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Project Summary

Factors Controlling Minimum Soil Liner Thickness

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This report describes a three-part study to gather information on liquid flow through soil liners that are incorporated into double-liner systems used in hazardous waste disposal facilities.

In the first part of the study, a model was developed to simulate flow occurring through discreet channels in lifts (a layer of compacted soil) and in the horizontal layer between lifts. The model indicated that high overall field hydraulic conductivity values may result from excessive horizontal flow between lifts. In contrast, the model showed that even relatively high hydraulic conductivity lifts can be used to construct low conductivity soil liners if horizontal flow between lifts can be sufficiently reduced.

In the second part of the study, laboratory tests using large 60-cm-diameter permeameters showed that the conductivity to water typically increased by one order of magnitude with depth in a 23-cm-thick lift of compacted clay. Clod sizes ranging from 2.5 to 7.5 cm had little influence on the hydraulic conductivity. In addition, it was shown that exposure of the compacted soil to the atmosphere for as little as 24 hr resulted in severe cracking and associated high conductivities resulting from flow through the desiccation cracks. The data show that bulk density was a poor predictor of the conductivity of a compacted soil. Dye patterns in the permeameters also indicated flow through preferential channels and interclod spaces.

In the third part, field studies of a 3-lift liner revealed that horizontal flow does indeed occur at the interface between the lifts when channels penetrate the overlying lift.

This Project Summary was developed by EPA's Risk Reduction Engineering Laboratory, Cincinnati, OH, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

Compacted soil liners are a required component of a double-liner system in hazardous waste disposal facilities. The compacted soil can be incorporated into double-liner designs as the sole component of a secondary soil liner or as the lower component in a secondary composite liner.

The primary purpose of this project was to initiate the data base required to determine the minimum thickness necessary for a soil liner to meet the following performance objectives:

1. Maintaining an in-place hydraulic conductivity of less than or equal to 1 X 10^{-7} cm sec^{-1};
2. Retaining sufficient strength to support all potential overlying loads; and
3. Preventing the breakthrough of any contaminant before the end of the post-closure care period.

A literature review concentrated on the factors that influence hydraulic conductivity and strength in compacted soils. A computer model was developed that examined the influence of both the defects that penetrate a lift and those that cause horizontal flow between lifts. Laboratory and field studies of liquid flow patterns in a compacted soil were designed to examine both vertical and horizontal flow paths.

Computer Models

A useful model of liquid flow within and through a soil liner must include flow within each lift and flow between lifts (interlift flow). Flow within a lift must encompass both matrix flow and flow through channels that short-circuit the liner matrix. Channel flow may be caused by construction practices that result in liner defects such as cracks, clods, channels, continuous macropores, and incomplete bonding between lifts. Ignoring defects, the total permeability of a lift can be modeled as that of a slab with a population of vertical cylinders or pores, all of which have the same radius and all of which are equally spaced.

Actually, the pores are not equally spaced, they do not have the same radius, and they are not perfectly oriented in the vertical direction. In addition, they do not have the same radius throughout their length. This model is still a useful approximation to reality. Only through-going pores, those with outlets to both the top and bottom of a lift, are contributing to the permeability in this model. Through-going pores with radii significantly larger than those of the bulk of the pores are referred to as channels or defects.

Based on these assumptions, the contribution to the hydraulic conductivity to a lift made by the channels would be:

$$K = \frac{R^4 pg}{8uD^2}$$

where R is the radius of the channels, D is the spacing, p is the density of and u the viscosity of ordinary water, and g is the acceleration of gravity. The total permeability is caused by a combination of the channels and small pores in the matrix. The channel permeability is vastly greater than the matrix permeability if the channels have radii significantly greater than those of the pores contributing to the matrix permeability. Consequently, the smaller pores can be ignored in a bimodal distribution of grain sizes.

Figure 1 shows hydraulic conductivity (K) as a function of channel radius (R) and spacing (l), the two most important parameters in determining hydraulic conductivity. If all of the conductivity of a lift is due to cylindrical channels 10 µm in radius, the channels would have to be an average of 1.64 X 10^{-2} cm apart to maintain a conductivity of 10^{-5} cm sec^{-1}. If the channels were 2.5 cm in radius, they would have to be 4.23 km apart. Figure 1 demonstrates that only a few channels or defects can lead to large conductivities in compacted soil lifts. It is interesting to note that if all of the conductivity in a liner resulted from channels 850 µm in radius, the channels would have to be 47.5 m apart for the liner to meet the EPA standard of 10^{-7} cm sec^{-1}. This would correspond to less than one such flaw per 0.2 ha.

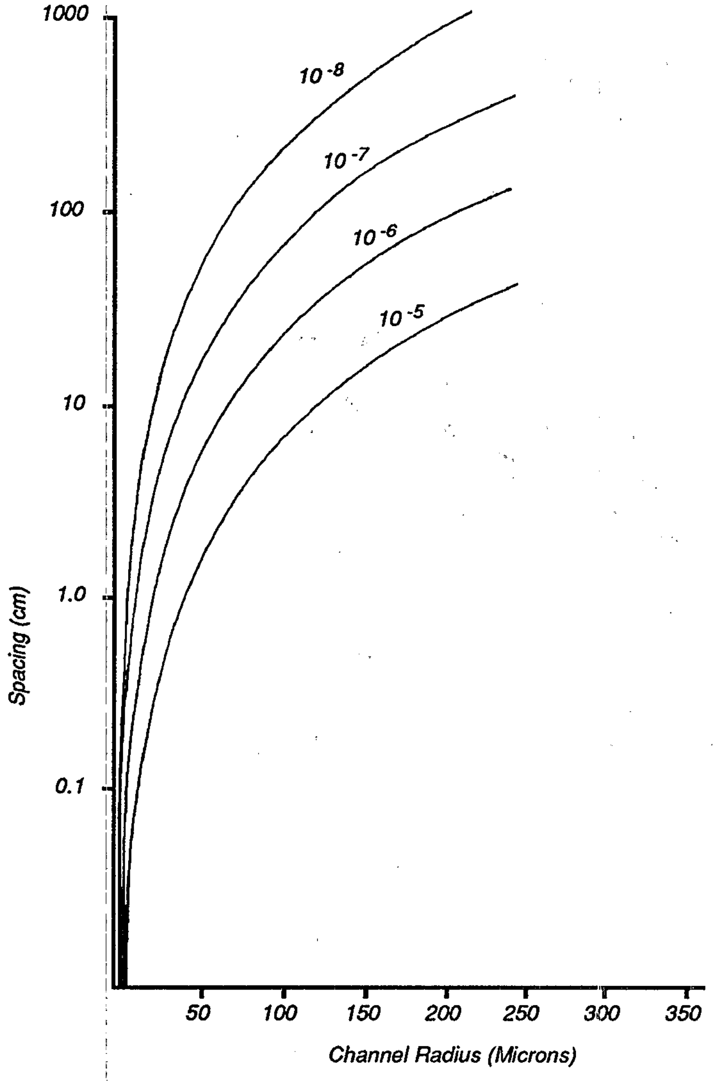

Figure 1. Spacing versus channel radius for K = 10^{-5}, 10^{-6}, 10^{-7} and 10^{-8} cm sec^{-1}.

Channel density is important in interpreting laboratory and field hydraulic conductivity measurements. If the conductivity of a lift is controlled by a few large channels and a small area is sampled, it is likely that these channels would be missed and the actual conductivity would be underestimated.

Suppose a lift has two populations of through-going pores. One population has a diameter of 1 mm (500 µm radius) spaced 164.2 cm apart. The other population has a radius of 1 µm spaced 0.208 mm apart. The first population will result in a conductivity of 1 X 10^{-5} cm sec^{-1}, whereas the second population will result in a conductivity of 1 X 10^{-8} cm sec^{-1}. The resulting actual conductivity would be 1.001 X 10^{-5} cm sec^{-1}. Suppose a sample of the soil was taken with a standard 7.62-cm-diameter shelby tube for laboratory measurement. It would probably contain 106,000 through-going pores each of whose radius is 1 µm. But since there is only one channel of the millimeter population per 2.7 M^2, there is only a 0.17% chance of such a flaw being present in the 7.62-cm-diameter sample. Thus, the analyst will measure a conductivity of 1 X 10^{-8} cm sec^{-1}, having totally missed the channels that contribute 99.9% of the conductivity. The chance of detecting one of the larger pores would not be greatly improved by taking several samples. With a 1.5 X 1.5 m infiltrometer, however, there would be an 86% chance of finding one of the larger pores.

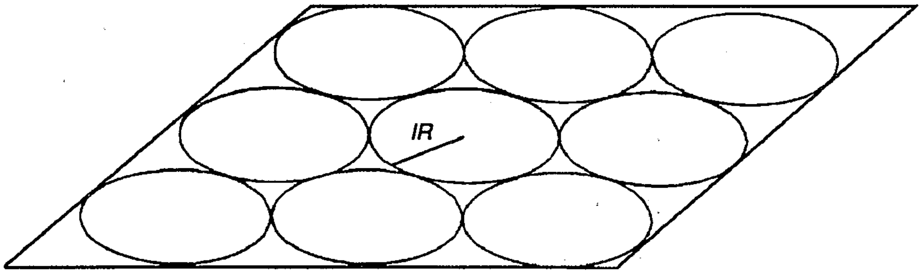

Figure 3. The pocket model for interlift flow.

Thus, if the conductivity of a lift is the result of only closely spaced small pores, a small sample will suffice. If it is caused by a few large pores, however, a very large sample is needed. Consequently, it is easy to understand the magnitude of discrepancies often found between laboratory and field measurements of hydraulic conductivity.

Compacted soil liners typically consist of several lifts. Since a lift is generally compacted to a 15-cm-thickness and since a liner is typically 61 to 122 cm thick, there should be four to eight lifts. If most of the conductivity in each lift is caused by a few widely spaced channels, then the interlift flow becomes important. Interlift flow is defined as the horizontal flow in the plane between two lifts. If interlift flow is restricted so that the continuous pores in adjacent lifts cannot communicate, the conductivity of a soil liner can be substantially less than that of the individual lifts.

Two models for interlift flow follow. The first is the "channel-centered model" (Figure 2). In this model, it is assumed that there is a circular disk area in the interlift plane at the bottom of every channel, centered on that channel. Inside the disk, flow is considered to be unrestricted. The lateral distance from a channel at the bottom of a lift where liquid can flow freely is designated the interlift flow radius (IR). This radius defines the disk. In this model, it is assumed that if any top of a channel in the lower lift is within the IR of a channel in the upper lift, liquid will flow from the channel in the upper lift into the channel in the lower lift. Further, if a channel in the lower lift is not within the IR of channel in the upper lift, then the channels will not constitute a flow path (through-going channel) (Figure 2).

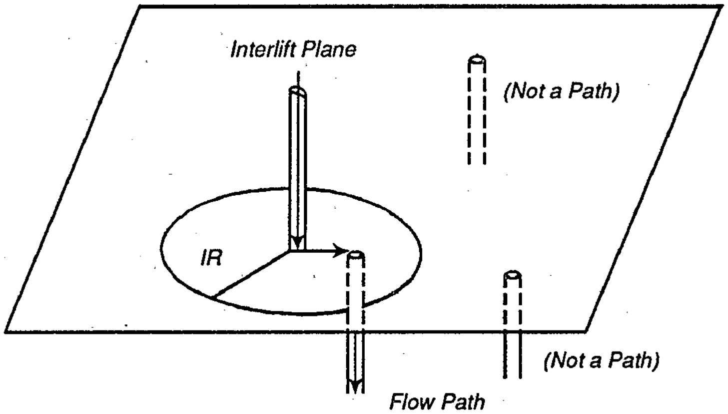

Figure 2. The channel-centered model for interlift flow

The second model is the "pocket model" (Figure 3). This model assumes an inhomogeneous interlift plane. The plane is divided into disks with radii of IR. In this case, the disks are not necessarily centered on channels. These disks are pockets of favorable horizontal flow. If any channels from an upper lift end in the same pocket that a channel begins in a lower lift, then liquid can flow from the upper channel into the lower one. If a channel does not have its opening in a pocket or if it does not have its opening in a pocket with another channel from another lift, then that channel is not a flow path.

A program was written for each of the models. Variables for the models included: 1) the desired effective hydraulic conductivity, 2) the channel radius, 3) the IR, and 4) the number of lifts. The program then computes the number of channels there would have to be in a 1.5 X 1.5 m section of each lift to attain the selected conductivity. The channels were assigned positions randomly. In the channel-centered model, the program then measures the distance between defects in adjacent lifts. If a defect was not matched up with the interlift flow from a channel above it, it was considered "dead" and did not figure in computations in the next interlift plane.

In this way, a determination can be made of how many effective flow paths there are through a certain number of lifts as a function of IR. Each computation is a stochastic experiment, so the program must be run many times and the results tabulated. Furthermore, each run must be carefully examined in the form of a tree diagram to find the number of through-going flow paths. Figures 4 and 5 show examples in which the through-going flow passes through one channel, but it may exit at several points.

The "channel-centered model" was run for two through eight lifts. The assumptions for each lift were a hydraulic conductivity of 1 X 10^{-5} cm sec^{-1} and a channel radius of 250 μm. Thus, the number of channels required in the 1.5 X 1.5 m lift section is 13. The model also assumed the existence of one circular interlift flow area (IR). For each set of lifts, many computer runs were made, and the results averaged.

The results of the computer runs of the channel-centered model are summarized in Figure 6 for two to eight lifts. It is apparent in Figure 6 that IR and the number of lifts have a great effect on the total hydraulic conductivity of a soil liner. The

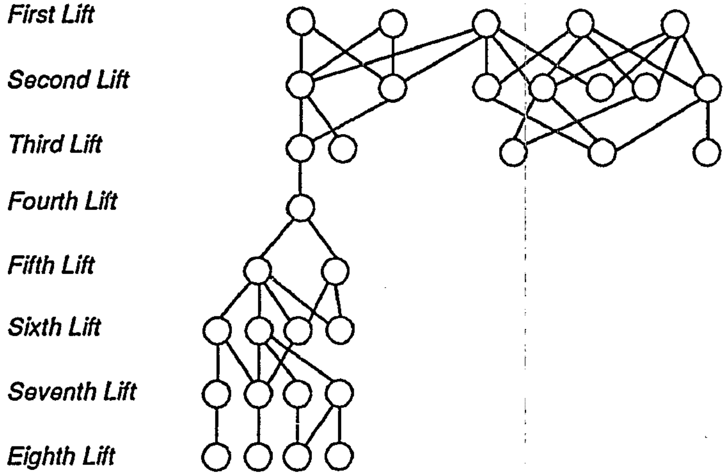

Figure 4. The difference between the number of effective flow paths and the number of active channels in the last lift. Circles represent channels and lines represent interconnection. Notice the constriction at the fourth lift. Although there are four active defects in the last lift, the number of effective passageways is one.

results, of course, would have been different if the assumptions were changed as to the average diameter of a channel. But the implications of this experiment are clear. Suppose that a lift with a matrix conductivity of 10^{-8} cm sec^{-1} contains 13 channels (with diameters of 1/2 mm) in each 2.3 m^2 area. The lift would have an effective hydraulic conductivity of 10^{-5} cm sec^{-1}. Even then, however, the EPA standards of 1 X 10^{-7} cm sec^{-1} would be satisfied with eight lifts if interlift flow radii could be limited to 20 cm. If IR is limited to 10 cm, just four lifts will result in a conductivity of less than 1 X 10^{-7} cm sec^{-1}.

The "pocket model" was run for two through eight lifts with the same assumptions, i.e., hydraulic conductivity (1 X 10^{-5} cm sec^{-1}) and channel radius (250 μm). The results of these experiments are given in Figure 7. Again, increasing the number of lifts and decreasing the IR decreased the total conductivity of the liner.

Pockets with IR = 15 cm resulted in a total conductivity of less than 1 X 10^{-7} cm sec^{-1} if there were at least five lifts. If there were seven lifts, 20 cm of interlift flow yielded a conductivity of 4.4 X 10^{-8} cm sec^{-1}.

In both models, there was a substantial decrease in conductivity as the number of lifts increased and as IR decreased. As IR approached 100 cm, the conductivity became that of individual lifts, and the number of lifts became unimportant. Except for two cases (IR = 10 cm with four lifts and IR = 15 cm with eight lifts), the pocket model gave lower conductivities than the channel-centered model.

Interlift Flow Breakthrough Model

A unifying model would be one that combined the channel-centered model, for which there has been supporting evidence in field studies, to its physical basis. In this model, IR would not be constant, but rather a function of time. IR begins to grow from the time liquid reaches a particular through-going channel and grows as a function of head, conductivity, and time. In the program, each channel has its own IR. The program gives an evolving picture of the flow in a liner and marks the moment that liquid first reaches a channel in a new lift. When the bottom lift has liquid in a channel, it is assumed that breakthrough has occurred.

To operate the program, the same assumptions (vertical hydraulic conductivity and channel radius) are supplied as for the previously described models. The program also assumes 30 cm of liquid on top of the first lift. Additional variables include horizontal conductivity at the bottom of a lift, starting head, liquid density, and liquid viscosity.

The program generates the connections between channels in neighboring lifts as a function of time, and it tells when a new lift has been penetrated. If the same parameters are used as in models presented above (i.e., a vertical hydraulic conductivity of 10^{-5} cm sec^{-1} caused by channels 250 μm in radius in a eight-lift liner) with a horizontal hydraulic conductivity in the interlift plane of 10^{-5} cm sec^{-1}, the result would be very rapid breakthrough. To break through a liner such as this would take slightly more than 2 wk. If the conductivity between flaws is 10^{-8} cm sec^{-1}, and increases to 10^{-5} cm sec^{-1} at the bottom of each lift because of density variation caused by improper compaction, the liner would also be broken through in 2 wk. A 7.62 cm shelby tube sample taken at the surface would likely give a laboratory conductivity of 10^{-8} cm sec^{-1}.

When using 10^{-7} cm sec^{-1} as the horizontal conductivity between lifts, the average time of 50 model runs to breakthrough was 4.7 yr. When the horizontal conductivity between the lifts was modeled as 10^{-8} cm sec^{-1}, the average breakthrough time was in decades (71 yr).

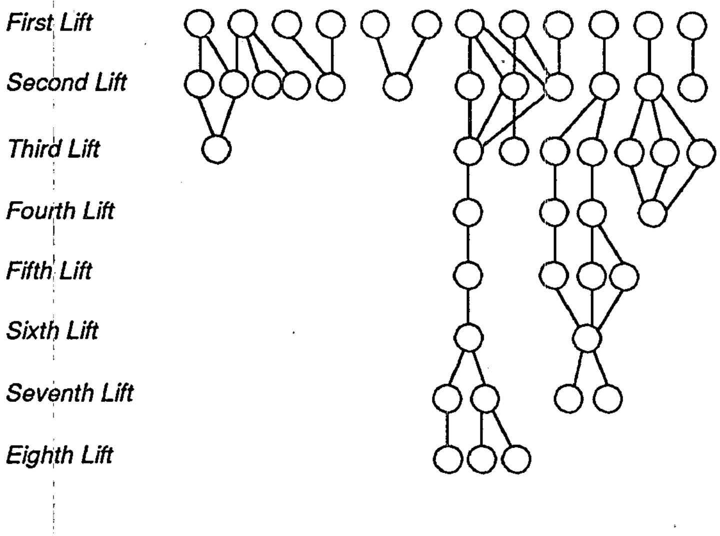

Figure 5. The difference between the number of effective flow paths and the fewest number of active channels in a lift. The fewest number of interconnections between lifts is three, yet the number of flow paths is one.

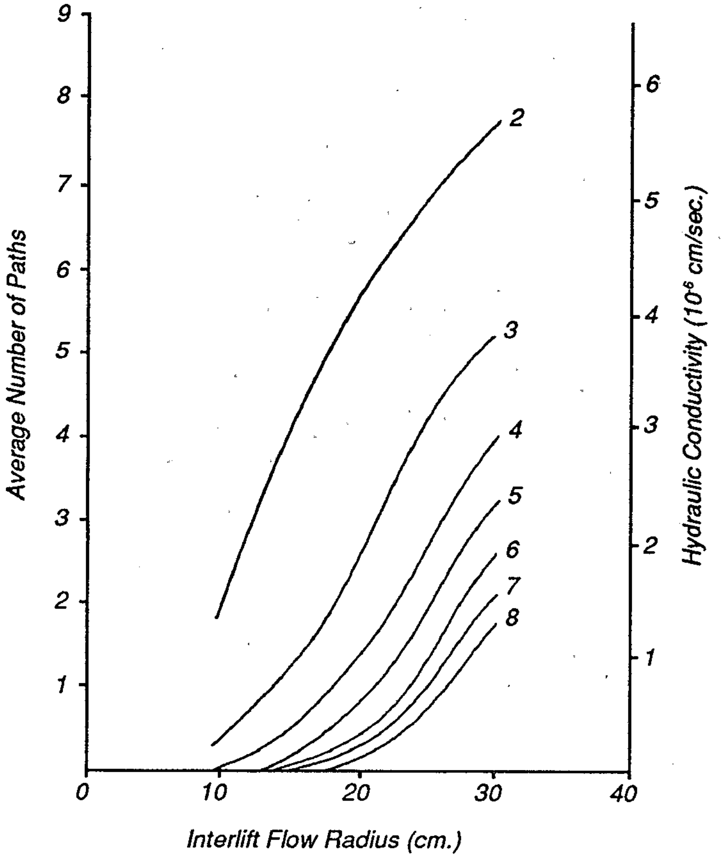

Figure 6. Interlift flow radius vs. average number of flow paths for two to eight lifts.

Laboratory Study

The laboratory portion of this research was conducted to evaluate the effects of clod size on the hydraulic conductivity of compacted soils and the uniformity of conductivity with depth within a lift of compacted soil. The study used two soils: 1) Beaumont clay (primarily smectite) and 2) Kosse clay (primarily kaolinite). The hydraulic conductivity as measured in the laboratory with water as the permeant averaged 1.5 X 10^{-9} and 0.8 X 10^{-7} cm sec^{-1} for the Beaumont and Kosse soils, respectively. The soils were sieved to create maximum clod sizes of <2.5, <5.0, and <7.5 cm. The sieved samples were brought to optimum moisture content, equilibrated for 1 wk, and then compacted in 60-cm-diameter permeameters using a specially constructed compaction foot. Soils were compacted to form a single lift averaging 23 cm in thickness. After compaction, the permeameters were equipped with head tanks to allow the addition of a 1 m head of water above the soil. A fluorescent dye was added to the permeant to aid in identifying flow paths through soil. For all clod sizes of the Beaumont soil, the hydraulic conductivity of the complete 23 cm lift was much greater than that measured in the laboratory using small-diameter permeameters. However, the hydraulic conductivity of the complete compacted lift of the Kosse soil approximated that measured in the small laboratory permeameters. Under the carefully controlled conditions imposed in this study, clod size did not have a significant effect on the hydraulic conductivity of the Beaumont clay.

To evaluate the uniformity of conductivity with depth, 7.5 cm of soil was removed from each permeameter and the conductivity was again measured in the remaining soil. Results indicated that after removing the upper 7.5 cm of soil, the conductivity ranged from 0.9 to 2.5 times that of the complete lift. Removing an additional 7.5 cm of soil resulted in conductivities ranging from 0.9 to 13 times that of the entire lift. It appears that for each soil, the lower portion of the 23 cm-thick-lift of compacted soil is about 10 times more permeable than the top.

Each 7.5 cm layer of soil was removed in 2.5 cm increments. After each 2.5 cm increment was removed, the soil surface was viewed under ultraviolet light to observe dye patterns. Drawings of dyed areas with depth generally showed that a large fraction of the cross section was dyed at the 2.5 cm depth and that the dyed fraction decreased with depth.

From the data collected in the laboratory study, it appears that the compactive effort applied during construction destroys the original clods present in the upper portion of a soil lift and results in a more platy structure. The amount of platy structure decreases and the number of highly conductive pores increases with depth within a single lift of compacted soil. Therefore, water flow through a lift of compacted clay is initially through a tortuous path between soil structural units and at deeper depths occurs through highly conductive interclod macropores.

Field Study

A field study of a compacted liner, using soil with properties considered to be ideal, was conducted to investigate the possible existence of zones of high, horizontal, hydraulic conductivity in interlift areas. The test was run on a compacted soil liner consisting of three approximately 20 cm lifts. A tracer solution was allowed to infiltrate through auger holes for 10 days, at which time excavations were made to expose a vertical plane extending outward from the auger boreholes. Three auger boreholes completely drained the solution within a matter of minutes. Two boreholes were excavated, including one in which rapid draining had occurred. Observations revealed that pockets of dye had accumulated in the interlift zone around that borehole. These pockets were completely saturated with dye. Another interesting observation was the occurrence of debris-enveloping voids. A dye-stained root was unearthed in the infiltrated area, which suggested that fluids flow preferentially along the periphery of such features.

Evidence gathered during the field study indicated there was preferential interlift fluid flow because of the existence of high permeability zones lying between liner lifts. Pockets of dye 1 to 4 cm wide in the vertical dimension were found in the bottom portion of lifts in some places. In other places, only a thin horizontal band of dye, 1 to 5 mm thick, was observed. The leading edge of the dye (IR) was located at an average distance from the borehole of 36 cm after 10 days of flow. This indicated that the rate of horizontal flow at interlifts far exceeded that of vertical flow within a lift.

The results of the field study indicated that the concept of the channel-centered interlift flow model was valid for compacted soil liners. Breaches will occur in a soil liner if the IR of a channel overlaps channels in underlying lifts. Consequently, the IR is a critical factor in the analysis of liner integrity.

Conclusions/Recommendations

1. Hydraulic conductivity is the most important property in determining the thickness required in a soil liner. Conductivity achieved in the liner is affected by several factors including liner thickness, soil matrix permeability, lift thickness, horizontal flow between lifts, and the presence of channels or defects.
2. Hydraulic conductivity of the soil liner is also the most important factor affecting the time it takes for hazardous constituents to break through the liner.

The computer model presented in this report simulates flow occurring through discrete channels (defects) in each lift and describes how these channels affect the overall conductivity of the liner. The channels can be interconnected by horizontal flow between lifts to form a continuous flow route through the liner. Minimizing horizontal flow will reduce the conductivity of the overall liner by reducing the number of interconnected channels. The computer model can also be used to simulate the effects of different horizontal hydraulic conductivities between lifts on breakthrough of leachate. Breakthrough time was found to be primarily a function of horizontal conductivity.

The following studies should aid in expanding the data base necessary to determine the required thickness for a soil liner:

1. Field and laboratory studies to investigate the horizontal flow of liquids between lifts and aid in determining factors that affect the rate and extent of interlift flow;
2. Studies of the depth functions for density, effective porosity, tracer movement, strength, and hydraulic conductivity within individual compacted lifts of varying thickness;
3. Investigation into whether constructing soil liners with a greater number of lifts effectively reduces flow between lifts and total flow through the liner, and
4. Field morphological studies of dye tracer movement through a liner and individual lifts to develop relationships between dye-filled porosity and liner performance variables including hydraulic conductivity and strength.

Ideally, studies such as these would be conducted on a variety of soils compacted over a range of moisture contents and with the use of a selection of commonly available equipment.

Studies conducted during this project suggest that flow through soil liners is controlled by a combination of vertical conductivity within lifts and horizontal conductivity between lifts. Consequently, the construction quality assurance program for a hazardous waste disposal facility should determine if such preferential flow paths exist in a given liner by conducting dye tracer studies on the soil liner of the test fill. It is suggested that dye be placed in the field infiltrometers and augured boreholes used on the test fill so that subsequent dissection will reveal the extent and routes of preferential liquid flow.

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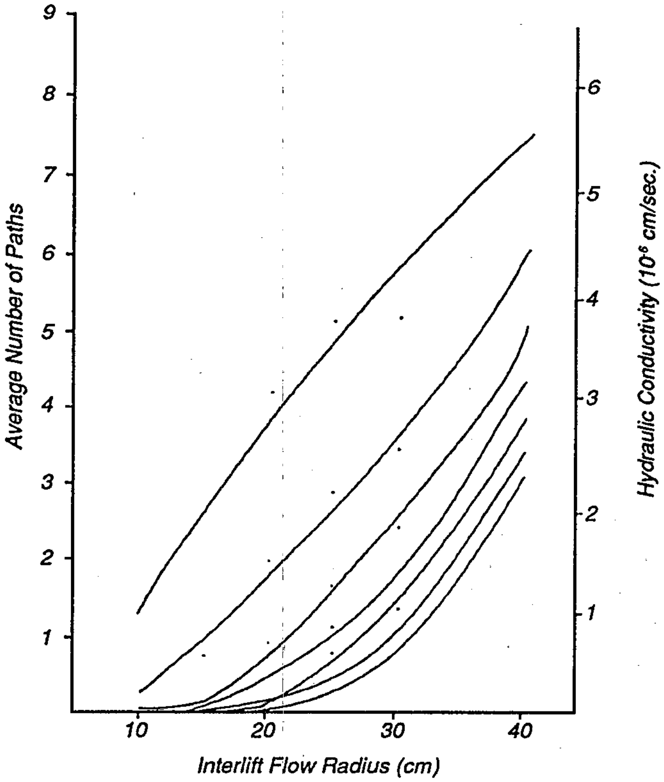

Figure 7. Pocket radius vs. average number of flow paths for two to eight lifts.

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G. Kenneth Dotson *is the EPA Project Officer (see below).*

The complete report, entitled "Factors Controlling Minimum Soil Liner Thickness," (Order No. PB91-191346AS; Cost: $31.00, subject to change) will be available only from:

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