top (dh/dz = 1.0), the seepage quantity from equation (4) becomes:

$$e = k_{s2} \qquad (5)$$

As an example, consider a saturated liner constructed of a clay having $k_{s2} = 1x10^{-7}$ cm/sec. We can use equation (5) to calculate the monthly quantity of leachate seeping through this liner:

$$e = \frac{1x10^{-7}\ \text{cm}\quad 2678400\ \text{sec}}{\text{sec} \qquad\qquad \text{mo}} = 0.268\ \text{cm/mo}$$

An upper bound for the seepage quantity in a liner/drain module would be the case where liquid mounds within the drain layer to a depth h_{max}. In this case equation (4) becomes:

$$e = \left(\frac{d + h_{max}}{d}\right) k_{s2} \tag{6}$$

As an example, consider a two foot thick clay liner having $k_{s2} = 1x10^{-7}$ cm/sec and $h_{max} = 1.3$ feet. Equation (6), in combination with the previous example problem result, gives:

$$e = \left(\frac{2 + 1.3}{2}\right) (0.268) = 0.442 \text{ cm/mo}$$

In evaluating surface impoundments, the hydraulic gradient is augmented by the liquid ponded within the lagoon. In this case, the flow quantity is given by:

$$e = \left(\frac{d + H}{d}\right) k_{s2} \tag{7}$$

where

H = depth of liquid in the lagoon.

For example, consider a lagoon impounding liquid to a depth of 10 feet. It has a two foot thick clay liner with $k_{s2} = 1x10^{-7}$ cm/sec. Equation (7) gives:

$$e = \left(\frac{2 + 10}{2}\right) (0.268 \text{ cm/mo}) = 1.61 \text{ cm/mo}$$

3.3.2 Comments on Steady State Seepage Quantities

The equations presented in section 3.3.1 cannot be used to calculate the velocity with which liquid moves through the liner. Neither can they be used to predict the velocity with which a pollutant is carried through the liner by the liquid. This is because the flow process occurs by liquid moving randomly through a multitude of pores, each varying in size, orientation, and tortuosity. The actual flow velocity is a microscopic characteristic, varying greatly from location to location. Moreover, physico-chemical forces of attraction such as Van der Waal's forces and ion hydration cause a significant portion of the liquid to be relatively securely retained by the soil particles. This causes the remainder of the liquid to flow in even smaller channels and at even higher velocities.

In short, the Darcy coefficient of permeability, k_{s2}, used in equations (4) through (7) is a macroscopic parameter calculated by measuring the quantity of liquid flowing through a soil sample in a given period of time. That quantity (k_{s2}) can, in turn, only be used to calculate the quantity of liquid that will pass through the same soil in a given period of time. Any attempt to use the coefficient of permeability to speculate about flow velocities or pollutant transport velocities at the microscopic level will be conceptually and numerically incorrect.

It is also erroneous to attempt to predict the time required for leachate to appear at the bottom of a clay liner wetting up for the first time using calculations based only on the saturated coefficient of permeability, k_{s2}. The reason for this is that Darcy flow assumes that the gravitational potential is the only force tending to move liquid through the soil. As explained in the Appendix, flow through partially saturated soil occurs both as a result of the gravitational potential and capillary potential. During initial wetting up, the capillary potential can greatly exceed the gravitational potential in the soil. Thus, the flow process during initial wetting up usually occurs much faster than the gravity-induced Darcy flow that governs the process after the clay liner has become saturated.

3.4 Efficiency of a Liner/Drain Module

The efficiency of a liner/drain module is a quantitative measure of the proportion of liquid that moves along the drain layer to be collected by the collector drain pipes, relative to the proportion that seeps through the liner. For liner/drain modules located above the waste, a highly efficient module means that very little water seeps downward into the waste where it may become contaminated. For liner/drain modules located below the waste, a highly efficient module means that most of the leachate is collected for treatment or recirculation.

3.4.1 Calculating the Efficiency

Wong (1977) proposed an approximate technique for quantifying the efficiency of a liner/drain module based upon saturated Darcy flow in both the drain layer and the clay liner. Figure 7 describes the geometry assumed in Wong's calculations.

The approach postulates that at some initial time, a rectangular slug of liquid is placed upon the saturated liner to a depth h_0. The liquid flows both horizontally along the slope of the module and vertically into the clay liner. The fraction of liquid moving into the collector drain pipes at time, t, is given by:

$$\frac{s}{s_0} = 1 - \frac{t}{t_1} \tag{8}$$

and the fraction of liquid seeping into the clay liner at that instant is given by:

$$\frac{h}{h_0} = \left(1 + \frac{d}{h_0 \cos \alpha}\right) e^{-Ct/t_1} - \frac{d}{h_0 \cos \alpha} \qquad 0 \leq t \leq t_1 \tag{9}$$

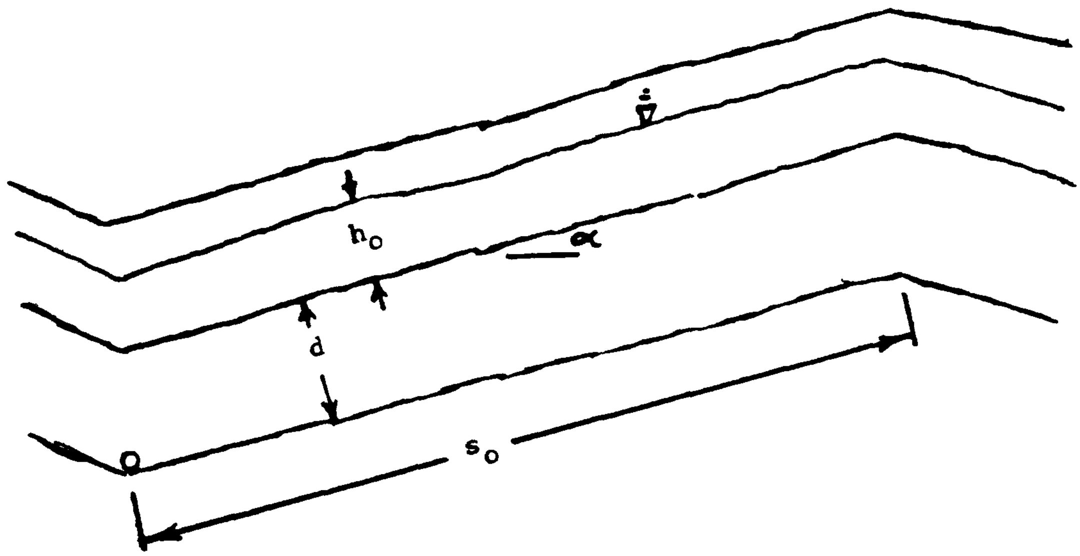


Figure 7 - Geometry for calculating efficiency of liner/drain systems using method proposed by Wong (1977).

where

$$t_1 = \frac{s_o}{k_{s1} \sin \alpha} \tag{10}$$

and

$$C = \left(\frac{s_o}{d}\right)\left(\frac{k_{s2}}{k_{s1}}\right)\cot \alpha \tag{11}$$

and

s = length of saturated volume at time, t (cm)
h = thickness of saturated volume at time, t (cm)
s_o = initial length of saturated volume (cm) = $L/2\cos(\alpha)$
h_o = initial thickness of saturated volume (cm) = (impingement quantity)/n
n = soil porosity
k_{s1} = saturated permeability of the material above clay liner (cm/sec)
k_{s2} = saturated permeability of the clay liner (cm/sec)
α = slope of angle of the module (degrees)
d = thickness of the clay liner (cm).

Figure 8 shows the geometry at some time, t.

If the module is allowed to drain completely, its efficiency can be determined using figure 9, which graphs h/h_o versus s/s_o and t/t_1. Equations (8) and (9) can be solved parametrically in t/t_1 to yield the line shown on figure 9. The line is actually a curve; however, for practical liner/drain configurations it can be approximated as a straight line. In figure 9 the efficiency of the module is given by the area labeled E. This area is most easily determined by calculating the value of h/h_o when $t/t_1 = 1.0$ (or $s/s_o = 0$). This parameter, called N, can be obtained by solving equation (9) with $t/t_1 = 1.0$:

$$N = \left(1 + \frac{d}{h_o \cos \alpha}\right)e^{-C} - \frac{d}{h_o \cos \alpha} \tag{12}$$

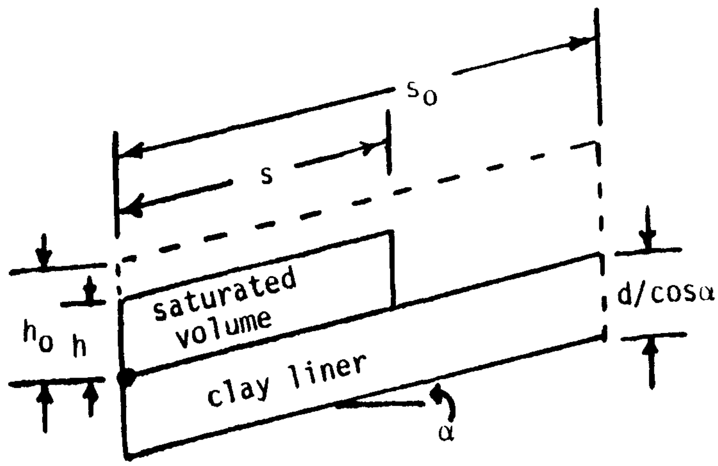


Figure 8 - Geometry for calculating efficiency of liner/drain systems. (after Wong, 1977)

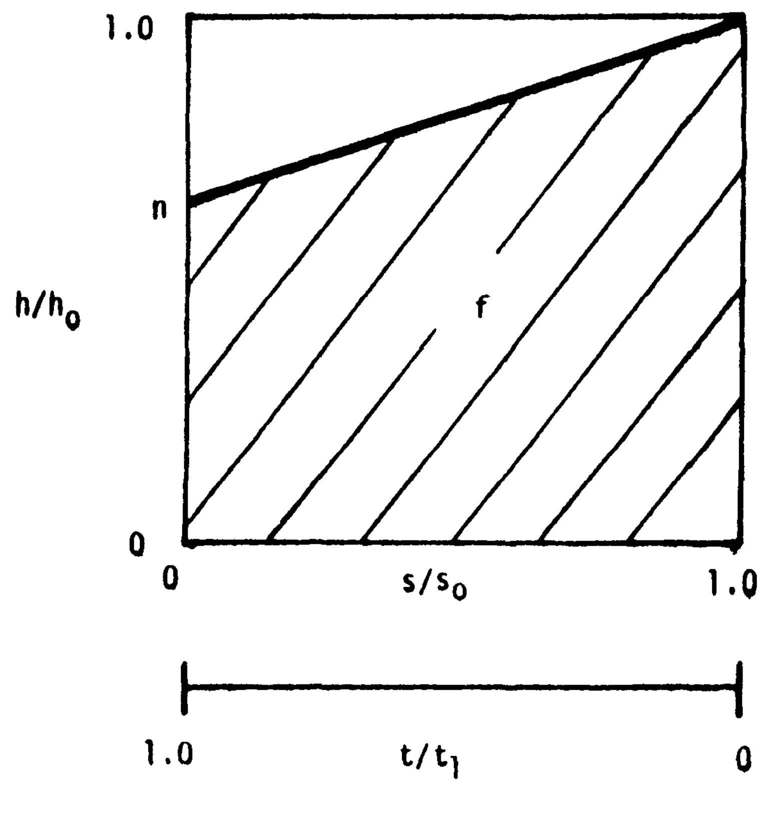


Figure 9 - Diagram for computing efficiency of liner/drain systems. (after Wong, 1977)

The value of N can be either positive or negative; however, most efficient designs will have $N \geq 0$. The efficiency, E, is given by either

$$E = \frac{1 + N}{2} \qquad \text{for } N \geq 0 \tag{13a}$$

or

$$E = \frac{1}{2(1-N)} \qquad \text{for } N \leq 0 \tag{13b}$$

Thus the efficiency varies from 0 to 1.0.

The following procedure is used to calculate the quantity of liquid collected in the drain pipes and the quantity of liquid seeping through the clay liner at the end of one month. First, calculate t_1 using equation (10). Next, solve for N' using t = one month:

$$N' = \left(1 + \frac{d}{h_o \cos \alpha}\right) e^{-Ct/t_1} - \frac{d}{h_o \cos \alpha} \tag{14}$$

Then calculate an efficiency at the end of one month using equations analogous to equations (13a) and (13b):

$$E' = \frac{1 + N'}{2} \qquad \text{for } N' \geq 0 \tag{15a}$$

$$E' = \frac{1}{2(1-N')} \qquad \text{for } N' \leq 0 \tag{15b}$$

Thus, the quantity of liquid flowing to the collector drain pipes per meter of liner/drain module in cubic meters during the month is:

$$Q_d = E' h_o s_o n \tag{16}$$

The quantity of liquid seeping through the clay liner and impinging below is:

$$e = (1 - E') h_o n \tag{17}$$

As an example of the above calculations, consider a module having a 30 cm thick compacted clay liner with $k_{s2} = 1.0 \times 10^{-7}$ cm/sec, overlain by a gravel layer having $k_{s1} = 1 \times 10^{-3}$ cm/sec. The entire module slopes at 17.6 ft/100 ft, and the spacing between drain pipes is 30 m. Assume that in the month in question 1.25 cm of liquid impinges on a sand drain layer having a porosity of 0.5.

$\alpha = 10^\circ$ (17.6 ft/100 ft)
$k_{s1} = 1 \times 10^{-3}$ cm/sec
$k_{s2} = 1 \times 10^{-7}$ cm/sec
d = 30 cm = 0.3 m
n = 0.5
h_o = 1.25/0.5 = 2.5 cm
$s_o = L/2\cos(\alpha)$ = 30 m/2cos(10) = 1523 cm

From equation (11):

$$C = \frac{30 \text{ m}}{2 \times 0.3 \text{ m} \cos(10)} \frac{1 \times 10^{-7} \text{ cm sec}}{1 \times 10^{-3} \text{ sec cm}} \cot(10) = 0.0288$$

From equation (12):

$$N = \left(1.0 + \frac{0.3 \text{ m}}{0.025 \text{ m} \cos(10)}\right) e^{-0.0288} - \frac{0.3 \text{ m}}{0.025 \text{ m} \cos(10)} = 0.626$$

From equation (13):

$$E = \frac{1 + 0.626}{2} = 0.813$$

Thus 81.3% of the liquid is ultimately diverted to the drain pipes.

To determine the quantity of liquid flowing to the collector drain pipes and the quantity impinging below, begin by calculating the value of t_1 as given by equation (10):

$$t_1 = \frac{30\ \text{m}\qquad\qquad \text{sec}\qquad 100\ \text{cm}\qquad\qquad \text{mo}}{2\cos(10)\times 1\text{x}10^{-3}\ \text{cm}\ \sin(10)\ \text{m}\quad 2678400\ \text{sec}} = 3.27\ \text{mo}$$

Then, from equation (14), determine N':

$$N' = \left(1 + \frac{0.3\ \text{m}}{0.025\ \text{m}\cos(10)}\right) e^{-0.0288(1/3.27)}$$

$$- \frac{0.3\ \text{m}}{0.025\ \text{m}\cos(10)} = 0.88$$

Next, put this value of N' into equation (15a) to give:

$$E' = \frac{1 + 0.88}{2} = 0.94$$

Finally, the quantity of liquid flowing to the collector drain pipes at the end of one month per meter of drain pipe is given by equation (16) to be:

$$Q_d = \frac{0.94 \times 2.5\ \text{cm}\ \ 30\ \text{cm}\ \ 0.5\ \ \text{m}}{2\cos(10)\ \ 100\ \text{cm}} = 0.18\ \text{m}^3/\text{mo/m}$$

The quantity of liquid seeping through the clay liner during the month is given by equation (17) to be:

$$e = (1.0 - 0.94)\ 2.5\ \text{cm}\ (0.5) = 0.075\ \text{cm/mo}$$

3.4.2 Comments on the Efficiency of Liner/Drain Modules

This section examines the interrelationships among the parameters affecting a liquid transmission control module's performance. The objective is to determine which parameters can be most practically adjusted to achieve satisfactory system performance. The parameters to be examined include:

the impingement rate on the liner/drain module (e_i),
the slope of the module (α),
the thickness of the clay liner (d),
the spacing between collector drain pipes (L),
the saturated coefficient of permeability of the sand or gravel drain layer (k_{s1}), and
the saturated coefficient of permeability of the clay liner (k_{s2}).

To show these interrelationships, we will consider two contrasting designs. For the particular site under consideration, liner/drain module A will be shown to perform efficiently, whereas liner/drain module B performs inefficiently. Table 1 compares the design characteristics for these two modules.

Selecting a value for the impingement rate, e_i, on the liner is a complicated process because this quantity is highly dependent upon geographic location, season of the year, and position of the liner/drain module within the landfill. The U.S. EPA Municipal Environmental Research Laboratory in Cincinnati used the computer programs described in SW-868 to provide hydrologic information for a typical landfill cover configuration used at six sites representing a range of climatic conditions for the continental United States. Seepage quantities varying from zero to perhaps 0.5 inch/month (4.9×10^{-7} cm/sec) could be expected through a well designed and well

Table 1 - Parameter values for modules A and B.

PARAMETER	MODULE A VALUE	MODULE B VALUE
L	2286 cm = 75 ft	3810 cm = 125 ft
d	152 cm = 5 ft	61 cm = 2 ft
α	10 degrees	5 degrees
k_{s1}	$1\text{x}10^{-3}$ cm/sec	$1\text{x}10^{-3}$ cm/sec
k_{s2}	$1\text{x}10^{-7}$ cm/sec	$1\text{x}10^{-6}$ cm/sec
k_{s1}/k_{s2}	$1\text{x}10^{-4}$	$1\text{x}10^{-3}$

Table 2 - Values used for parameter studies.

FIGURE	α	d	L
13a	5 to 10 degrees	106.5 cm	3048 cm
13b	7.5 degrees	61 to 152 cm	3048 cm
13c	7.5 degrees	106.5 cm	2286 to 3810 cm

maintained cover. Moreover, during landfilling and prior to construction of the cover, the liner/drain module could be subjected to direct rainfall amounting to 15 inches/month ($1.5x10^{-5}$ cm/sec) or more.

Because the rainfall amounts vary so much, it is not practical to select a single value for e_i. Rather, the performance of the liquid transmission control system should be evaluated by using a range of values appropriate to the particular site and design.

For purposes of this discusssion we will examine the performance of liner/drain modules A and B using impingement rates varying from zero to $1x10^{-5}$ cm/sec (10.2 inches/month). Figure 10a plots efficiency, E, versus impingement rate, e_i, for these modules; figure 10b plots the seepage quantity, e_s, through the clay liner versus impingement quantity, e_i, for the same modules.

For both designs, as the impingement rate approaches zero, the efficiency also approaches zero. This is an algebraic consequence of equations (8) through (13) and will be the case for any design, good or poor. However, note that design A shows a substantial increase in efficiency over the relevant range of impingement rates; whereas design B shows a disappointingly small increase in efficiency as impingement rate increases. If a particular liner/drain module has a low efficiency, it may be poorly designed. Conversely, it may be quite well designed, but have a low impingement rate -- perhaps due to other well designed liner/drain modules or a good cover overlying it. Thus, low efficiency should not be used as the sole basis for rejecting a liner/drain design.

Figure 10b shows that both modules allow very little seepage for low impingement rates. However, as impingement rate increases, design A quickly reaches a low asymptotic value above which the steady state seepage quantity never rises. Conversely, design B does not exhibit an apparent upper limit over the range of impingement rates examined. Rather, design B stays dangerously close to the 45 degree line representing zero efficiency; that is, most of the liquid that impinges on the module continues seeping downward through the liner.

In conclusion, a well designed liner/drain module not only performs well under the conditions that could be reasonably anticipated in the landfill, but also exhibits increasing efficiency if the actual amount of impinging liquid exceeds the expected amount.

We now examine what makes design A function better than design B. Figure 11a shows two designs that have module A's design features of high slope, thick clay liner, and close spacing between drain pipes. Design A1 has a k_{s2}/k_{s1} ratio of $1x10^{-4}$, while design A2 has a k_{s2}/k_{s1} ratio of $1x10^{-3}$. Clearly, module A1 performs significantly better than module A2. A similar conclusion can be drawn from figure 11b, which shows two designs that have module B's design features of low slope, thin clay liner, and long spacing between drain pipes. Design B1 has k_{s2}/k_{s1} equal to $1x10^{-4}$, whereas design B2 has a k_{s2}/k_{s1} ratio of $1x10^{-3}$.

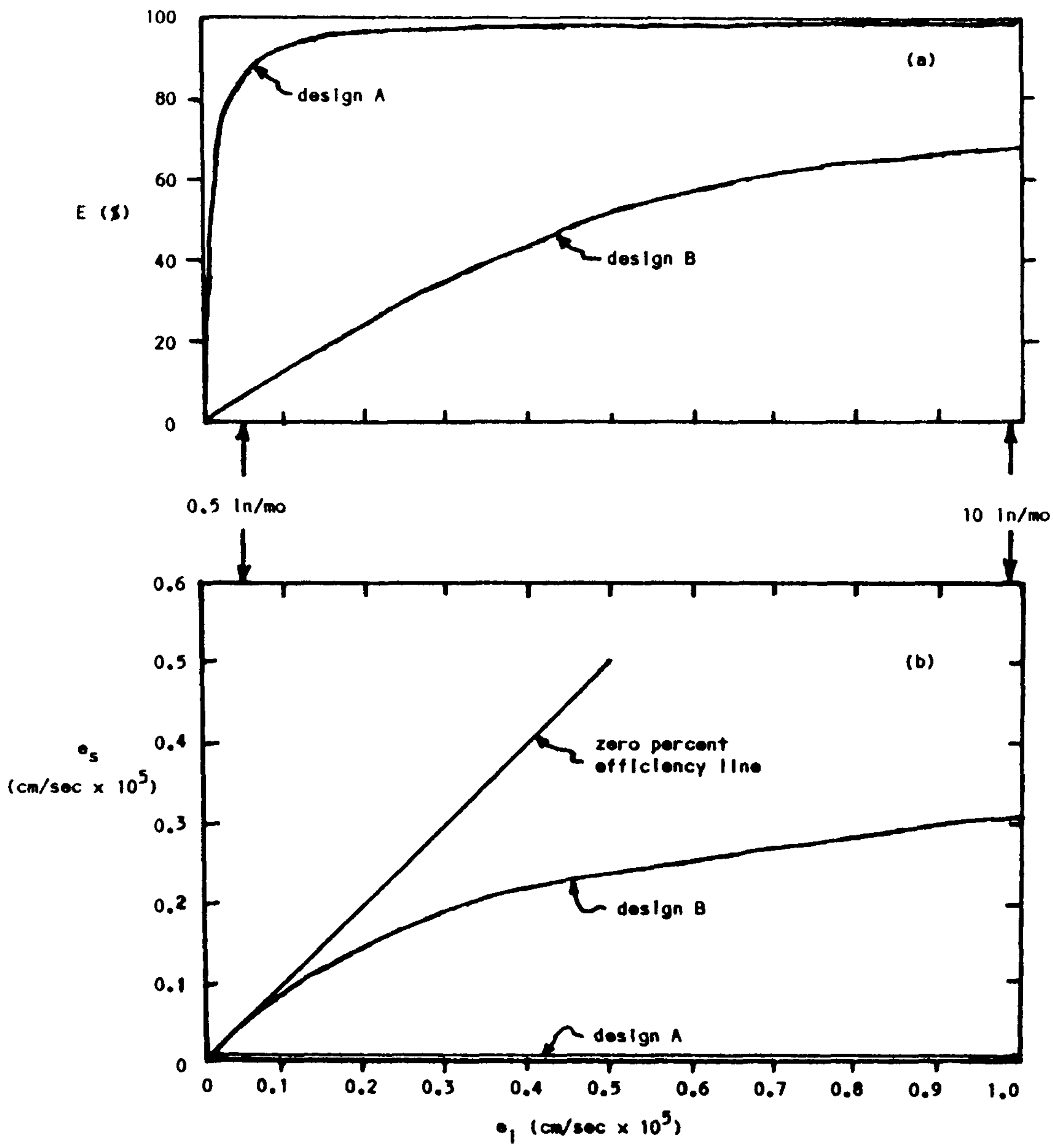


Figure 10 - Efficiency and effectiveness as a function of liquid impingement rate for designs A and B.

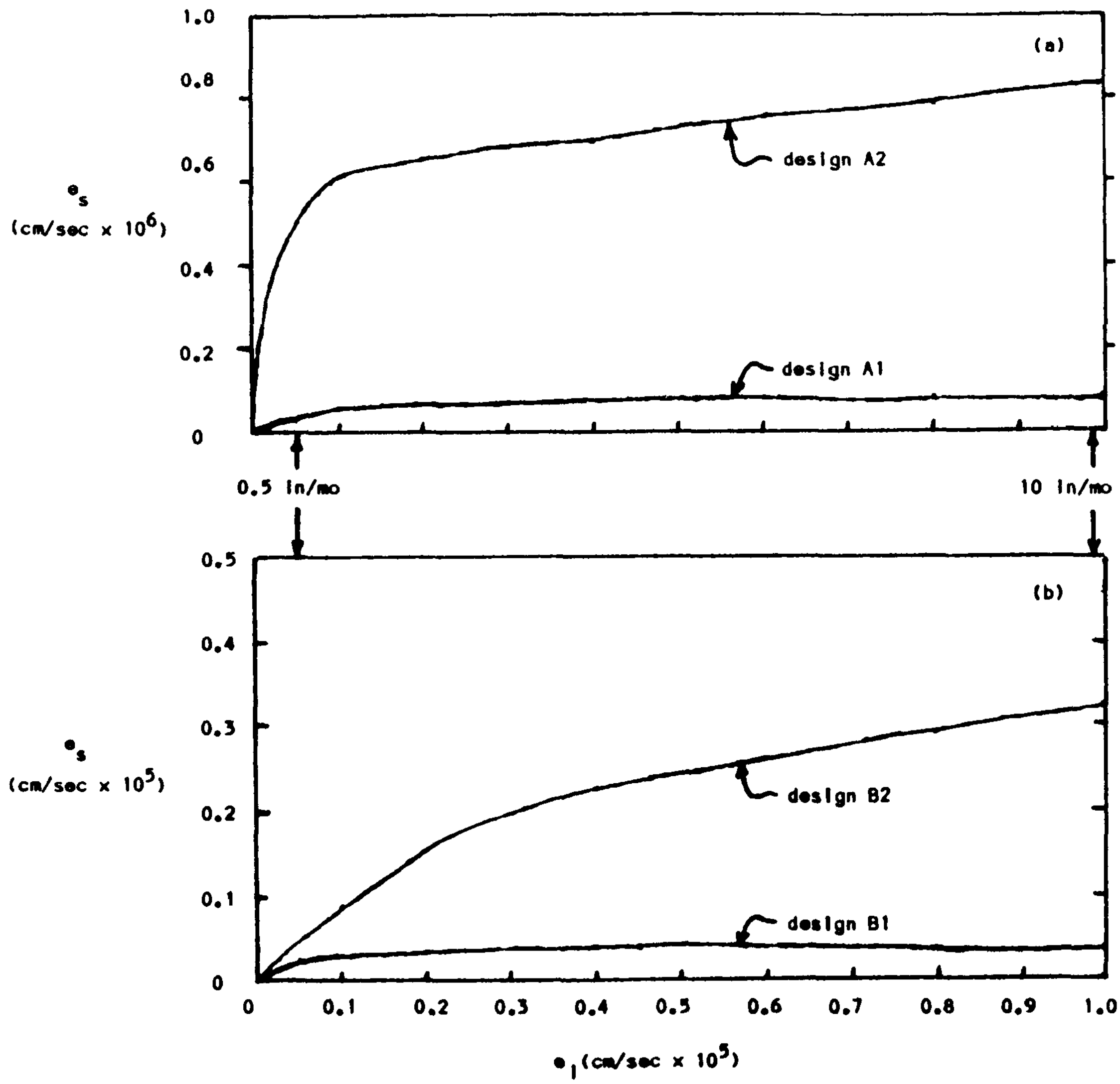


Figure 11 - Effectiveness as a function of impingement rate for designs A1, A2, B1, B2.

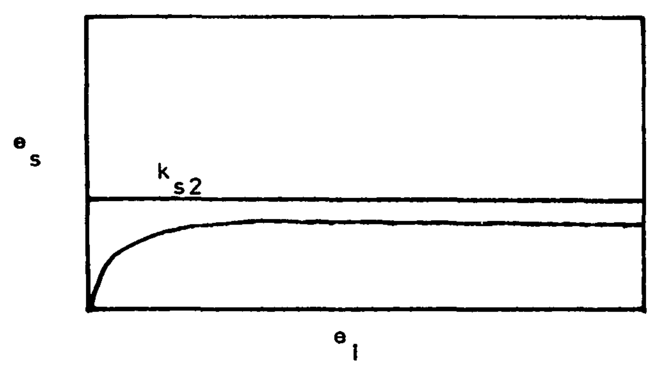


Figure 12 - Seepage rate versus impingement rate with maximum potential steady state seepage rate superimposed.

These comparisons demonstrate that the ratio of the permeabilities of the drain layer to the clay liner strongly affects the efficiency of the liner/drain module.

Nevertheless, the reader is cautioned against concluding that specifying the k_{s2}/k_{s1} ratio alone will insure an adequate design: The above calculations are based on theories (expressed in equations (8) through (13)) that assume saturated Darcy flow. This means that the quantity of liquid present must substantially fill the pore space in the soil mass. This, in turn, implies that the size of the largest particle in the drain layer must be considerably smaller than the mounded liquid depth as expressed, for example, by h_{max}. In the extreme, a k_{s2}/k_{s1} ratio of $1x10^{-4}$ could be achieved by having a boulder drain layer overlying a sand liner. This clearly would neither constitute an acceptable design, nor would it constitute a module within which the flow approximates the assumptions used in the theories.

To avoid such situations, we need to use the analytical tools provided by equations (5) and (6). These equations predict the maximum potential steady state seepage quantity based upon the coefficient of permeability of the clay liner, k_{s2}. Assuming for the moment that h_{max} is relatively small, we can use equation (5) which predicts that the maximum potential steady state seepage quantity through the clay liner is equal to k_{s2}. Thus, we can superimpose the value of k_{s2} on the e_s axis of the e_i versus e_s plot of figure 10b (redrawn as figure 12). If the asymptote approached by the e_i versus e_s relationship for a particular liner/drain module lies well below the k_{s2} line, and if the k_{s2} line is acceptably low, then the liner/drain module performs effectively.

Finally, we examine the influence of varying liner/drain slope, α, clay liner thickness, d, and collector drain spacing, L, on liner/drain module effectiveness. For this evaluation, $k_{s1} = 1x10^{-3}$ cm/sec, $k_{s2} = 1x10^{-7}$ cm/sec and $e_i = 5x10^{-7}$ cm/sec for all cases. The combinations of α, d, and L evaluated are summarized in Table 2, and the results are presented in figure 13.

It can be seen that both α and L have a measurable influence on the effectiveness of the liner/drain module. Clearly, they should be considered when optimizing a design. However, their effect is not nearly as great as the effect of the k_{s2}/k_{s1} ratio. It is also apparent that the clay liner thickness, d, has no influence on the effectiveness of the module, provided that there is no liquid standing on the liner.

The analytical techniques that were presented in this section are based on the work of Wong (1977). Other methods for determining efficiencies have been presented by Lentz (1981) and by Skaggs (1982). Lentz's method has the advantage of being able to incorporate multiple sequential applications of liquid slugs onto the liner. However, his method presumes that liquid is always in contact with the clay liner along its entire length. Moreover, his method does not explicitly incorporate the thickness of the clay liner into the calculations. Skaggs's method involves a computer program to implement numerical solutions.

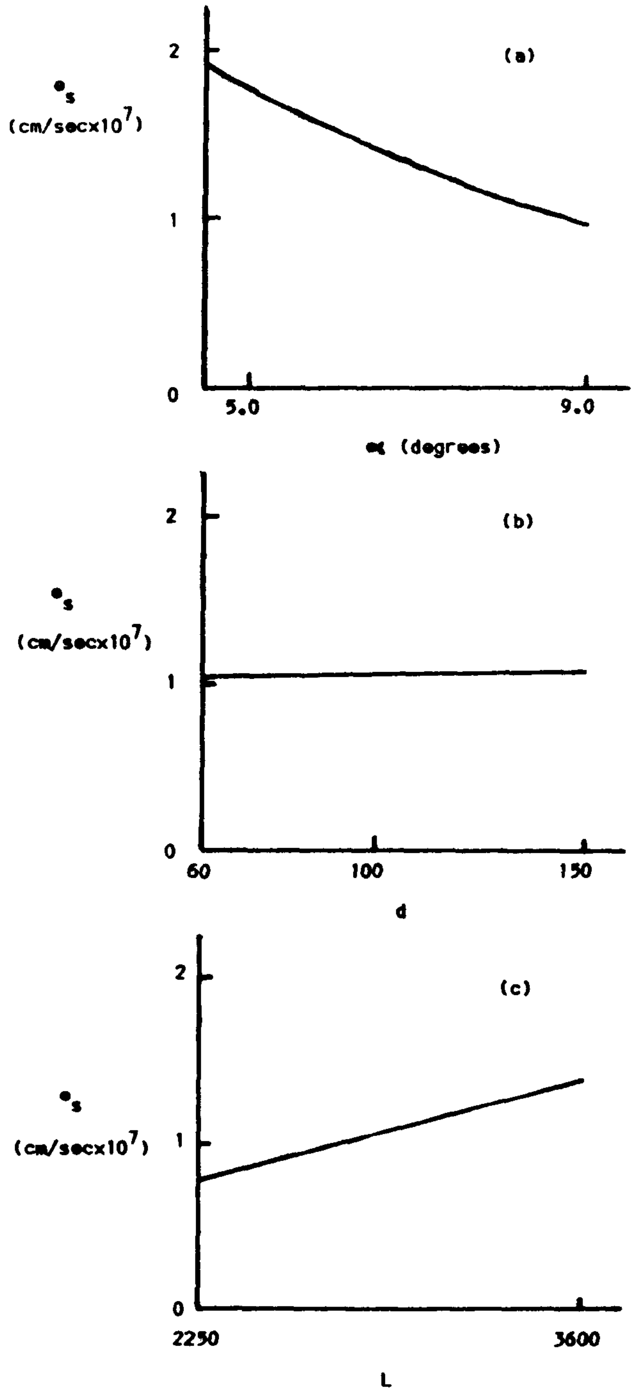


Figure 13 - Effect of varying α, d, and L on liner/drain module effectiveness.

3.5 Efficiencies for Multiple Liner/Drain Modules

3.5.1 Calculating the Efficiency

By incorporating multiple liner/drain modules into a landfill, it is possible to greatly increase the efficiency of leachate containment. When a system incorporating multiple modules is used, it is necessary to evaluate not only the efficiency of each individual liner/drain module, but also to evaluate the cumulative efficiency of the system composed of the several liner/drain modules. The analytical techniques presented in section 3.4.1 for determining the efficiency of a single liner/drain module are extended in this section to analyze multiple modules.

Figure 14 presents a liquid routing diagram for a landfill containing multiple liner/drain modules and defines the following seepage rates (cm/sec) to be used in subsequent definitions and calculations:

e_{prec}	= precipitation rate	(18)
e_{s0}	= seepage rate through the cover as determined from hydrologic simulation (SW-868)	(19)
e_{i1}	= impingement rate on module 1, usually taken equal to e_{s0} under the assumption of plug flow	(20)
e_{s1}	= seepage rate through the clay liner of module 1	(21)
e_{i2}	= impingement rate on the bottom control module	(22)
e_{s2}	= seepage rate impinging on the regime underlying the landfill	(23)

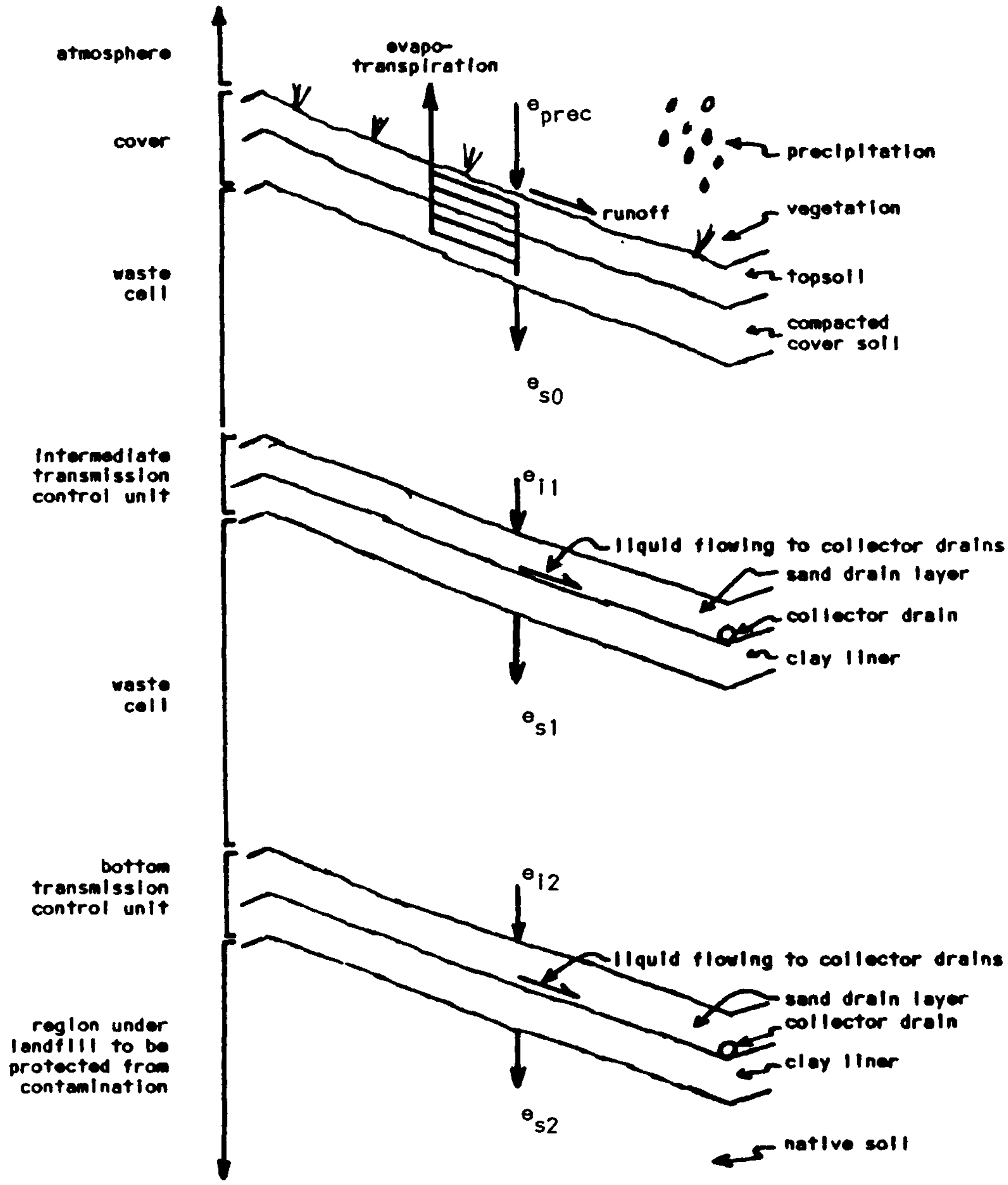


Figure 14 - Cross section of landfill showing liquid transmission control system and liquid routing diagram.

We can define the efficiencies of the individual liner/drain modules as follows:

$$E_0 = \frac{e_{prec} - e_{s0}}{e_{prec}} \quad \text{for the cover} \quad (24)$$

$$E_1 = \frac{e_{i1} - e_{s1}}{e_{i1}} \quad \text{for the intermediate transmission control module} \quad (25)$$

$$E_2 = \frac{e_{i2} - e_{s2}}{e_{i2}} \quad \text{for the bottom control module} \quad (26)$$

We also define the following cumulative efficiencies for segments of the design composed of more than one liner/drain module:

$$E_{01} = \frac{e_{prec} - e_{s1}}{e_{prec}} \quad \text{for cover plus the intermediate transmission control module} \quad (27)$$

$$E_{02} = \frac{e_{prec} - e_{s2}}{e_{prec}} \quad \text{for cover plus the intermediate and bottom transmission control modules} \quad (28)$$

$$E_T = E_{02} \quad \text{where } E_T \text{ is the total efficiency of the transmission control system} \quad (29)$$

Here the subscripts (E_{0n} for example) indicate that the efficiency is the cumulative efficiency for all layers above and including the nth layer. This approach can, of course, be extended to accommodate any desired number of liner/drain modules.

As an example of a calculation for multiple liner/drain systems, consider a landfill consisting of a cover, an intermediate liner/drain module, and a bottom liner/drain module. Suppose that the amount of precipitation impinging per month on the the landfill is 5.0 cm. Analysis following the techniques described in SW-868 showed that 0.78 cm of liquid seeped through the cover. An analysis using the techniques described in section 3.4.1 showed that 0.50 cm of liquid seeped through the intermediate liner/drain module. A similar analysis showed that 0.20 cm of liquid seeped through the bottom liner/drain module.

According to the definitions presented above,

$$e_{prec} = 5.0 \text{ cm}$$

$$e_{s0} = 0.78 \text{ cm}$$

$$e_{s1} = 0.50 \text{ cm}$$

$$e_{s2} = 0.20 \text{ cm}$$

The following efficiencies can be calculated for the individual modules:

$$E_0 = \frac{5.0 - 0.78}{5.0} = 84.4\%$$

$$E_1 = \frac{0.78 - 0.50}{0.78} = 35.9\%$$

$$E_2 = \frac{0.50 - 0.20}{0.50} = 60.0\%$$

The cumulative efficiencies are:

$$E_{01} = \frac{5.0 - 0.5}{5.0} = 90\%$$

$$E_{02} = E_T = \frac{5.0 - 0.2}{5.0} = 96\%$$

3.5.2 Comments on the Cumulative Efficiency of Liner/Drain Systems

It is important to use the cumulative efficiency to evaluate the containment capability of liner/drain systems. As pointed out in section 3.4.2, a liner/drain module can be inefficient either because it is poorly designed or because it has very little liquid impinging upon it. It would not be appropriate to penalize low efficiency in a liner/drain module that is well designed, but that has very little liquid impinging upon it. Using the cumulative efficiency overcomes this difficulty. Thus, even though additional liner/drain modules may display low individual efficiencies, they will contribute significantly to the cumulative efficiency of the entire system.

It is important to make certain that the liner/drain modules displaying low efficiencies when subjected to low impingement rates also display higher efficiencies with increasing impingement rates. Such modules will contribute a margin of safety to the design because they could respond efficiently to unanticipated increases in impingement rates.

4. PROCEDURES FOR EVALUATING PROPOSED DESIGNS

This chapter presents two evaluation procedures. Section 4.1 describes a procedure for evaluating hazardous waste landfills; section 4.2 describes a procedure for evaluating hazardous waste surface impoundments.

4.1 Evaluating Hazardous Waste Landfills

4.1.1 Operating Conditions

This evaluation procedure has been prepared with the assumption that the operating conditions for the hazardous waste landfill meet the basic requirements of good engineering design. For example, it is presumed that:

(1) *surface water has been intercepted and directed from the site so that* only the rainfall impinging directly on the landfill need be accounted for;

(2) proper precautions have been taken to insure the integrity of cover soils so that erosion will not degrade cover performance;

(3) synthetic liners have been properly installed so that their integrity is assured for their design life;

(4) ground water flowing laterally into the landfill has been intercepted or otherwise diverted around the site;

(5) artesian pressures in strata underlying the landfill have been relieved so that the hydrostatic head in the artesian aquifer lies below the base of the landfill;

(6) water on the site has been controlled during the construction of the landfill; and

(7) the designs proposed for the components of the landfill form a properly functioning system.

4.1.2 Quantifying the Performance of a Landfill Design

A well designed hazardous waste landfill contains a liquid transmission control system that consists of a cover and one or more liner/drain modules. These modules collectively must accomplish the following:

(1) They must assure that liquid does not mound up so high in the drain layer that it overtops the layer, thus coming into contact with waste

where it can become further contaminated. To quantify this, perform the computations described in section 3.2 to determine the height of mounding for liquid in each drain layer.

(2) They must maximize the amount of contaminated liquid diverted to and collected by drain pipes. To quantify this, perform the computations described in section 3.4 to determine the efficiency of the liner/drain module comprising each liquid diversion interface.

(3) They must minimize the amount of liquid seeping through the landfill and impinging on the underlying environment. To quantify this, perform the computations described in section 3.3 to determine an upper bound to the seepage quantity through each clay liner.

The following two sections present an evaluation procedure that implements the considerations listed above using the analytical procedures developed in Chapter 3.

4.1.3 Information Required to Use the Evaluation Procedure

Figure 15 shows the input required to use the evaluation procedure. The sources of input are as follows:

(1) The plans developed by the designer supply the typical cross sections needed for step (1). These cross sections are used both to construct the liquid routing diagrams for step (2) and to locate the liquid diversion modules for step (3). The designer may have provided liquid routing diagrams as part of the plans and specifications and may also have delineated the liquid diversion modules.

(2) Area precipitation records provide the maximum monthly precipitation used in steps (4), (5), (7), and (12).

(3) The Hydrologic Simulation on Solid Waste Disposal manual (SW-868) provides input to step (5) -- amount of liquid impinging on first module. This quantity is available on a daily basis as the quantity, Q. We recommend expressing these values on a monthly average basis. Alternatively, monthly percolation can be determined using SW-168 (Water Balance Method of Fenn, Hanley, and DeGeare (1975)) or other infiltration models.

(4) The plans and specifications must also provide the following additional information for each liner/drain module:

(a) the thickness of the sand or gravel drain layer, to be used in step (6),

(b) the soil porosity, n, to be used in steps (6), (7), and (8),

(c) the thickness, d, of the clay liner, to be used in steps (7) and (9),

(d) the coefficient of permeability, k_{s1}, for the sand or gravel drain layer, to be used in steps (6) and (7),

(e) the coefficient of permeability, k_{s2}, for the saturated clay liner, to be used in steps (7) and (9),

(f) the slope, α, of the clay liner, to be used in steps (6) and (7), and

(g) the length, s_0, from the high point of the liner to the drain, to be used in steps (7) and (8).

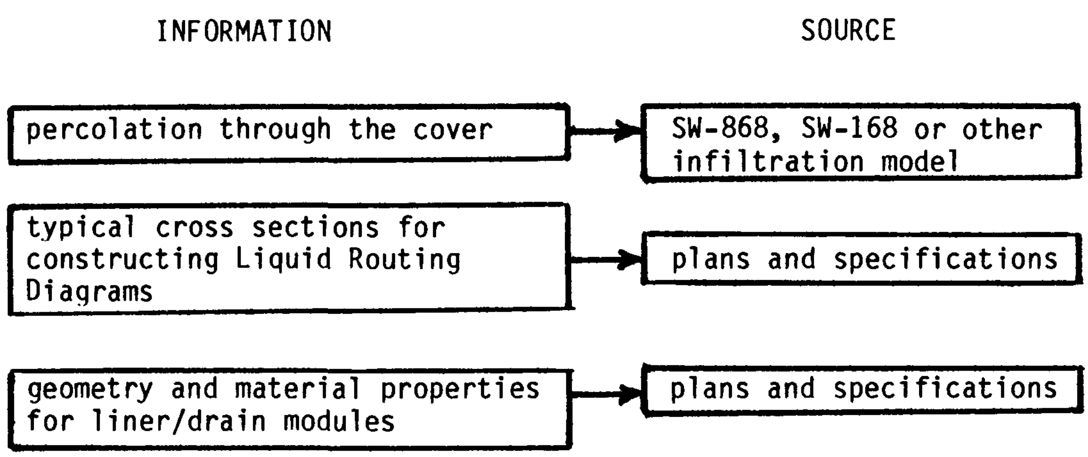


Figure 15 - Information required to use the evaluation procedure.

4.1.4 Evaluation Procedure for Landfill Designs

Figure 16 diagrams the evaluation procedure and designates the criteria that should be used to assess the acceptability of a design. Table 3 summarizes the equations used. The procedure is as follows:

(1) From the design drawings, select a typical cross section through the landfill. If the vertical profile through the landfill differs from place to place, more than one cross section will require evaluation.

(2) Construct a liquid routing diagram, similar to that shown in figure 4, to track the course of the liquid as it moves through the cross section.

(3) On the liquid routing diagram, designate each liquid diversion interface consisting of low permeability liners overlain by high permeability drain layers.

(4) Examine the precipitation record for the landfill vicinity. Select the maximum monthly precipitation.

(5) Determine the maximum monthly percolation through the cover as predicted by the techniques presented in SW-868, SW-168, or other infiltration models. This amount of liquid plus any liquid introduced by the waste itself or by recirculated leachate is taken to be the amount of liquid impinging upon the first module.

(6) Using either equation (3) or figure 6, plus the impingement quantity determined in step (5), calculate h_{max} for the uppermost liner/drain module. Determine whether h_{max} is less than the design thickness of the drain layer. If not, change the design of the cover or the thickness of the drain layer so that h_{max} is less than the drain layer thickness.

(7) Using equations (11) through (13), calculate the efficiency of the liner/drain module for impingement rates, e_i, ranging from zero to a maximum value determined by the maximum monthly precipitation quantity from step (4). Be sure to evaluate the case where e_i is equal to the anticipated impingement rate determined in step (5) above. Using this information assess the performance of the liner/drain module based on the following criteria:

(a) Evaluate the efficiency of the module at the anticipated impingement rate as determined in step (5) above. If the efficiency is above 75%, the design is acceptable.

(b) If the efficiency is below 75%, do not categorically reject the design. Rather, determine whether low efficiency results from poor design or from a low impingement rate on the module. To do this, evaluate the way in which the efficiency increases with increasing impingement rates up to the maximum monthly precipitation rate determined in step (4) above. If the asymptote at high values of e_i is above 90%, more effort on this aspect of the design is not warranted. If the value is below 90%, further improvement in the design should be considered.

(8) Using equations (10), (11), (14), (15) and (17), determine the anticipated monthly seepage quantity, e_s, through the liner. When calculating E', use a value of h_0 based upon the anticipated monthly impingement quantity from step (5). If this is the bottom liner/drain module, determine whether the hydrogeologic environment underlying the landfill is capable of assimilating this seepage quantity.

(9) Using equation (5), determine the hypothetical monthly seepage quantity corresponding to a constantly wet liner, but with no mounding of liquid.

(10) Using equation (6), determine the hypothetical monthly seepage quantity corresponding to a liner with liquid constantly mounded to a height equivalent to h_{max} as determined in step (6).

(11) Repeat steps (6) through (10) above for each successive liner/drain module included in the liquid routing diagram. Use step (4) precipitation rates where called for; however, when step (5) liquid impingement values are called for, use the anticipated monthly seepage quantity as calculated in step (8) for the module immediately overlying the one being analyzed. In step (7) include hypothetical seepage quantities, as determined in steps (9) and (10), when evaluating the response of the module to seepage rates in excess of the anticipated seepage rate determined in step (8).

(12) If the liner/drain module being evaluated is the bottom one in the system, use equations (28) and (29) to calculate the cumulative efficiency for the module being analyzed plus all overlying modules and the landfill cover. If the cumulative efficiency exceeds 90%, the system as a whole performs adequately.

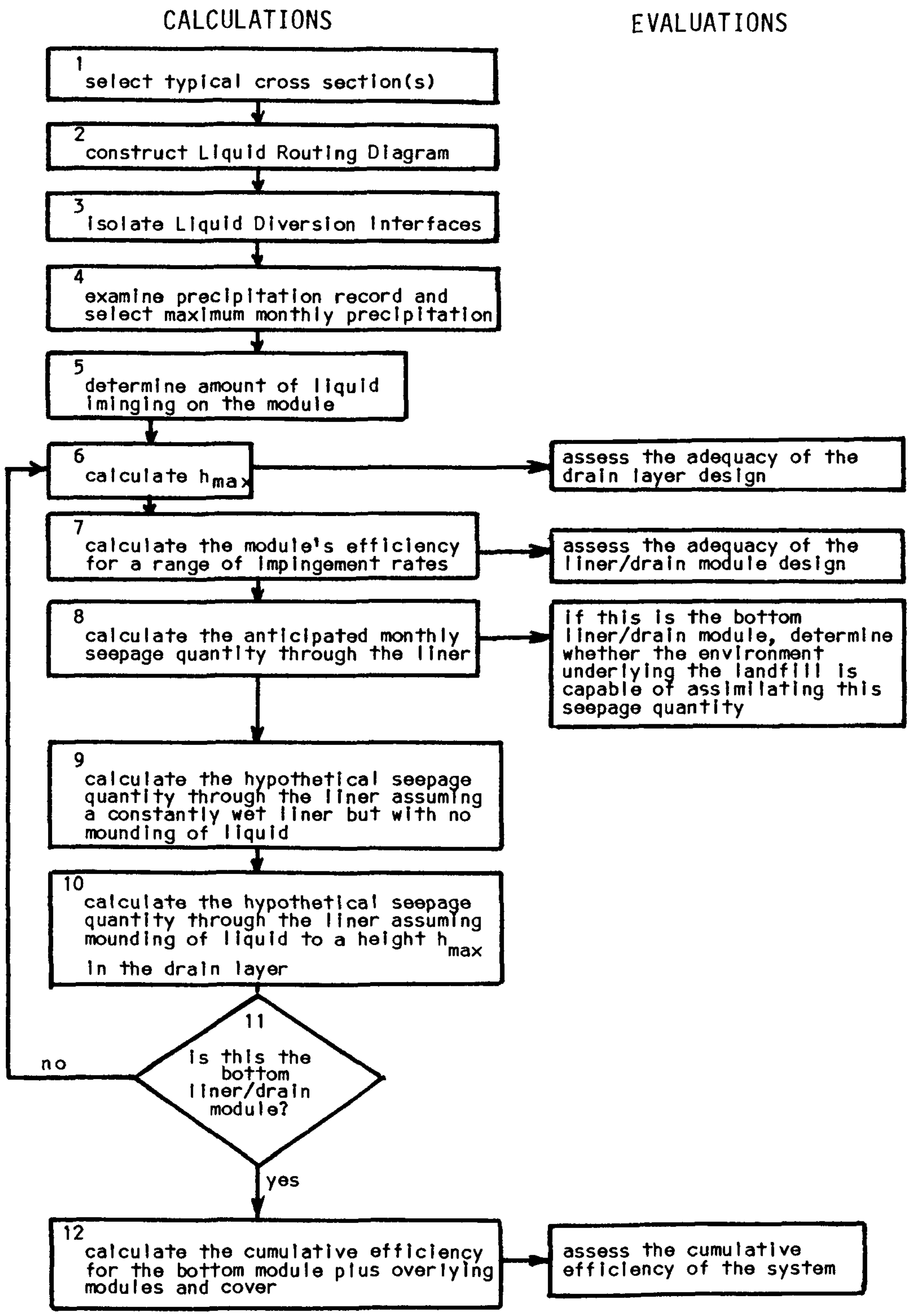


Figure 16 - Diagram of the evaluation procedure.

Table 3 - Equations used in evaluation procedure.

EQUATION	EQUATION NUMBER	STEP(S) IN WHICH USED
$h_{max} = \frac{L}{2n}\left[\sqrt{\frac{e}{k_{s1}} + \tan^2 \alpha} - \tan \alpha\right]$	(3)	(6)
$C = \left(\frac{s_o}{d}\right)\left(\frac{k_{s2}}{k_{s1}}\right) \cot \alpha$	(11)	(7),(8)
$N = \left(1 + \frac{d}{h_o \cos \alpha}\right) e^{-C} - \frac{d}{h_o \cos \alpha}$	(12)	(7)
$E = \frac{1 + N}{2}$ for $N \geq 0$	(13a)	(7)
$E = \frac{1}{2(1-N)}$ for $N \leq 0$	(13b)	(7)
$t_1 = \frac{s_o}{k_{s1} \sin \alpha}$	(10)	(8)
$N' = \left(1 + \frac{d}{h_o \cos \alpha}\right) e^{-Ct/t_1} - \frac{d}{h_o \cos \alpha}$	(14)	(8)
$E' = \frac{1 + N'}{2}$ for $N' \geq 0$	(15a)	(8)
$E' = \frac{1}{2(1-N')}$ for $N' \leq 0$	(15b)	(8)
$e = (1 - E')\, h_o\, n$	(17)	(8)
$e = k_{s2}$	(5)	(9)
$e = \left(\frac{d + h_{max}}{d}\right) k_{s2}$	(6)	(10)
$E_{02} = \frac{e_{prec} - e_{s2}}{e_{prec}}$	(28)	(12)
$E_T = E_{02}$	(29)	(12)

4.2 Evaluating Hazardous Waste Surface Impoundments

4.2.1 Operating Conditions

This evaluation procedure has been prepared with the assumption that the operating conditions for the hazardous waste surface impoundment meet the basic requirements of good engineering design. For example, it is presumed that:

(1) surface water has been intercepted and directed from the site;

(2) synthetic liners have been properly installed so that their integrity is assured for their design life;

(3) ground water flowing laterally into the surface impoundment has been intercepted or otherwise diverted around the site;

(4) artesian pressures in strata underlying the surface impoundment have been relieved so that the hydrostatic head in the artesian aquifer lies below the base of the surface impoundment;

(5) inlet and outlet structures have been designed and rate of flow controlled to eliminate scour of liners;

(6) freeboard design and slope protection result in no detrimental wave action; and

(7) the designs proposed for the components of the surface impoundment form a properly functioning system.

4.2.2 Quantifying the Performance of a Surface Impoundment Design

A well designed hazardous waste surface impoundment contains a bottom liner that minimizes the amount of liquid seeping to the underlying environment. To quantify this, perform a computation described in section 3.3 to determine an upper bound to the seepage quantity through the clay liner. The next two sections present an evaluation procedure based upon this computation.

4.2.3 Information Required to Use the Evaluation Procedure

The plans and specifications must provide the following information required to use this evaluation procedure:

(1) typical cross sections,

(2) the thickness, d, of the clay liner,

(3) the coefficient of permeability, k_{s2}, for the saturated clay liner, and

(4) the depth, H, of liquid in the lagoon.

4.2.4 Evaluation Procedure for Surface Impoundment Designs

The procedure is as follows:

(1) From the design drawings, select a typical cross section through the surface impoundment. If the vertical profile through the lagoon differs from place to place, more than one cross section will require evaluation.

(2) Construct a liquid routing diagram to track the course of the liquid as it moves through the cross section.

(3) Using equation (7), determine the anticipated monthly seepage quantity, e_s, through the liner. Determine whether the hydrogeologic environment underlying the lagoon is capable of assimilating this seepage quantity.

5. EXAMPLE EVALUATIONS

This chapter contains numerical examples to illustrate the use of the evaluation procedure. Section 5.1 presents the evaluation of a hazardous waste landfill, while section 5.2 presents the evaluation of a hazardous waste lagoon.

5.1 Evaluation of a Landfill

The example hazardous waste landfill is to be located in a region where the ground water must be protected from contamination. Figures 17 and 18 contain excerpts from the plans and specifications respectively. The solution procedure follows that recommended in Chapter 4. The steps referred to in the calculations correspond to the steps of the recommended procedure.

Step 1. Select a typical cross section.

The plans give one typical cross section as shown in figure 17.

Step 2. Construct a liquid routing diagram.

Excerpt 1 from the specifications, as shown in figure 18, describes the leachate control system and provides the basis for constructing the liquid routing diagram. The modules that are considered to be part of the leachate control system are the vegetated cover, the intermediate liner/drain module, and the bottom liner/drain module. The intermediate cover is not included because the designer provided too little information about its construction to allow the evaluator to analyze its effects. The liquid routing diagram is shown in figure 19.

Step 3. Designate the liquid diversion interfaces.

There are two modules containing liquid diversion interfaces: the intermediate liner/drain module and the bottom liner/drain module.

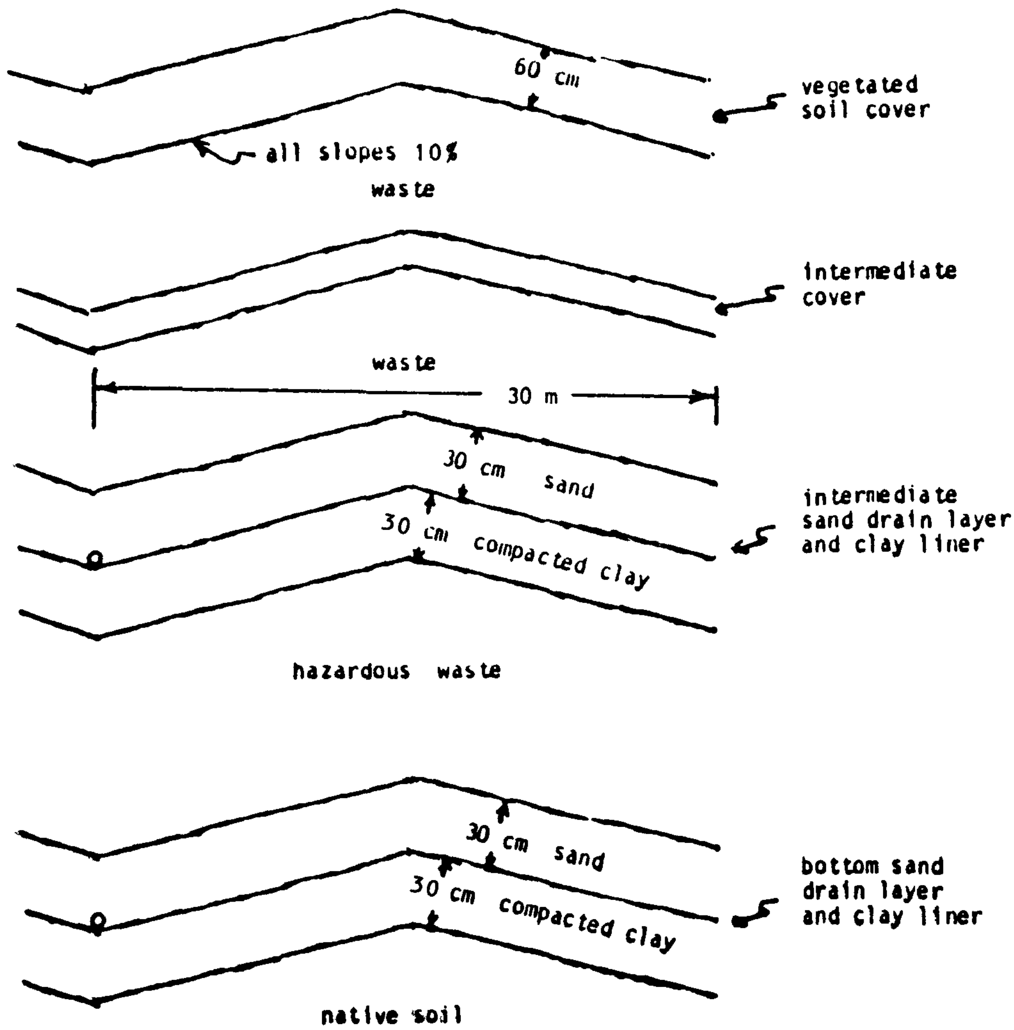


Figure 17 - Excerpt from plans for proposed landfill.

-excerpt 1-

CONTROL OF LEACHATE

Leachate will be controlled by vegetated final cover, by an intermediate sand drain layer underlain by a compacted clay layer, and a bottom liner overlain by sand. The clay for both liners is compacted at 2% above optimum water content and to 95% of standard Proctor density. The sand layers are carefully placed at controlled thickness. Collector pipes are placed as shown on the plans. Intermediate cover will also provide some degree of control of liquid flow rates.

-excerpt 2-

LABORATORY TESTS ON SAND

Laboratory permeability tests were performed on the sand compacted to the field density and then saturated. The coefficient of permeability was found to be 1×10^{-3} cm/sec.

Laboratory permeability tests were performed on the clay compacted at 2% above optimum moisture content to field density. After saturation, the coefficient of permeability was found to be 1×10^{-7} cm/sec.

Figure 18 - Excerpts from specifications for proposed landfill.

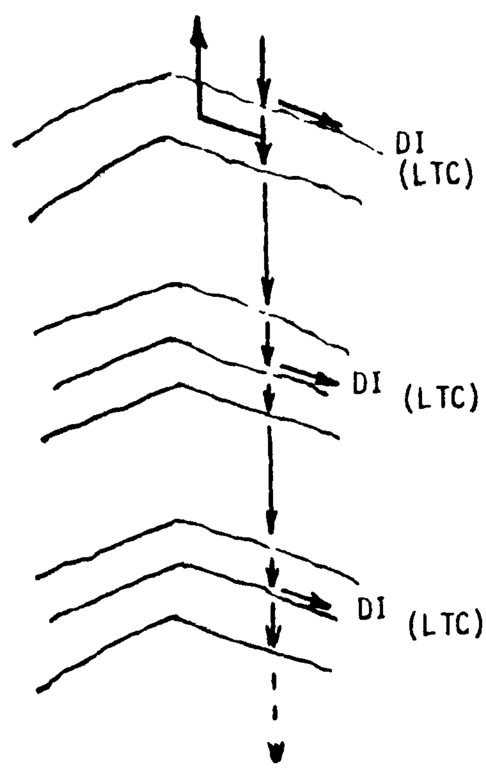


Figure 19 - Liquid routing diagram for proposed landfill.

Step 4. Examine the precipitation record.

Table 4 shows the monthly precipitation record for the region. The month showing the maximum precipitation is March, with 12.21 cm of precipitation; thus,

$$e_{prec} = 12.21 \text{ cm/mo} = 4.56 \times 10^{-6} \text{ cm/sec}$$

Table 4 - Site precipitation and percolation data.

MONTH	PRECIPITATION (cm)	PERCOLATION (cm)
January	0	0
February	0	0
March	12.21	1.83
April	6.48	3.25
May	9.47	2.51
June	10.60	0.05
July	9.27	0
August	9.04	0
September	8.56	0
October	5.18	0.61
November	1.70	1.60
December	0	0
Annual	72.51	9.85

Step 5. Determine the maximum monthly percolation through the cover.

This example uses the water balance method described in SW-168. Table 4 shows the resulting values for monthly percolation. The maximum monthly percolation is 3.25 cm in April. Note that the month showing the maximum percolation is one month later than the month showing the maximum precipitation. This lag reflects the time required for water to flow through the cover. Assuming no generation of liquid by the waste and assuming no recirculation of leachate, we obtain:

$$e_{s0} = 3.25 \text{ cm/mo} = 1.21\text{x}10^{-6} \text{ cm/sec}$$

Step 6. Calculate h_{max} and compare with drain layer thickness.

From equation (3):

$$h_{max} = \frac{30 \text{ m}}{2(0.5)} \left[\left(\frac{1.21\text{x}10^{-6} \text{ cm sec}}{1\text{x}10^{-3} \text{ sec cm}} + \tan^2(5.71) \right)^{1/2} - \tan(5.71) \right]$$

$$= 0.176 \text{ m} = 17.6 \text{ cm}$$

Because 17.6 cm is less than the design thickness of 30 cm, the leachate will not overtop the drain layer. Thus, the design is adequate in this respect.

Step 7. Calculate the efficiency of the first module.

The value of C is not a function of impingement rate. Therefore, the same value is used for all calculations in this step. C can be calculated from equation (11):

$$C = \frac{30 \text{ m}}{2 \times 0.3 \text{ m} \cos(5.71)} \frac{1\text{x}10^{-7} \text{ cm sec}}{1\text{x}10^{-3} \text{ sec cm}} \cot(5.71)$$

$$= 5.025\text{x}10^{-2}$$

We now calculate the efficiency of the module for a range of values for impingement rate. For the first calculation, use the anticipated monthly impingement rate of 3.25 cm/mo from step (5). Assuming a porosity of 0.5, calculate h_o:

$$h_o = \frac{3.25}{0.5} = 6.50 \text{ cm}$$

Putting the above values for C and h_o into equation (12) gives:

$$N = \left(1 + \frac{30 \text{ cm}}{6.50 \text{ cm} \cos(5.71)}\right) e^{-5.025\text{x}10^{-2}} - \frac{30 \text{ cm}}{6.50 \text{ cm} \cos(5.71)}$$

$$= 0.724$$

From equation (13a):

$$E = \frac{1 + 0.724}{2} = 86.2\%$$

A second calculation based on the maximum monthly precipitation quantity of 12.21 cm from step (4) gives:

$$h_o = \frac{12.21}{0.5} = 24.42 \text{ cm}$$

The resulting value for E is 94.5%.

Table 5 presents the efficiency of the module for the above values of impingement rate as well as for some additional values. This allows us to plot efficiency versus impingement rate as shown in figure 20.

Table 5 - Efficiencies for various impingement rates.

e(cm/mo)	h_o	E(%)
0.5	1.0	32.6
1.0	2.0	60.6
2.0	4.0	79.1
3.0	6.0	85.2
3.25	6.5	86.2
4.0	8.0	88.3
5.0	10.0	90.2
7.0	14.0	92.3
10.0	20.0	93.8
12.0	24.0	94.5
12.21	24.42	94.5

Step 7a. Evaluate the efficiency at the anticipated impingement rate.

At the anticipated impingement rate of 1.21×10^{-6} cm/sec (h_o = 6.50 cm), the efficiency exceeds the limiting value of 75%; therefore, the module performs adequately in this respect.

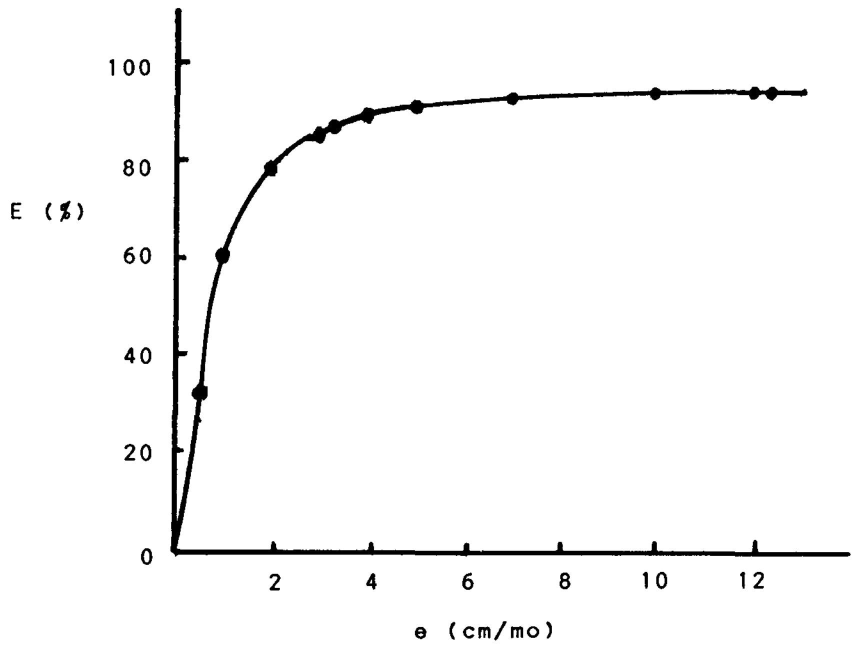


Figure 20 - Efficiency of first liner/drain module as a function of impingement rate.

Step 8. Calculate the anticipated monthly seepage quantity through the clay liner.

The anticipated monthly seepage quantity through the clay liner is calculated using equations (10), (11), (14), (15) and (17). Equation (10) gives:

$$t_1 = \frac{30\ \text{m} \quad \text{sec} \quad 100\ \text{cm} \quad \text{mo}}{2\cos(5.71) \times 1\text{x}10^{-3}\ \text{cm}\ \sin(5.71)\ \text{m} \quad 2678400\ \text{sec}} = 5.66\ \text{mo}$$

Equation (11) previously gave $C = 5.025\text{x}10^{-2}$. Equation (14) then gives:

$$N' = \left(1 + \frac{30\ \text{cm}}{6.50\ \text{cm}\ \cos(5.71)}\right) e^{-5.025\text{x}10^{-2}(1/5.66)} - \frac{30\ \text{cm}}{6.50\ \text{cm}\ \cos(5.71)}$$

$$= 0.95$$

From equation (15a) we obtain the efficiency at the end of one month:

$$E' = \frac{1 + 0.95}{2} = 97.5\%$$

From equation (17) we obtain the amount of liquid seeping through the clay liner:

$$e_{s1} = (1 - 0.975)(6.50\ \text{cm})(0.5) = 0.08\ \text{cm}$$

Step 9. Determine the hypothetical monthly seepage quantity for a constantly wet liner, but with no mounding.

From equation (5) the seepage quantity is found to be:

$$e = \frac{1X10^{-7}\ \text{cm}\ 2678400\ \text{sec}}{\text{sec}\qquad \text{mo}} = 0.268\ \text{cm/mo}$$

Step 10. Determine the hypothetical monthly seepage quantity assuming liquid constantly mounded to a height, h_{max}, on the liner.

Using h_{max} = 17.6 cm from step (6) and also using equation (6):

$$e = \left(\frac{30 + 17.6}{30}\right) \frac{1x10^{-7}\ \text{cm}\ 2678400\ \text{sec}}{\text{sec}\qquad \text{mo}} = 0.425\ \text{cm/mo}$$

Step 11. Repeat steps (6) through (10) for the next liner/drain module.

Note that this module also happens to be the bottom module.

Step 6. Calculate h_{max} and compare with drain layer thickness.

$$e = e_{i2} = e_{s1} = 0.08\ \text{cm/mo} = 2.99x10^{-8}\ \text{cm/sec}$$

$$h_{max} = \frac{30\ \text{m}}{2(0.5)} \left[\left(\frac{2.99x10^{-8}\ \text{cm sec}}{1x10^{-3}\quad \text{sec cm}} + \tan^2(5.71)\right)^{1/2} - \tan(5.71)\right]$$

$$= 0.0045\ \text{m} = 0.45\ \text{cm}$$

Because 0.45 cm is less than the design thickness of 30 cm, the leachate will not overtop the drain layer. Thus, the design is adequate in this respect.

Step 7. Calculate the efficiency of this module.

Because this module happens to have the same design parameters as the overlying module, the calculations previously performed in step (7) above can be used to evaluate the present module. It is necessary, however, to calculate the efficiency for this module's anticipated impingement rate of 0.08 cm/mo.

Step 7a. Evaluate the efficiency at the anticipated impingement rate.

$$h_o = \frac{0.08}{0.5} = 0.16 \text{ cm}$$

Using equations (11) through (13) as in the previous step (7), we obtain:

$$E = 5.4\%$$

The efficiency of 5.4% is well below the limiting value of 75%. Therefore, we proceed to step (7b) to determine whether low efficiency results from poor design or simply from low impingement rates on the liner.

Step 7b. Evaluate the efficiency at high impingement rates.

Figure 20, which plots E versus e_i for the previous step (7) also happens to apply to this step (7). Figure 21 duplicates figure 20 and also shows the efficiencies at additional impingement rates. In particular, it is also useful to calculate the efficiencies for the impingement rates associated with a constantly wet liner with no mounding of liquid ($e = 0.268$ cm/mo) and for mounding to a height h_{max} ($e = 0.425$ cm/mo). These give efficiencies of 17.8% and 27.9% respectively. Figure 21 shows that the liner/drain module is, indeed, a well designed one despite its low efficiency at the anticipated impingement rate. This decision was made based on the observation that as the impingement rate approaches the maximum monthly precipitation rate of 12.21 cm/mo from step (4), the efficiency increases to 94.5%. Because this exceeds the limiting value of 90%, this aspect of the design is adequate.

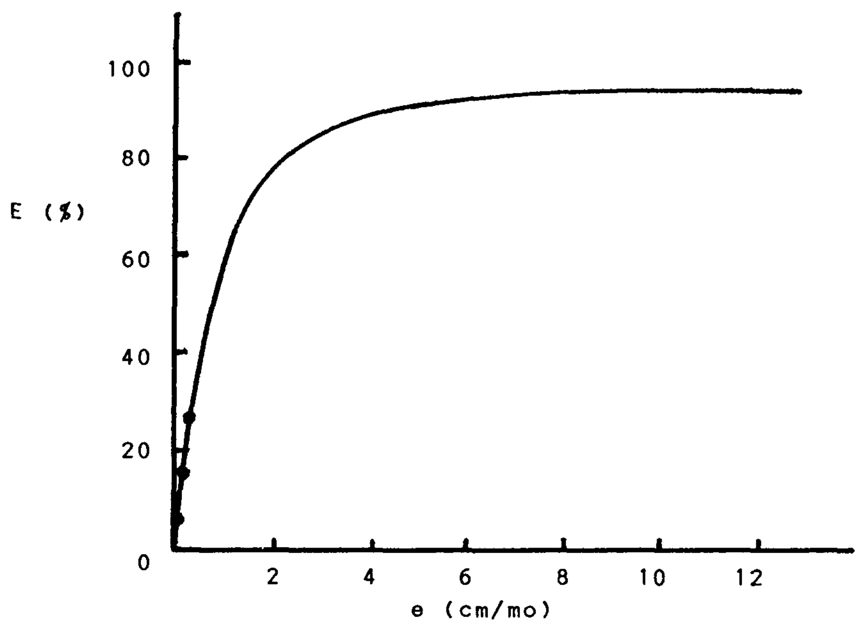


Figure 21 - Efficiency of bottom liner/drain module as a function of impingement rate.

Step 8. Calculate the anticipated monthly seepage quantity through the clay liner.

The anticipated monthly seepage rate through the clay liner is calculated using equations (10), (11), (14), (15), and (17). Equation (10) gives t_1 = 5.66 mo, as in the case of the overlying liner/drain module. C also retains its previous value of $-5.025\text{x}10^{-2}$. Thus, equation (14) gives:

$$N' = \left(1 + \frac{30\ \text{cm}}{0.16\ \text{cm}\ \cos(5.71)}\right) e^{-5.025\text{x}10^{-2}(1/5.66)}$$

$$- \frac{30\ \text{cm}}{0.16\ \text{cm}\ \cos(5.71)}$$

$$= -0.67$$

From equation (15b) we obtain the efficiency at the end of one month:

$$E' = \frac{1}{2(1 - (-0.67))} = 29.9\%$$

From equation (17) we obtain the amount of liquid seeping through the clay liner:

$$e_{s2} = (1 - 0.299)(0.16\ \text{cm})(0.5) = 0.056\ \text{cm}$$

Because this is the bottom liner/drain module, the value of e_{s2} = 0.056 cm/mo represents the quantity of leachate released to the environment. This quantity should be compared with the quantity that the environment is capable of assimilating.

Step 9. Determine the hypothetical monthly seepage quantity for a constantly wet liner, but with no mounding.

From equation (5):

$$e = \frac{1x10^{-7}\ cm\ \ 2678400\ \ sec}{sec \qquad\qquad mo} = 0.268\ cm/mo$$

Step 10. Determine the hypothetical monthly seepage quantity assuming liquid constantly mounded to a height, h_{max}, on the liner.

From equation (6):

$$e = \left(\frac{30 + 0.45}{30}\right)(0.268) = 0.272\ cm/mo$$

Because this module is the bottom liner/drain, we now proceed to step (12).

Step 12. Calculate the cumulative efficiency.

From equations (28) and (29):

$$E_{02} = E_T = \frac{e_{prec} - e_{s2}}{e_{prec}} = \frac{12.21 - 0.056}{12.21} = 99.5\%$$

Because 99.5% exceeds the limiting value of 90% for total system efficiency, this liquid transmission control system performs adequately.

5.2 Evaluation of a Lagoon

The example hazardous waste lagoon is to be located in a region where the ground water must be protected from contamination. Figures 22 and 23 contain excerpts from the plans and specifications respectively. The solution procedure follows that recommended in Chapter 4. The steps referred to in the calculations correspond to the steps of the recommended procedure.

Step 1. Select a typical cross section.

The plans give one typical cross section as shown in figure 22.

Step 2. Construct a liquid routing diagram.

The excerpt from the plans reproduced in figure 22 forms the basis for constructing the liquid routing diagram. The leachate control system consists of one module, the compacted clay liner. The liquid routing diagram is shown in figure 24.

Step 3. Calculate the anticipated monthly seepage quantity through the clay liner.

The anticipated monthly seepage quantity through the clay liner is calculated using equation (7):

$$e = \left(\frac{75 + 200}{75}\right) \frac{1.25\text{x}10^{-5}\ \text{cm}}{\text{sec}} \ \frac{1\ \text{mo}\ 2678400\ \text{sec}}{\text{mo}} = 122.8\ \text{cm/mo}$$

This is the quantity of leachate that must be assimilated by the underlying hydrogeologic regime.

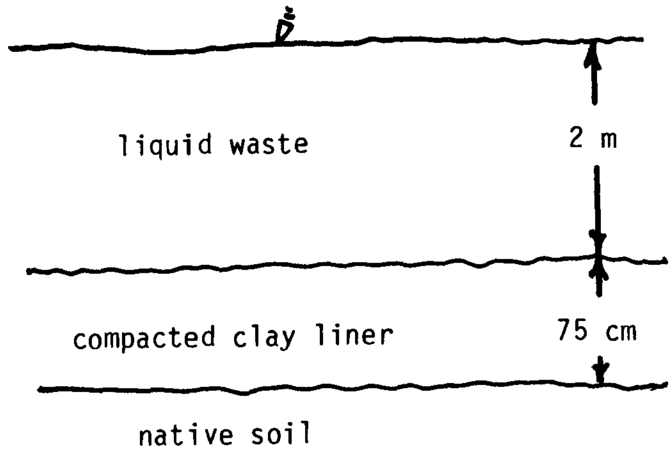


Figure 22 - Excerpt from plans of proposed lagoon.

-excerpt 1-

CONTROL OF LEACHATE

Leachate will be controlled by a clay liner. The clay will be compacted at 2% above optimum water content and to 95% of standard Proctor density.

-excerpt 2-

LABORATORY TESTS ON CLAY

Laboratory permeability tests were performed on the clay compacted at 2% above optimum water content and at field density. After saturation, the coefficient of permeability was found to be 1.25×10^{-5} cm/sec.

Figure 23 - Excerpt from specifications for proposed lagoon.

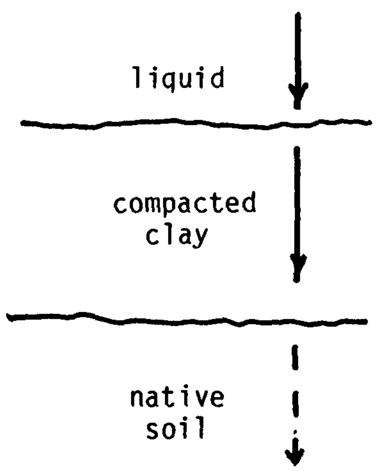


Figure 24 - Liquid routing diagram for proposed lagoon.

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APPENDIX

Principles of Partially Saturated Flow

The evaluation procedure presented in this manual does not incorporate the time to first appearance of leachate for a particular design. The engineer may, however, wish to determine this parameter as a part of the design procedure. Messuri (1982) reports recent research on methods designed to assist engineers in determining the laboratory parameters required to perform these predictions.

The physical laws governing liquid moving downward through a low permeability clay liner are somewhat more complex than those governing liquid moving in sand and gravel drain layers. Because of the nature of the micropores that exist in clay soils, water moves not only by gravitational forces, but also by capillary forces that tend to draw the liquid into the soil. The smaller the pore radius, the larger the capillary attraction force. Thus, soils with a high clay content will have very small micropores and therefore very large capillary attraction forces. As the grain size of the soil increases, the capillary attraction forces decrease; thus silty soils have lower capillary action than clays. Sandy soils have such large micropores that capillary attraction forces can reasonably be neglected, as we in fact did in section 3.2.

The rest of this section presents a non-mathematical discussion of the physical factors affecting the time to first appearance of leachate at the base of a compacted clay liner.

When liners are emplaced, they are usually compacted at or slightly wetter than optimum water content. The optimum water content is defined to be that water content at which, for a given compaction procedure, the maximum amount of soil particles could be packed into a given volume. Soil compacted at optimum water content exhibits desirable properties such as high strength and stiffness while still maintaining reasonably non-brittle behavior. While the optimum water content originally meant optimum with respect to a soil's performance as a highway subgrade, the same water content also imparts optimum behavior in many other situations. For reasons beyond the scope of this discussion, it is best to compact landfill liners somewhat wet of optimum water content. In any case, any practical compaction water content for soil liners will result in the soil being partially saturated. That is, the voids in the soil mass will be partly filled with liquid and partly filled with air.

If additional water is introduced, say, at the surface of a clay liner constructed of partially saturated soils, the liner will imbibe this water at a relatively rapid rate. The physical reason for this is shown in figure 25. The isolated water packets labeled B represent the water placed in the soil upon compaction. The water labeled A is the new water moving into the soil

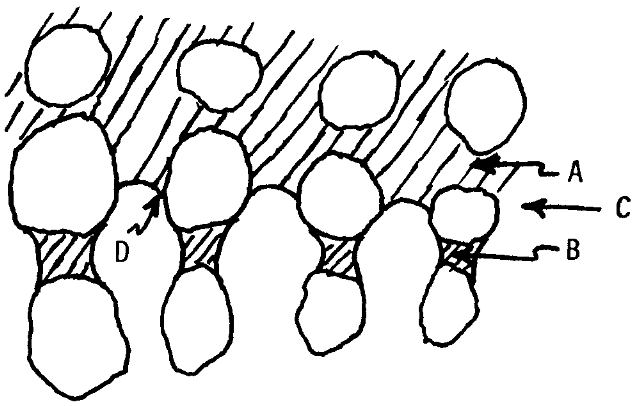

Figure 25 - Simplified microscopic view of wetting interface in a partially saturated soil.

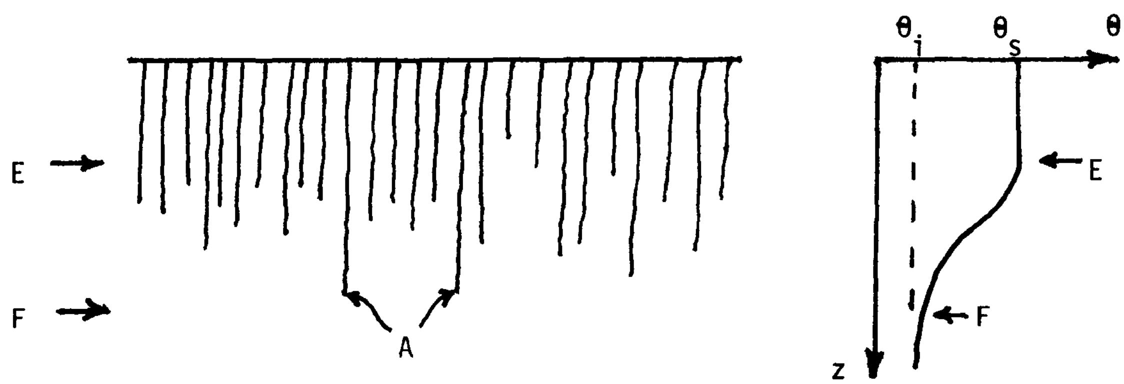

Figure 26 - Macroscopic view of wetting interface in a partially saturated soil.

from above. Level C is termed the wetting interface, and moves downward through the soil.

The forces causing the wetting interface to move are two. First, there is the gravitational potential due to the weight of the water above the wetting interface forcing the water into the soil. Second, there is the capillary potential produced by surface tension of the menisci forming the wetting interface (point D).

The gravitational force causing flow will always be directed vertically downward. However, this is not necessarily the case for the capillary potential because that is neither caused by nor related to gravity. In general, the capillary potential will be directed perpendicular to the wetting interface. It always tends to pull the wetting interface into new regions of partially saturated soil. For example, if the clay liner had been wet-up from the bottom rather than from the top, the capillary potential would tend to draw the water up into the liner against the gravitational forces tending to force the water down. In the former case, both the gravitational and capillary potentials cause the water to move downward through the soil. In the latter case, the potentials counteract each other. Thus infiltration from top to bottom occurs more rapidly than infiltration from bottom to top.

The situation depicted in figure 25 is oversimplified in that it implies that the wetting interface, C, appears as a precisely defined line. In fact, as shown in figure 26 drawn at a larger scale, this interface is distributed over a finite region E-F. The graph to the right of the figure shows how the water content varies with depth. Above point E the water content equals that of the saturated soil, Θ_s. Below point F the water content equals the initial compaction water content, Θ_i. Between points E and F the water content varies smoothly between Θ_s and Θ_i.

Without going into the mathematical details, we will now rationalize why the analytical treatment of partially saturated flow is complex. In the extreme case of a soil mass that is fully saturated, there are no capillary fringes, and flow is caused entirely by the gravitational potential. Flow in this case is rather easily treated using Darcy's law, which states that the flow velocity is linearly related to change in gravitational potential per unit distance. A constant of proportionality, called the saturation coefficient of permeability (or just coefficient of permeability), quantifies the flow rate for any particular soil. For situations where there is no ponding on the liner, the change in gravitational potential per unit distance is unity; therefore, the flow rate is numerically equal to the coefficient of permeability.

Flow in partially saturated soils is more complicated. Reference to figure 26 shows that in the region above point E (where the soil is saturated) there are no capillaries, therefore flow is simply saturated Darcian. In the region E-F, capillary forces greatly affect the flow process. However, even within this region the capillary forces vary with position. The longer saturated strings such as those marked A on figure 26, are moving into the smallest of soil pores, and thus the capillary forces are quite high. Conversely, near location E, the water is moving into larger pores and the capillary forces are not as great.

In this situation it becomes difficult to characterize the soil's ability to transmit water because this ability is related to the water content at the particular point being considered. In the region where the soil is saturated (above point E), the saturated coefficient of permeability characterizes flow in the entire region. However, where the water content varies (region E-F), the partially saturated coefficient of permeability governs. Between points E and F the soil is quite non-homogeneous with respect to moisture content, and thus, with respect to coefficient of permeability.

In calculating the flow through such a partially saturated soil mass, it is necessary to address the variability of permeability with position by mathematically integrating over the entire depth. During this integration process, the variability in the coefficient of permeability can be accounted for in a relatively direct manner.

The problem is further complicated, however, because the interface region, E-F, is not stationary, but rather, moves downward with time. Thus the integration process must be carried out not only in space (throughout the depth of the soil), but also in time. This double integration complicates the mathematics somewhat.