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Minimum Thickness of Compacted Soil Liners: II. Analysis and Case Histories

By Craig H. Benson[1] and David E. Daniel,[2] Members, ASCE

Abstract: The stochastic models described in a companion paper were used to analyze compacted soil liners with a variable number of 15 cm (6 in.) thick lifts. No optimum number of lifts could be defined based on first-passage time; first-passage time increased as the thickness increased. Both models showed that the flux through the liner and the equivalent hydraulic conductivity decreased and the mean hydraulic conductivity (modeled as a lognormally distributed random variable) of lifts decreased. There was little benefit to increasing the number of lifts beyond four to six lifts. An analysis of case histories of in situ hydraulic conductivity also showed little reduction in hydraulic conductivity when the number of lifts was increased beyond four to six. Based upon hydraulic conductivity considerations, the recommended minimum thickness of compacted soil liners is four to six lifts, or 60 cm to 90 cm (2 ft to 3 ft).

INTRODUCTION

Two models that simulate the flow of water in saturated, compacted soil liners are described in a companion paper (Benson and Daniel 1994). The models, which are illustrated in Figs. 4 and 7 of the companion paper, assume: one-dimensional (1-D) plug flow through a series of lifts that each have a randomly variable hydraulic conductivity [Fig. 4, Benson and Daniel (1994)]; three-dimensional (3-D) flow through randomly-sized and randomly distributed channels within each lift and horizontal flow in transmissive zones located between lifts [Fig. 7, Benson and Daniel (1994)]. The 1-D model is assumed to simulate flow in well-built soil liners while the 3-D model is assumed to simulate flow in poorly built liners that have defects within each lift and imperfect bonding between lifts.

The question being addressed in this paper is: how thick should a compacted soil liner be? The results of analyses performed with the two models, and an analysis of case histories, are used to assess the minimum thickness required to obtain adequate hydraulic performance of soil liners. Two performance factors were considered: (1) The first-passage time (when the liquid, originally covering the liner, first emanates from the base of the liner); and (2) the steady flux of liquid through the liner. Probability distributions were used to describe variable input parameters and the performance of a liner was judged on the characteristics of the distributions of first-passage time and flux rather than a single number. Furthermore, the hydraulic performance of liners of varying thickness was evaluated with the assumption that the liner had not been damaged after construction by desiccation, frost action, settlement, or chemical attack. These factors, or other criteria besides hydraulic conductivity, may be important on some projects

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and should be considered. In addition, first-passage time was calculated by ignoring molecular diffusion and mechanical dispersion. For liners with extremely low hydraulic conductivity (e.g., $K < 1 \times 10^{-8}$ cm/s) or very small hydraulic gradients, diffusion can be an important, if not dominant, mechanism of solute transport (Quigley et al. 1987; Rowe 1987; Shackelford et al. 1989).

PARAMETERS FOR ANALYSES

Various parameters must be prescribed for each analysis. Probability distributions were used to describe hydraulic properties such as hydraulic conductivity K, number of channels N_c, and transmissivity of the interlift zones T_r. Deterministic parameters were used for less variable parameters, such as porosity. Of the distributions incorporated in the model, it is primarily the distributions of hydraulic conductivity and interlift transmissivity that the geotechnical engineer controls during construction. The materials, molding water content, and compactive effort influence the distribution of hydraulic conductivity; interlift transmissivity is influenced by the type of compactor and the method used to prepare the surface of a completed lift prior to the placing the next layer of soil.

The only input parameter treated as a random variable in the 1-D analyses was hydraulic conductivity of a lift K, which was assumed to be lognormally distributed as shown in Table 1 of the companion paper. For comparative purposes, a typical soil liner was assumed. The typical liner was assumed to have lifts each with mean hydraulic conductivity, $\bar{K}$, or 5×10^{-7} cm/s, although sensitivity analyses were performed by varying $\bar{K}$ from 5×10^{-7} cm/s to 5×10^{-8} cm/s. The coefficient of variation (defined as 100 times the standard deviation divided by the mean) of hydraulic conductivity C_{VK} was estimated from the data summarized in Table 1. It was assumed that $C_{VK} = 150$, although values of 100 and 200 were used in sensitivity analyses. Similar values were used in the 3-D analyses.

For the 3-D model, the number of flow channels N_c and the cross-sectional area of the channels A_c within a partition were also treated as random variables [Table 1, Benson the Daniel (1994)]. The number of channels in a partition N_c was randomly selected from a Poisson distribution and the area of each channel A_c was selected from a normal distribution. The parameters of the normal distribution were selected so that the average fraction of void space in a partition equaled the effective porosity. A hydraulic conductivity was also randomly assigned to each partition from a lognormal distribution. A flow coefficient was then assigned to each channel by equating the total flow in a partition to the total flow from the channels. Larger channels were assigned larger flow coefficients using a weighting scheme based on the squared cross-sectional area of the channels; i.e. larger channels were assigned greater weights and hence had greater flow coefficient (see Benson and Daniel 1994).

TABLE 1. Data on Mean $\bar{K}$ and Coefficient of Variation C_{VK} of Hydraulic Conductivity

Reference (1)	$\bar{K}$ (cm/s) (2)	C_{VK} (3)	Number of samples (4)	Type of test (5)
Krapac et al. (1989)	3×10^{-8}	58	31	Infiltrometer
Reimbold (1990, personal communication)	3×10^{-7}	386	42	Lab tests
Benson (1989) and Rogowski (1990)	2×10^{-6}	200	184	Underdrain
Sunnyview landfill[a]	2×10^{-8}	95	24	Lab tests
Mallard Ridge landfill[a]	1×10^{-8}	78	24	Lab tests
Tork County landfill[a]	2×10^{-8}	176	64	Lab tests

[a]Data from files of Wisconsin Department of Natural Resources

The classic expression for Pouiselle flow in a capillary tube was not employed because macropores are not small tubes with smooth walls. Instead, they are tortuous paths with varying aperture. As a result, a partition with a few large macropores may exhibit either high hydraulic conductivity (corresponding to macropores that are not tortuous and have very little change in aperture) or low hydraulic conductivity (macropores that are highly tortuous and have highly variable aperture size). The writers believe this approach provides the best means to stochastically stimulate these different possibilities.

The assumed values for the deterministic parameters are summarized in Table 2. For the 1-D model, the effective porosity n_e was assumed to be 0.40 because, for a well-built liner, the number of defects should be small and n_e should be nearly equal to the total porosity, typically about 0.40 for compacted clay. In contrast, n_e for the 3-D model was assumed to be 0.05 because in poorly built liners, water is expected to flow primarily in relatively large pores that comprise only a small percentage of the soil. Low effective porosities, in the range of 0.05–0.10, for soil liners where flow occurs primarily in macropores has been documented by Elsbury et al. (1988) and Rogowski (1990). The head of liquid on the liner was fixed at 30 cm because changes in gradient result in only proportional changes in time of travel and flux.

The values of parameters described for the "typical" soil liner are admittedly arbitrary. However, the purpose of the analyses was to examine sensitivity of first-passage time and flux to number of lifts for a consistent set of assumed conditions. Other values could be assumed. By performing multiple analyses with a range of hydraulic conductivities and transmissivities (mean and coefficient of variation), the authors attempted to make certain that the conclusions were applicable to a range of reasonable conditions. More field data is needed, however, before it can be ensured that most realizations possible in the field have been simulated.

TABLE 2. Summary of Assumed-Fixed Parameters

Parameter (1)	Applicable model (2)	Magnitude (3)
Depth of liquid H_L	1-D and 3-D	30 cm
Lift thickness	1-D and 3-D	15 cm
Mean number of channels/m^2	3-D	100
Effective porosity	1-D	0.40
Effective porosity	3-D	0.05
Coefficient of variation of cross-sectional area of channels	3-D	10
Thickness of lift interface b	3-D	3 cm

INTERPRETATION OF RESULTS

In this analysis, the performance of a soil liner was evaluated by the characteristics of the distributions of first-passage time and flux. Liners that perform optimally have a long mean first-passage time, a small mean flux, and little dispersion in both distributions. Three methods were used to describe the distributions: (1) Probability density functions (PDFs); (2) percentiles in the form of box plots; and (3) moments. The PDF, $f_T(t)$, shown in Fig. 1(*a*) depicts the likelihood of realizing a particular first-passage time; times that are more probable correspond to points on the PDF with larger magnitude. The probability that a first-passage time is realized in the interval t to $t + dt$ is obtained by integrating the PDF over this region [shown as the shaded zone in Fig. 1(*a*)].

Percentiles, in the form of box plots, were also used to describe the

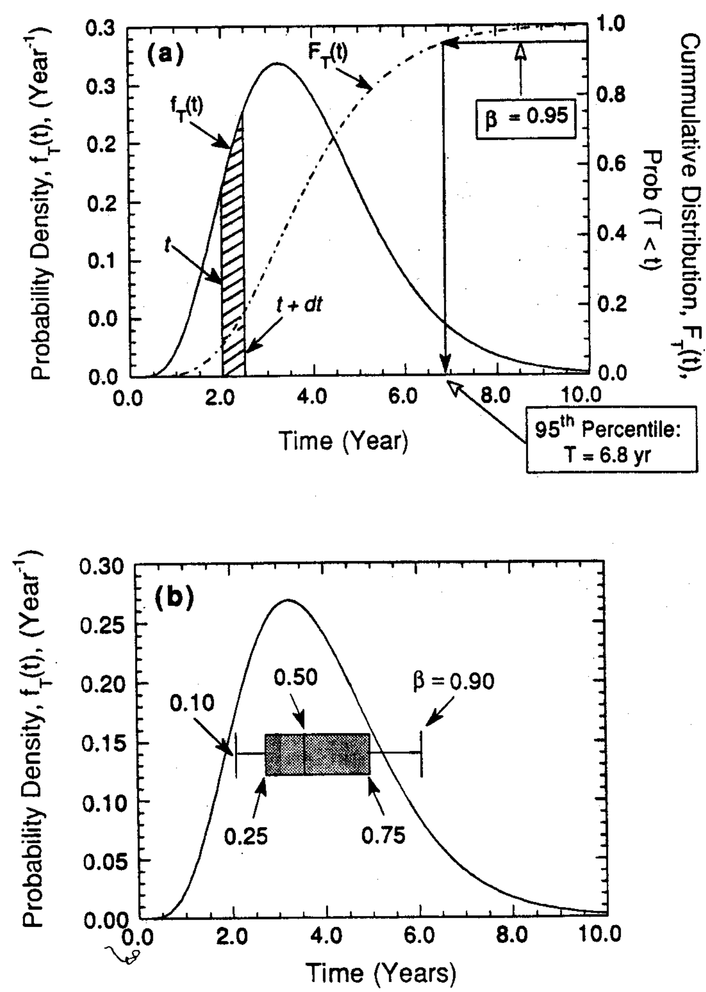

FIG. 1. Examples of: (*a*) Probability Density Function (PDF) and Cumulative Distribution Function (CDF) of First-Passage Time; (*b*) Box Plot of First-Passage Time

distributions. A percentile is best explained by the cumulative distribution function (CDF), F, of a distribution [Fig. 1(*a*)]. The magnitude of the CDF for the first-passage time at time t, $F_T(t)$, is obtained by integrating the PDF of first-passage time [Fig. 1(*a*)] from zero to t. Hence, the CDF yields the probability that the first-passage time is less than time t. The βth percentile first-passage time corresponds to the time at which the distribution function equals β. For example, $\beta = 0.95$ corresponds to 6.8 years for the CDF shown in Fig. 1(*a*). Fig. 1(*b*) shows the PDF and box plot for the distribution of first-passage time. The bar at the center of the box plot corresponds to $\beta = 0.5$ (the median) and the bars at the edges of the box correspond to $\beta = 0.25$ and $\beta = 0.75$. The bars at the extremities of the box plot correspond to $\beta = 0.10$ and $\beta = 0.90$.

The box plot serves as a compact method to describe the form of a probability distribution. Wide box plots correspond to very dispersed distributions, whereas narrow box plots correspond to distributions with little dispersion. The symmetry (or lack of symmetry) of the box about the center bar provides a measure of the skew of the distribution and the distance between the outermost bars is indicative of the weight of the distribution's tails.

Moments of first-passage time and flux were also used to describe the distributions. The mean is used as a measure of location of a distribution and the mean square (second absolute moment) and coefficient of variation are used to describe dispersion.

RESULTS OF STOCHASTIC MODELS: FIRST-PASSAGE TIME

Box plots for first-passage time computed with the 1-D model are shown in Fig. 2(*a*) as a function of thickness for mean hydraulic conductivity $\bar{K}$ of the lifts of 5×10^{-7}, 1×10^{-7}, and 5×10^{-8} cm/s. In each case, C_{VK} was 150. For a given thickness, as the mean hydraulic conductivity decreases, the box plots shift towards larger first-passage times and also become wider, indicating greater dispersion in the first-passage-time distribution. The shift toward longer, more dispersed first-passage time also occurs as the thickness

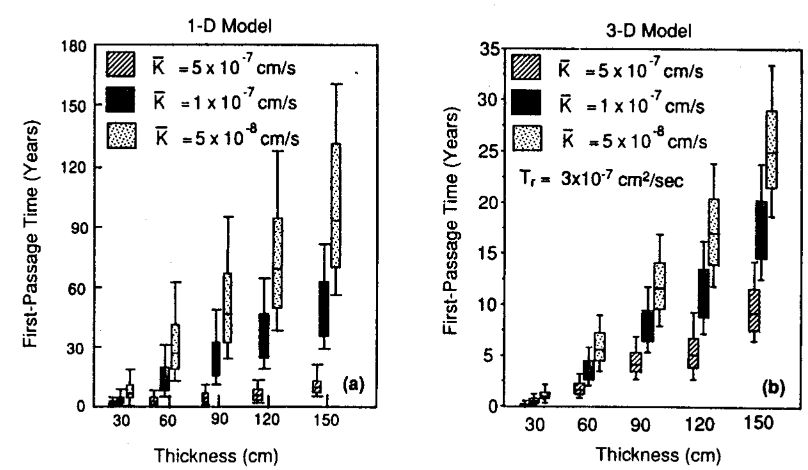

FIG. 2. First-Passage Time Box Plots as Function of Thickness for: (*a*) 1-D model; (*b*) 3-D Model for $\bar{K}$ = 5 × 10^{-7}, 1 × 10^{-7}, and 5 × 10^{-8} cm/s

is increased. Hence, thicker liners with lower mean hydraulic conductivity within individual lifts have an increased probability of very long first-passage times. This trend is precisely what one would expect.

Fig. 2(*b*) is a similar graph showing the results from the 3-D model; a reduction in the mean hydraulic conductivity or an increase in thickness again resulted in longer, more dispersed first-passage times. The first-passage times, however, are significantly shorter and the box plots are more symmetrical than in the 1-D case. The first-passage times are shorter because the effective porosity in the 3-D case was assumed to be 0.05 but was 0.40 for the 1-D case. Hence, the time of travel through the liner was necessarily shorter in the 3-D case.

As Fig. 2 shows, thicker liners correspond to longer first-passage times. Sensitivity analyses performed by varying C_{VK} and T_r also showed that thicker liners always correspond to longer first-passage times. Because there was no threshold in thickness beyond which significantly longer first-passage times were realized, no optimum thickness could be identified from the first-passage-time calculations.

RESULTS OF STOCHASTIC MODELS: FLUX DISTRIBUTION

The flux (flow rate per unit area) emanating from the base of the soil liner is the second performance criterion considered in this analysis. The flux was used to compute an equivalent hydraulic conductivity K_{eq}, which is defined as the flux through the liner divided by the average hydraulic gradient.

Mean and Coefficient of Variation of Hydraulic Conductivity

Fig. 3(*a*) and 3(*b*) show, respectively, dimensionless mean and mean square equivalent hydraulic conductivity K_{eq} computed with the 1-D model as a function of thickness for C_{VK} = 100, 150, and 200. To obtain the moments, a probability integral transform was used to convert the distribution of flux to a distribution of K_{eq}. The mean and mean square K_{eq} were computed by numerically integrating the PDF of equivalent hydraulic conductivity and were rendered nondimensional by dividing by the mean $\bar{K}$ or the mean squared $\bar{K}^2$ of the hydraulic conductivity of a lift.

The mean and mean square K_{eq} decreased substantially when the thickness of the liner was increased from 15 cm (one lift) to 60 cm (four lifts). Hence, as the thickness is increased, the flux becomes smaller and less dispersed. Further increases in thickness beyond four to six lifts yielded only a small decrease in the mean and mean squared K_{eq}.

The effect of thickness on K_{eq} computed with the 1-D model is further illustrated by the PDFs shown in Fig. 4. In this case, $\bar{K} = 5 \times 10^{-8}$ cm/s and $C_{VK} = 150$. As the thickness was increased, the PDF became narrower, more symmetrical, and the upper tail (large hydraulic conductivities) diminished. The distribution becomes narrower because of the central limit theorem; i.e. the high and low hydraulic conductivities tend to average out as the number of lifts is increased. Hence, K_{eq} for thicker liners is less uncertain than K_{eq} for thinner liners. The upper tail diminshes because, for one-dimensional flow, lower hydraulic conductivities have a much greater effect on the overall hydraulic conductivity than high hydraulic conductivities. Because of the large positive skew of the distribution of hydraulic conductivity, the fraction of lifts with conductivity less than the mean is greater than the fraction of lifts with hydraulic conductivity larger than the

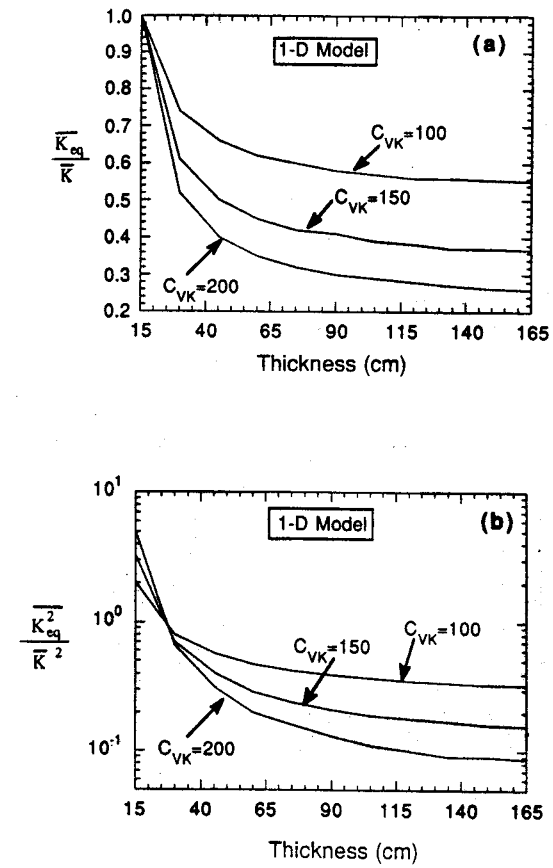

FIG. 3. Nondimensional: (*a*) Mean and (*b*) Mean Square Equivalent Hydraulic Conductivities as Function of Thickness for 1-D Model

mean. Hence, lifts of high hydraulic conductivity become increasingly less frequent and less significant as the thickness of the liner is increased.

Results from the 3-D model, shown in Fig. 5(*a*), also show that the magnitude and disperson of K_{eq} decreased as the thickness of the liner was increased. Fig. 5(*a*) also shows that the decrements in magnitude and dispersion of K_{eq} are less significant if $\bar{K}$ is reduced and diminish, for all $\bar{K}$, as the thicknesses exceed 60 cm to 90 cm (four to six lifts).

The effect of modifying the coefficient of variation of hydraulic conductivity C_{VK} in the 3-D model is shown in Fig. 5(*b*). Because zones of soil with large hydraulic conductivity, which act as pathways for rapid flow, increase in frequency as the coefficient of variation in hydraulic conductivity C_{VK} becomes larger, it is plausible to expect that an increase in C_{VK} may have a detrimental effect on the distribution of K_{eq}. It was found, however, that increasing C_{VK} resulted in smaller equivalent hydraulic conductivity for all thicknesses exceeding 15 cm, provided the mean hydraulic conductivity of each lift remained the same. Similar results were obtained for the 1-D model (Fig. 3).

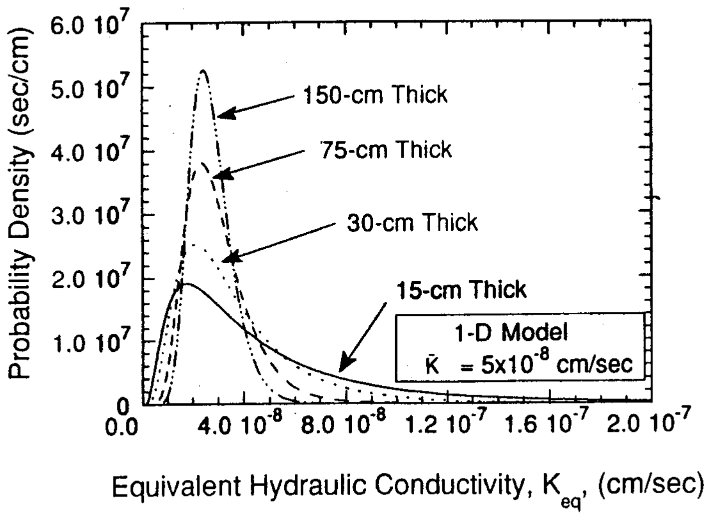

FIG. 4. Probability Density Functions of Equivalent Hydraulic Conductivity Obtained with 1-D Model for Thickness of 15, 30, 75, and 150 cm

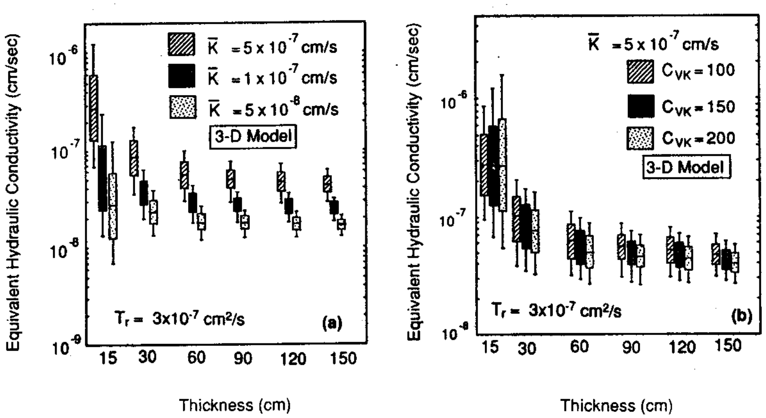

FIG. 5. Box Plots Obtained from the 3-D Model as Function of Thickness for: (*a*) $\bar{K}$ = 5 × 10^{-7}, 1 × 10^{-7}, and 5 × 10^{-8} cm/s; (*b*) C_{VK} = 100, 150, and 200

An examination of the lognormal PDF used to describe hydraulic conductivity of a single lift (Fig. 6) explains these counterintuitive observations. Fig. 6 shows that an increase in C_{VK} causes greater positive skew of the lognormal hydraulic conductivity distribution (provided $\bar{K}$ does not change), which results in a much greater increase in the probability of low hydraulic conductivities in comparison to the increase in the probability of high hydraulic conductivities. Thus, an increase in C_{VK} yields only a small change in the probability of high K_{eq}, but a large change in the probability of low K_{eq}.

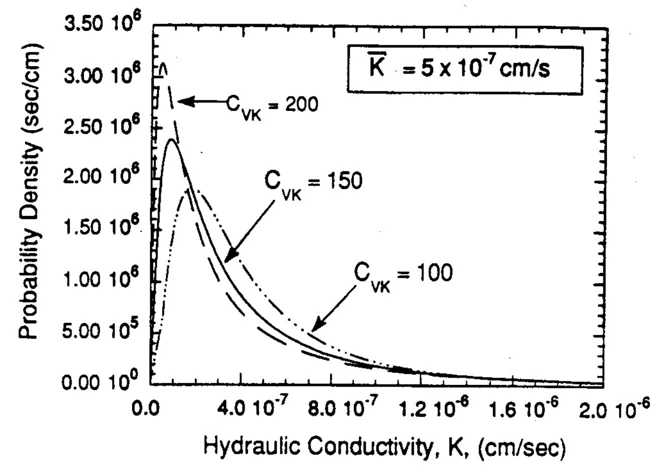

FIG. 6. Probability Density Functions of Hydraulic Conductivity for C_{VK} = 100, 150, and 200

Transmissivity of the Interlift Zone

The influence of transmissivity T_r of the interlift zone on K_{eq} is shown in Fig. 7 for three assumed mean values of T_r. In each case, C_{VT_r} was 150. Only one box plot (rather than three) is shown for a thickness of 15 cm (one lift) because there is no interlift zone with one lift. Note that the box plot is not centered on 5 × 10^{-7} cm/s $\bar{K}$ for a single lift, because the distribution of hydraulic conductivity is positively skewed and hence the median is smaller than the mean.

Fig. 7 shows: (1) As the thickness of the liner is increased, K_{eq} decreases, but increasing the thickness beyond 60 cm to 90 cm (four to six lifts) produces almost no further reduction in K_{eq}; (2) K_{eq} is very sensitive to interlift transmissivity (for liners ≥ 60 cm thick, the value of T_r was far more important than the thickness of the liner); and (3) as the liner becomes thicker, the dispersion of K_{eq} is reduced, but beyond a thickness of 60–90 cm, further reductions in the dispersion of K_{eq} are minimal.

The very low values of K_{eq} obtained by improving the interlift bond (Fig. 7) may not be fully realized in the field. First, from a practical standpoint, construction methods conducive to the formation of macroscopic defects in the lifts are also likely to result in poor interlift bonding. Having poorly built lifts that are carefully bonded is probably not realistic. Furthermore, in the model, liquid is required to flow in the interlift zone as it moves between channels in adjacent lifts; no direct connection of macropores in adjacent lifts is permitted nor is flow within the matrix of the lifts. Hence, when the transmissivity is reduced, it necessarily reduces K_{eq}. Second, when the lifts are carefully bonded, flow between macropores will be impeded. As a result, the hydraulic conductivity of the lifts will be governed by the matrix and not the macropores. Furthermore, because lateral flow is restricted, the flow field will be more nearly one dimensional. Hence, for carefully bonded lifts, the 1-D model may be a better representation of the flow field. Nevertheless, the point to be illustrated with Fig. 7 is that improving bonds between the lifts will reduce the connectivity of previous zones in adjacent lifts and hence the overall hydraulic conductivity of the liner will be reduced.

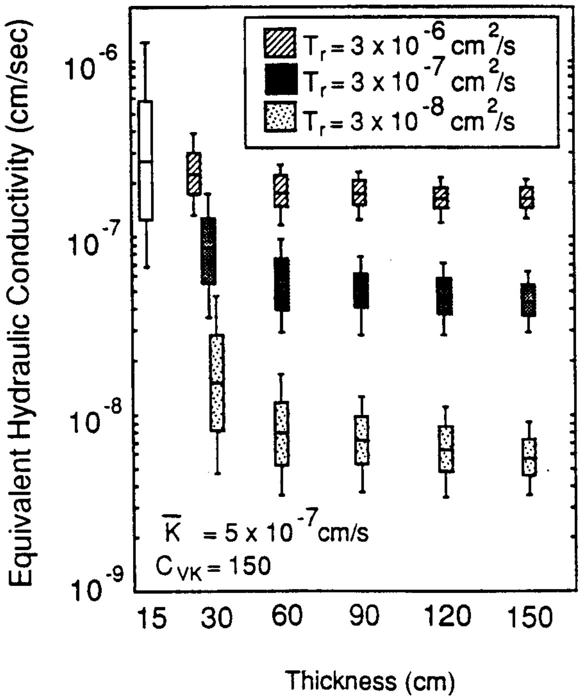

FIG. 7. Box Plots Obtained from 3-D Model as Function of Thickness for Mean Transmissivities of 3×10^{-6}, 3×10^{-7}, and 3×10^{-8} cm^2/s

Implications

The 1-D and 3-D analyses showed that reductions in the magnitude and dispersion of K_{eq} could be achieved by increasing the thickness of the liner. These reductions, however, were limited to thicknesses of 60 cm to 90 cm (four to six lifts) and were less significant if the mean hydraulic conductivity of the lifts was low. Furthermore, bonding of lifts (as reflected by the transmissivity of the interlift zone) affected K_{eq} for any thickness. If the bond was poor and the mean K of a lift was high, the liner had high K_{eq} even if the thickness was large. In contrast, if the bonding of lifts was excellent, a liner with low K_{eq} could be achieved with a thickness of only 60 cm. In real soil liners, hydraulic conductivities as low as 6×10^{-9} cm/s (Fig. 7, $T_r = 3 \times 10^{-8}$ cm^2/s) might not be achieved simply by improving bonding of the lifts. The results do suggest, however, that bonding of the lifts plays an important role in the connectivity of zones of high hydraulic conductivity. By carefully bonding lifts, the connectivity is reduced and consequently the equivalent hydraulic conductivity is lower.

These results suggest that to achieve a liner with low mean hydraulic conductivity: (1) The mean hydraulic conductivity of a lift should be minimized; (2) the lifts should be bonded together well; and (3) the liner should be at least 60–90 cm thick. Analyses showed that much lower mean hydraulic conductivity can be achieved from a relatively thin (60–90 cm thick), well-built liner than from a far thicker, but poorly built, liner. Simply making a liner thicker (beyond 60–90 cm thick) may not ameliorate construction deficiencies.

CASE HISTORIES

The computations that have been described in the present article represent assumed conditions and idealized models. Case histories, in the form of in situ measurements of hydraulic conductivity of soil liners with different thicknesses, were examined to determine if the trends were the same as those obtained from the 1-D and 3-D stochastic models.

In Situ Hydraulic Conductivity Measurements

Case histories of 53 in situ measurements of hydraulic conductivity K_{field} of compacted soil liners are summarized in Table 3. For each case history, a description of the quality of construction ("excellent," "good," or "poor") was assigned. "Excellent" was used for compaction wet of optimum with heavy rollers that had long, fully penetrating feet. "Good" was used for cases in which the soil was compacted with footed rollers, but the documentation was somewhat lacking. "Poor" was used to describe construction of liners with undocumented procedures or compaction of the soil dry of optimum or with relatively lightweight equipment.

The K_{field} measurements obtained from the case histories are plotted as a function of thickness in Fig. 8; the band containing most of the data was drawn by eye. The two dashed lines represent the geometric mean hydraulic conductivity for liners built with poor construction and liners built with good or excellent construction. Geometric mean hydraulic conductivities (shown as solid symbols for each construction type) were computed for liners in four groups: liners with thicknesses of 15–50 cm, 50–75 cm, 75–110 cm, and 110–150 cm.

Fig. 8 shows that the mean and dispersion of K_{field} decrease as the thickness of the liner increases. Soil liners with thickness less than 30 cm tended to be at least 10 times to 100 times more permeable than liners that were at least 60 cm thick. For liners at least 60 cm to 90 cm thick, the magnitude and dispersion of K_{field} were insensitive to thickness. Furthermore, the trend of decreasing hydraulic conductivity was observed for poor as well as good and excellent construction types.

Comparison of Field Data and Modeling Results

The similarity of the trends in mean and dispersion of K_{eq} shown in Fig. 8 and the trends exhibited by the modeling results (Figs. 3–7) are similar. The magnitude and dispersion of K_{eq} decrease when the thickness is increased from 15 cm to 90 cm, but further increases in thickness show little change in K_{eq}. To analyze the field data more rigorously, the data grouped by thickness were analyzed further. The hydraulic conductivities in each group were logarithmically transformed, and the mean and standard deviation of the transformed data in each group were computed. The trend in mean and standard deviation from group to group caused by differences in thickness were removed by normalizing the data in each group. To standardize the data in a group, the data were transformed by

$$Z = \frac{\ln K - \overline{\ln K}}{s_{\ln K}} \qquad (1)$$

where $\overline{\ln K}$ and $s_{\ln K}$ = mean and standard deviation of the logarithm of hydraulic conductivity in a particular group and Z = standard variate.

By transforming the data by (1), the functional relationship between the distribution of in situ hydraulic conductivity and thickness is removed. The

TABLE 3. Data on In Situ Hydraulic Conductivity

Reference (1)	Description (2)	Plasticity index (3)	Construction quality (4)	Thickness (cm) (5)	K_{field} (cm/s) (6)	Measurement technique (7)
Daniel (1984)	Central Texas	20	Poor	30	4×10^{-5}	Leak rate
—	North Texas	—	Poor	21	3×10^{-6}	Infiltrometer
—	South Texas	23–55	Poor	60	2×10^{-5}	Leak rate
—	Mexico	14–24	Good	48	1×10^{-6}	Leak rate
Day and Daniel (1985)	Prototype 1	11	Poor	15	9×10^{-6}	Underdrain
—	Prototype 2	45	Poor	15	4×10^{-6}	Underdrain
Rogowski (1990)	Test pad	12	Good	30	5×10^{-7}	Underdrain
Daniel and Trautwein (1986)	Cover	—	Excellent	90	8×10^{-8}	SDRI
Daniel (1987)	Confidential	—	Excellent	30	2×10^{-6}	Leak rate
Lahti et al. (1987)	Keele Valley	7–15	Excellent	120	9×10^{-9}	Lysimeters
Goldman et al. (1988)	Site K	49–69	Excellent	30	1×10^{-7}	Lysimeters
Mueser Rutledge (1988)	Pad A1	26–42	Excellent	60	1.3×10^{-7}	SDRI
—	Pad A2	26–42	Excellent	60	2.4×10^{-8}	SDRI
—	Pad B1	31–44	Excellent	60	5.6×10^{-8}	SDRI
—	Pad B2	31–44	Excellent	60	5.0×10^{-8}	SDRI
—	Pad B3	31–44	Excellent	60	9.4×10^{-8}	SDRI
—	Pad C1	27–41	Excellent	60	1.2×10^{-7}	SDRI
—	Pad C2	27–41	Excellent	60	3.7×10^{-8}	SDRI
—	Pad D1	13–25	Excellent	60	3.1×10^{-7}	SDRI
—	Pad D2	13–25	Excellent	60	3.9×10^{-7}	SDRI
Elsbury et al. (1988)	Test pad	41	Poor	30	1×10^{-4}	Underdrain
Edwards and Yacko (1989)	Test pad	—	Good	60	6×10^{-9}	Underdrain
Gordon et al. (1989)	Marathon County	16–54	Excellent	120	2×10^{-8}	Lysimeter
—	Marathon County	16–54	Excellent	120	5×10^{-9}	Lysimeter
—	Portage County	13–33	Excellent	150	5×10^{-9}	Lysimeter
—	Sauk County	13–63	Excellent	150	2×10^{-8}	Lysimeter
Albrecht and Cartwright (1989)	Test pad	7	Excellent	90	4×10^{-8}	SDRI
Mikus (1989)	Celanese pad	45–68	Excellent	60	4×10^{-8}	SDRI
—	Transwestern pad	11–20	Excellent	90	1×10^{-8}	SDRI
—	Phillips pad 1	9–38	Excellent	90	2×10^{-8}	SDRI
—	Phillips pad 2	9–38	Excellent	90	1×10^{-7}	SDRI
—	UC-onsite clay	45–58	Excellent	60	5×10^{-8}	SDRI
—	UC-offsite clay	36–47	Excellent	60	2×10^{-8}	SDRI
—	Dupont-gray clay	25–44	Excellent	105	3×10^{-8}	SDRI
—	Dupont-tan clay	34–36	Excellent	105	3×10^{-8}	SDRI
—	Shell pad	15–37	Excellent	75	3×10^{-8}	SDRI
—	BP pad	19–32	Excellent	60	1×10^{-7}	SDRI
—	Gulf Coast Authority	28–52	Excellent	60	1×10^{-7}	SDRI
Krapac et al. (1989)	Test pad	10	Excellent	90	4×10^{-8}	Infiltrometer
Clough-Harbor (1989)	Test pad	—	Good	60	1×10^{-7}	SDRI
Fernuik and Haug (1990)	Residual soil	11–14	Excellent	60	2×10^{-7}	Infiltrometer
Johnson et al. (1990)	Liner A	35	Excellent	60	3×10^{-8}	SDRI
—	Liner B	34	Excellent	60	1×10^{-8}	SDRI
Trautwein and Williams (1990)	Case history 1	—	Poor	60	6×10^{-7}	SDRI
—	—	—	Excellent	60	5×10^{-8}	SDRI
—	Case history 2	20	Poor	30	2×10^{-6}	SDRI
—	—	20	Excellent	30	1×10^{-7}	SDRI
Benson and Hardianto (1992)	Site A	10	Poor	75	2×10^{-7}	SDRI
Swan (1992)	Test pad A	25	Poor	110	1.5×10^{-7}	Infiltrometer
—	Test pad B	—	Good	90	1.5×10^{-8}	SDRI
—	Test pad C	—	Good	105	6×10^{-8}	SDRI
—	1978 cell	23	Excellent	120	1×10^{-9}	Lysimeter
—	1984 cell	21	Poor	120	1×10^{-7}	Lysimeter

Note: SDRI = Sealed Double-Ring Infiltrometer.

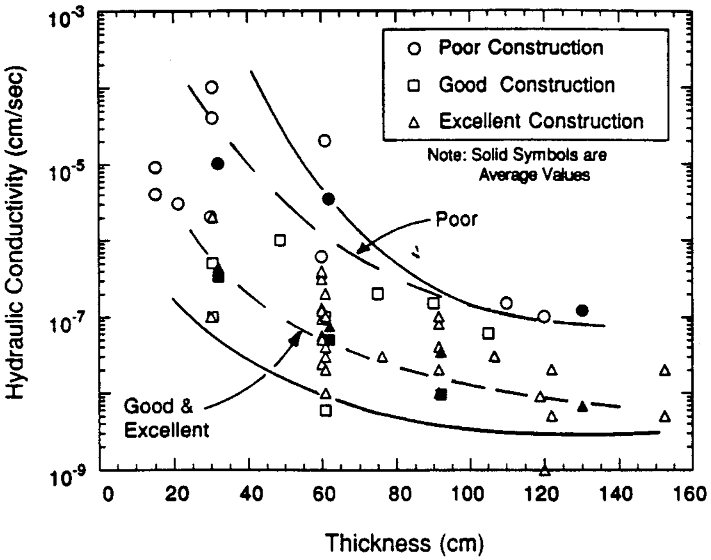

FIG. 8. In Situ Measurements of Hydraulic Conductivity as Function of Thickness

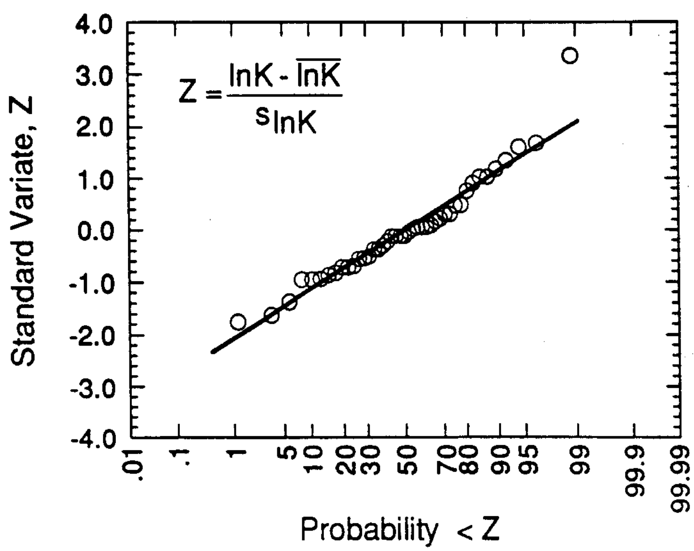

FIG. 9. Normal Probability Plot of Standardized In Situ Hydraulic Conductivity Measurements

large mean and variance of hydraulic conductivity associated with thin liners and the small mean and variance associated with thicker liners are adjusted so each group has the same mean and variance. Therefore, the standardized data can be placed in one group and analyzed statistically.

The standardized data, analyzed as a single group, were graphed as a normal probability plot (Fig. 9) to determine if the data were approximately lognormal. Because the probability plot is nearly linear, the data were assumed to be lognormal (Haan 1977) and the mean and standard deviation, computed for each group of log conductivities, were used as parameters in the lognormal distribution. From the lognormal distribution, the probability of the hydraulic conductivity exceeding 1×10^{-7} cm/s was computed for each group.

The probability of exceeding 1×10^{-7} cm/s computed with the in situ measurements was compared with results from the 3-D and 1-D models. For the 3-D model, the parameters of the distributions were assumed to be $\bar{K} = 6 \times 10^{-7}$ cm/s, $C_{VK} = 150$, $\bar{T} = 2 \times 10^{-7}$ cm²/s, and $C_{VT_r} = 150$. The mean hydraulic conductivity of a lift and the mean transmissivity of interlift zone were selected to obtain a reduction in hydraulic conductivity with thickness that was similar to the rate of decrease in hydraulic conductivity exhibited by the field data in Fig. 8. Because the 1-D model was assumed to simulate a well-built liner, $\bar{K}$ was specified as 1×10^{-7} cm/s, which is lower than $\bar{K}$ assumed for the 3-D model, to simulate improved construction. The C_{VK} for the 1-D model was also assumed to be 150.

Fig. 10(*a*) shows the probability of exceeding an equivalent hydraulic conductivity of 1×10^{-7} cm/s, which was computed with all the field data and the 3-D stochastic model. The results of the models and the field data exhibit a similar trend; a reduction in the probability of exceeding 1×10^{-7} cm/s is realized as the thickness is increased. For thicknesses greater than 90 cm, however, the probability of exceedance is small and does not decrease significantly with increasing thickness.

To compare the field data and the 1-D model, the field data were reanalyzed, but with the data for poor and good construction excluded. Fig. 10(*b*) is a graph of the probability of exceeding 1×10^{-7} cm/s based on analysis of the field data and results from the 1-D model. It shows the 1-D model yields a lower probability of exceeding 1×10^{-7} cm/s. The discrepancy between the model results and the field data is likely caused by two factors. The primary factor causing the discrepancy is that the field data are derived from many sites and hence the reduction in hydraulic conductivity shown in the field data is likely to be caused by factors other than thickness. For example, it is likely that the thicker liners were built with better construction methods and hence should have lower hydraulic conductivity. Also, hydraulic conductivities of many of the thick liners were computed from lysimeter data at greater overburden pressures (resulting in lower hydraulic conductivity) whereas hydraulic conductivities of the thin liners were often measured with infiltration tests with essentially no overburden pressure.

The second factor affecting the discrepancy is that actual liners will exhibit to some extent three-dimensional flow, a phenomena that cannot be simulated with the 1-D model. Hence, in an actual liner the flow will circumvent some of the regions with low conductivity and as a result have greater hydraulic conductivity than would be predicted with a one-dimensional analysis. This hypothesis is nearly impossible to verify, however, without measurements of hydraulic conductivity being conducted on a single liner as its thickness is increased. Nevertheless, the field data and the modeling results show a distinct similarity; for liners thinner than 90 cm, K_{eq} decreases with increasing thickness, but for thicknesses beyond 90 cm, further reductions in K_{eq} become small. Apparently, four to six lifts provide a liner with sufficient redundancy to minimize the probability of pervious pathways penetrating the entire liner.

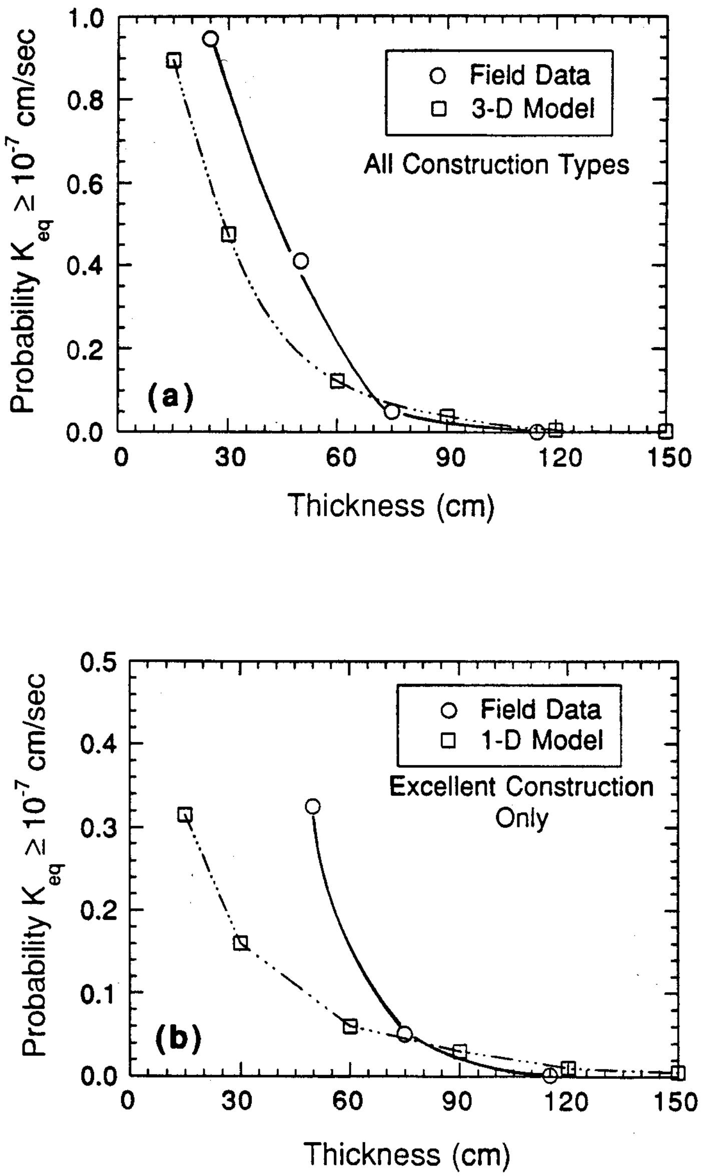

FIG. 10. Probability of Hydraulic Conductivity Exceeding 1×10^{-7} cm/s as Function of Thickness for (*a*) All In Situ Data and 3-D Model; (*b*) Data for Excellent Construction Only and 1-D Model

PRACTICAL IMPLICATIONS

Based on analysis of the field data and results of the models, emphasis should be placed on constructing lifts of low mean hydraulic conductivity that are carefully bonded. The improvement of performance obtained by

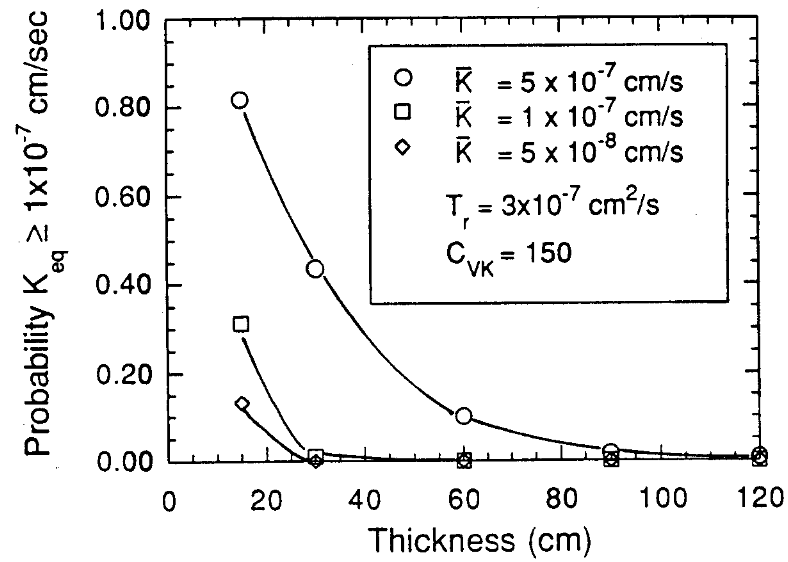

FIG. 11. Influence of Mean Hydraulic Conductivity on the Probability of Hydraulic Conductivity Exceeding 1×10^{-7} cm/s

high-quality construction far outweighs the benefits of simply increasing the thickness. This point is illustrated in Fig. 11 with results obtained with the 3-D model for the typical soil liner. Fig. 11 shows that a reduction in the mean hydraulic conductivity has a tremendous influence on thickness necessary to achieve K_{eq} less than 1×10^{-7} cm/s with near certainty. By reducing the mean hydraulic conductivity only one-half order of magnitude, from 5×10^{-7} to 1×10^{-7} cm/s, the minimum thickness to achieve equivalent hydraulic conductivity below 1×10^{-7} is reduced from 90 cm to about 30 cm. Improving the bonding of the lifts is also likely to reduce the probability of excessive hydraulic by impeding flow between pervious zones in adjacent lifts.

CONCLUSIONS

Based on the results of analyses and case histories described herein, the following conclusions are drawn:

1. The minimum first-passage time of a conservative solute passing through a soil liner by purely advective transport increases with increasing thickness (number of lifts) of the liner. Based on the modeling results, no optimum thickness could be defined from first-passage time.
2. The equivalent hydraulic conductivity K_{eq} of a multilift soil liner decreases with decreasing mean hydraulic conductivity within each lift. The analyses show that more variability in hydraulic conductivity results in lower K_{eq} provided the mean hydraulic conductivity of the lifts does not change. Thus, when a soil liner is constructed, emphasis should be placed on lowering the mean hydraulic conductivity of a lift $\bar{K}$ rather than minimizing scatter

in hydraulic conductivity within a lift. In reality, however, sound construction practices that minimize $\bar{K}$ probably also tend to minimize scatter in K.

3. The field data and models show that soil liners that are only 15–30 cm thick (one or two lifts) tend to be much more permeable than liners that are 60–90 cm thick (four to six lifts). Decreasing hydraulic conductivity with increasing thickness was observed for poorly built liners and well-built liners. Little reduction in hydraulic conductivity is achieved, however, when the thickness is increased beyond 60–90 cm (four to six lifts). Similar results were obtained with the models. Apparently, four to six lifts provide a liner with sufficient redundancy to minimize the probability of pervious pathways penetrating the entire liner.

4. If at least four lifts are used, the degree of bonding between lifts, i.e. the degree to which zones of high horizontal hydraulic conductivity at lift interfaces are eliminated, is far more important than the number of lifts. Stated in practical terms, the overall hydraulic conductivity of a well-built liner composed of four lifts (60 cm) will be far lower than the hydraulic conductivity of a poorly built liner containing many more lifts. Adding more lifts beyond a minimum of four to six lifts (60–90 cm) will not ameliorate the problems left from poor construction (poor bonding between lifts or high mean hydraulic conductivity within a lift).

5. A reasonable minimum thickness for low-hydraulic-conductivity, compacted soil liners is 60–90 cm (four to six lifts). Thicker soil liners may be recommended to account for a variety of site-specific factors, e.g. to lengthen the minimum first-passage time or to increase the geochemical attenuation capacity of the liner.

In the present study, it was assumed that the liner will not be damaged by freeze/thaw cycles, desiccation, settlement, or other environmental or chemical stresses. If such damaging conditions exist, other factors beyond the scope of this investigation will need to be considered in determining an appropriate thickness.

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APPENDIX II. NOTATION

The following symbols are used in this paper:

A_c = cross-sectional area of channel (3-D model);
C_{VX} = coefficient of variation of random process X;
K = hydraulic conductivity;
$\bar{K}$ = mean hydraulic conductivity;
$\bar{K}_{eq}$ = mean equivalent hydraulic conductivity;
$\bar{K}_{eq}^2$ = mean square equivalent hydraulic conductivity;
$\overline{\ln K}$ = sample mean of natural logarithm of hydraulic conductivity;
N_c = number of channels in partition (3-D model);
$s_{\ln K}$ = sample standard deviation of natural logarithm at hydraulic conductivity;
T_r = transmissivity of interlift zone;
$\bar{T}_r$ = mean transmissivity of interlift zone; and
Z = standardized variate.