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LEAK RATES INTO DRAINAGE SYSTEMS UNDERLYING LINED RETENTION FACILITIES

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Summary

A study was undertaken to evaluate the rate at which liquids leak through flaws in flexible membrane liners (FML). The variables studied included flaw size and shape, FML type and thickness, the influence of a geotextile between the FML and the subbase, and the liquid head. Testing was done in 60 cm diameter permeameters. Each permeameter base was filled with gravel and overlain with the FML having either a round hole, a slit, or a seam flaw to be tested. A 15 cm layer of gravel was placed over the FML in the 100 cm deep head chamber to provide ballast.

Flow through flaws in FMLs over very permeable subbases were highly dependent on flaw size, shape, and liquid head. Measured flow rates in all cases were lower than those calculated from theoretical considerations. The type of FML material made only a small difference with the polyvinylchloride (PVC) and chlorosulfonated polyethylene (CSPE) materials having a slightly slower flow rate than high density polyethylene (HDPE) and ethylene propylene rubber (EPDM) materials under similar conditions. The presence or absence of an underlying geotextile made no significant difference in leakage rate from an FML. The FML thickness did not significantly effect the leakage rate. A table of anticipated maximum leakage volumes is presented which may be used to design drain systems to be used below FMLs.

Introduction

Most facilities presently being constructed for the retention of hazardous liquids employ flexible membrane liners (FML) as the primary barrier for the retention of liquids. Often a drainage system is installed between the primary FML and the underlying liners. This drainage system serves both to indicate the the presence of leaks in the overlying FML as well as to remove leachate, thus minimizing the potential for breaching the second underlying liner.

The correct sizing of these drainage systems is important since leaks in FMLs are common. Bass et al. [1] surveyed 27 lined facilities and found 12 failures at 10 sites. They documented the nature of the failures as including chemical attack of the FML, physical tears or punctures of the FML (5 of 12 sites), problems with field seaming or other field installation activities (1 to 3 of the

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12 sites), and problems with large gas bubbles. Giroud [2] also surveyed 29 facilities and found defective seaming in the field to be the most frequent cause of FML failure. In addition, he concluded that leaks were a result of poor quality control of installation and improperly trained crews. Kastman [3] during final inspection of a 60 mil HDPE liner installation measured two pinholes per 100 m of seam, 2.3 specific cuts and punctures from unknown causes per 1000 m^2, and 27 rock proturbences per 1000 m^2 of sheet material.

A listing of potential stresses to FMLs which may result in a failure is given by Forseth and Kmet [4]. Whatever the cause of the leaks, it is apparant that leaks occur and the drainage system must be sized to handle the volumes of liquid to be removed.

While it is possible to predict the flow rate through round holes in a sheet of material from theoretical considerations, it is not possible to predict the influence of the interaction between an FML and the underlying gravel for the type of flaws which may be encountered. Therefore, as a basis for designing such drainage systems, data are needed on the flow rate of liquids through flaws in FMLs as a function of the type and thickness of the FML, the flaw shape and size, the liquid head, and the presence or absence of a geotextile below the FML. This project was therefore undertaken to develop data on the dependence of flow rate of liquids through flaws in FMLs on these parameters.

Materials and methods

Samples of commercially available FMLs obtained for study included: 0.05 and 0.08 cm thickness of polyvinylchloride (PVC); 0.08, 0.20, and 0.25 cm thicknesses of high density polyethylene (HDPE); 0.08 cm thick ethylene propylene rubber (EPDM); and 0.09 and 0.11 cm thicknesses of chlorosulfonated polyethylene (CSPE). Appropriate amounts and types of cleaners and adhesives for seaming were obtained from the manufacturers, except for the HDPE which was heat seamed at the factory.

Square pieces, 66 cm on a side, were cut from each FML material and the desired flaw was created in the center. Flaw sizes and shapes were arbitrarily selected and included round holes with diameters of 0.08, 0.16, 0.64, and 1.27 cm. These holes were made by drilling through the material with the appropriate diameter sharp drill while the FML was clamped firmly between two boards. In addition, 5 and 15 cm long vertical slits were made in selected materials by laying the FML on a piece of wood and striking it with a sharpened metal plate of appropriate length. Faulty seams were simulated by putting 5 and 15 cm wide by 20 cm long pieces of 28 ga. sheet metal between the pieces of FML to prevent adhesion of these areas when the seam was made. After seaming was complete, the metal strips were removed, resulting in a very precise gap in the seam.

Specially constructed permeameter bases, 57.2 cm in diameter and 30.5 cm

TABLE 1

Physical properties of the geotextiles used in this study

Properties	Geotextiles	
	A	B
Fabric weight ($g\ cm^{-2}$)	0.027	0.031
Thickness (cm)	0.32	0.28
Grab strength (kg)	118/102	82
Grab elongation (%)	85/90	100
Trapezoid tear strength (kg)	45/43	50
Puncture strength - 5/16" (kg)	57	57
Mullen burst strength (MPa)	2.6	
Vertical water flux ($l\ s^{-1}\ cm^{-2}$)	1.9×10^{-2}	

tall, were filled with gravel ranging in size from 0.1 to 0.5 cm and having a hydraulic conductivity of 1.3×10^{-1} cm s^{-1}. For tests involving a geotextile, a 57 cm diameter circle of material was cut and placed between the gravel and the FML. The manufacturers data on the physical properties of the geotextiles are given in Table 1. Since there were no significant differences in the influence of the two geotextiles, only average values are presented. The FML sample to be tested was then placed over the gravel and a 57.2 cm diameter head tank was bolted in place by means of a flange. A water tight seal was achieved by using a closed cell gasket. Fifteen cm of gravel were placed on the FML to serve as ballast to prevent the FML from floating. A small piece of 0.3 cm hardware cloth was placed over the hole in the FML to prevent a piece of gravel from lodging in the hole. The desired head of water was then applied and measurements of head drop with time were made using a Stevens Type F* water stage recorder geared to give a chart reading of 1.16 cm per cm drop in head. Because of the large number of combination of parameters which could have been tested, it was necessary to test the influence of one or two parameters at a time, while holding the others constant. To provide data suitable for statistical analysis, each measurement was replicated three times in different parameters.

Furthermore, for convenience of discussion, only data collected at 50 and 100 cm heads will be presented. Statistical evaluation employed a one way analysis of variance.

Results and discussion

Preliminary testing of the gravel subbase in the absence of a FML indicated that it had a conductivity of 0.13 cm s^{-1} and would not be limiting to the flow

*Mention of brand name does not constitute an endorsement.

through any of the FML sections to be tested. Leak rates of water through round holes in 0.08 and 0.25 cm HDPE increased greatly as the area of the holes increased (Figs. 1 and 2). The increase was curvilinear and resembled curves of discharge from pipes (Barfield et al., [5]). The discharge rate at 100 cm was significantly greater than at 50 cm; however, it was less than double that of the 50 cm head. The maximum discharge from round holes was calculated using Bernouilli's equation (Bird et al. [6]):

$$w = C_d S_o \frac{1}{\rho} \sqrt{\frac{2\rho\,(P_1 - P_2)}{1-(S_o/S)^2}}, \qquad (1)$$

Where w = discharge (cm^3/s), C_d = discharge coefficient = 0.61 (for high Reynolds number as suggested by Bird et al., [6]), S_o = area of the orifice (cm^2), ρ = density of liquid (g/cm^3), $P_1 - P_2$ = pressure difference on the liquid, and S = area surrounding the orifice (cm^2).

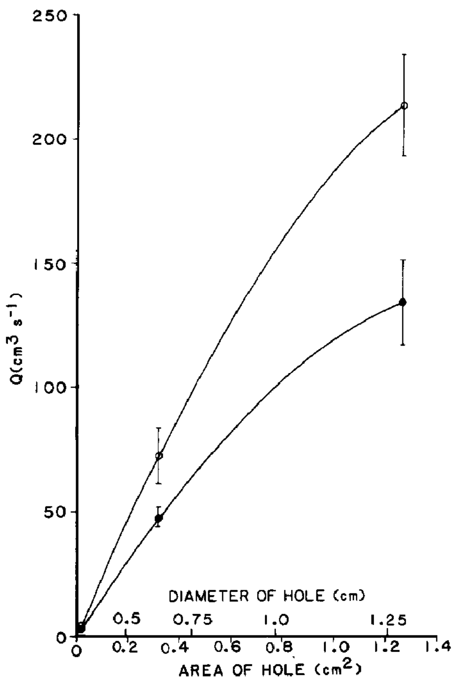
For the present system, $(S_o/S)^2$ approaches zero, $\rho = 1.0$ g/cm^3, P_2 approaches zero and the pressure (P_1) can be represented as ρgh, where r = the radius of the orifice, ρ = the liquid density, g = the acceleration due to gravity, and h = the heigth of water level above the FML surface (reference plane); eqn. (1) further reduces to:

$$w = 1.91\, r^2 \sqrt{960h} \qquad (2)$$

Equation 2 was used to calculate the maximum flow from various size of orifices under 50 and 100 cm heads of water (Fig. 1). In all cases, the actual losses were smaller than that predicted from Bernouilli's equation. The observed differences become larger as the hole size increases. These differences between the observed and calculated discharge rates are likely due to the presence of the gravel beneath the FML. The gravel likely partially obstructs the flow path and thus presents an additional resistance to flow resulting in somewhat lower than theoretical discharge rates.

The flow rates of water through slits and seams was much more variable than that through round holes as evidenced by the much larger standard deviations (Table 2). While insufficient data were available to determine statistical signifcance on the 5 cm slits, it is apparent that the flow through the 15 cm slits were much larger. Likewise, flow through the 15 cm seam flaws was much greater than through the 5 cm flaws. Significant ($P = 0.05$) differences were found at a 50 cm head, while the data from the 100 cm head differed only at $P = 0.10$. Visual observations indicated that large changes in flow rates may be attributed to the degree of alignment of the two sides of the slit or to the degree to which the flaws in the overlapping pieces of seamed material were pressed together by the ballast.

A comparison of the discharge rates through 0.64 cm diameter round holes in 0.08 to 0.09 cm thicknesses of four FMLs at 50 and 100 cm heads indicated



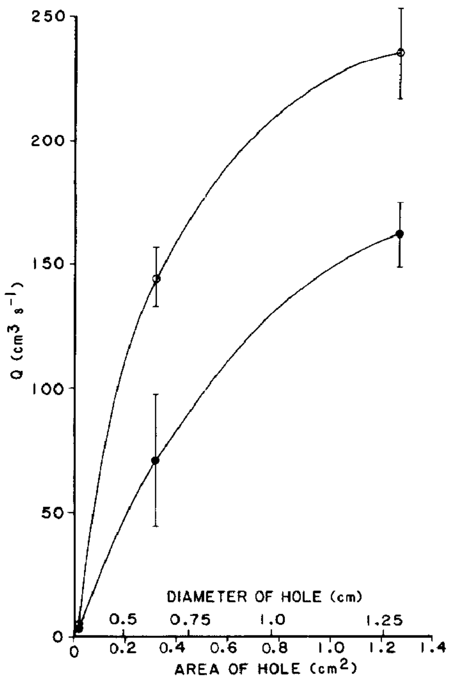


Fig. 1. Calculated and measured flow rate of water through various size holes in 0.08 cm HDPE at two heads over gravel. ● 50 cm head and ○ 100 cm head. (Vertical bars indicate mean ±1 standard deviation.)

Fig. 2. Flow rate of water through various size holes in 0.25 cm HDPE at two heads over gravel. ● 50 cm head and ○ 100 cm head, (Vertical bars indicate mean ±1 standard deviation).

significant differences between materials (Table 3). The PVC and CSPE liners had significantly lower discharge rates than the EPDM at both heads and were significantly lower than the HDPE at 50 cm head. Thus, the PVC and CSPE materials of similar thickness appear to offer more resistance to flow through a hole and have greater head loss and lower discharge rates. PVC and CSPE are much more flexible than EPDM and HDPE and it is possible that the slower flow rates through PVC and CSPE may be a result of partial blockage of the flow as these membranes deform against the gravel.

Flow rates through round holes in liners with and without a geotextile beneath suggested that the geotextile has a minimal effect (Figs. 3 and 4). At a 50 cm head, the flow rates only differed significantly for the 0.64 cm diameter hole. At a 100 cm head, the flow rates only differed significantly for the 1.27 cm diameter hole. Four of the 6 sets of data did not differ significantly suggesting that the geotextile has a minimal effect on flow rates of water through round holes in FMLs.

Flow rates through 15.2 cm slits in 0.08 cm HDPE over gravel with and

TABLE 2

Flow rates of water through silts, seam flaws, and round holes in 0.08 cm HDPE at two heads over a gravel subbase

Flaw	Flow rate[a] at head	
	50 cm	100 cm
5 cm slit	No data	2.5
15 cm slit	122.6±87.1	178.3± 83.6
5 cm seam	12.8±11.1	10.3± 3.1
15 cm seam	149.1±83.6	229.7±149.5
0.16 cm dia. hole	2.9± 0.4	4.2± 0.8
0.64 cm dia. hole	48.0± 4.8	72.7± 12.7
1.27 cm dia. hole	135.2±17.6	214.5± 20.6

[a]Flow rate mean ± standard deviation in $cm^3\ s^{-1}$.

without a geotextile showed no significant difference (Table 4). Flow through 15.2 cm seam flaws, however, was significantly decreased in the presence of a geotextile. This may have been caused by the textile bridging the gaps between gravel particles and creating a supporting surface under the liner, thus, allowing the gravel overburden to better close the seam flaw.

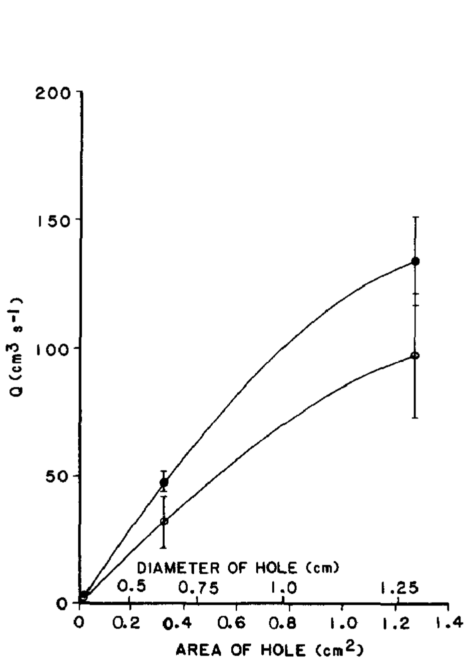
For 0.64 cm diameter holes, flow rates were not influenced by liner thickness at a hydraulic head of 100 cm (Table 5). At a 50 cm head, there were no significant ($P=0.05$) differences in the PVC and CSPE liners. The flow rate from the 0.08 cm HDPE liner was slower than that from the 0.20 cm and 0.25 cm thicknesses. This observed difference is, however, opposite to that which would be expected. One possible explanation for the reduced flow in the thin material is that it is less rigid and, thus, more likely to deform around the gravel subbase material, thus inhibiting the flow of liquid through the opening. The

TABLE 3

Mean discharge rates through 0.64 cm diameter round holes in four FMLs of similar thickness

Head cm	Flow rate ($cm^3\ s^{-1}$)			
	HDPE 0.08 cm	PVC 0.08 cm	CSPE 0.08 cm	EPDM 0.08 cm
50	48.0a*	26.3b	25.4b	56.9a
100	72.7ab	40.3b	42.3b	96.0a

*Values in a given row followed by the same letter do not differ significantly at $P=0.05$.



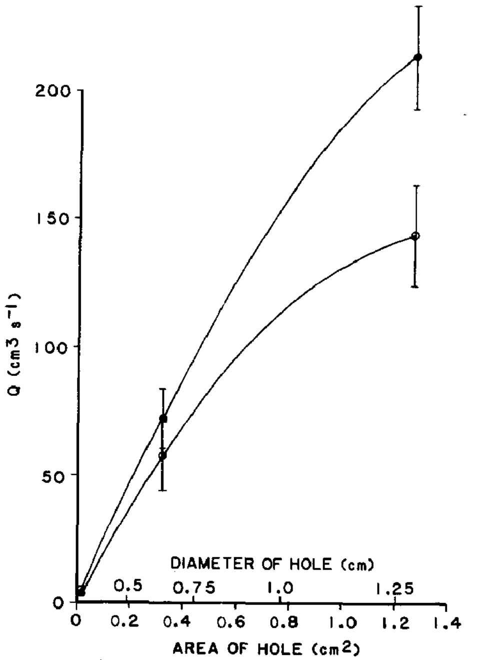


Fig. 3. Flow rate of water through various size holes in 0.08 cm HDPE at 50 cm head with and without a geotextile between the FML and gravel. ● without and ○ with geotextile, (Vertical bars indicate mean ±1 standard deviation).

Fig. 4. Flow rate of water through various size holes in 0.08 cm HDPE at 100 cm head with and without a geotextile between the FML and gravel. ● without and ○ with geotextile, (Vertical bars indicate mean ±1 standard deviation).

present data suggest, however, that as a first approximation, the flow rate into a gravel subbase is independent of the liner thickness.

The maximum anticipated leakage from different flaw shapes and sizes in a 0.08 cm thick HDPE liner under two hydraulic heads is given in Table 6. The data in Table 6 suggest that even with the small heads tested here, large volumes of liquid may flow through a single hole in a flexible membrane liner. While round holes and slits of a size to allow the flows predicted here may be detected visually, the results indicate the need to thoroughly test all seams, since seam flaws are not as easily observed.

To put values shown here into perspective, it is interesting to note that a 1 meter thick saturated clay liner with a hydraulic conductivity of 10^{-7} cm s^{-1} covered with a 1 m thick layer of water would allow a flow of 63.2 m^3 ha^{-1} y^{-1}.

This flow rate could result from a single 5 cm long slit per hectare of FML. From another perspective, a simple seam flaw 15 cm in length per hectare could allow flows which would be similar to those which would occur through a 1 m

TABLE 4

Flow rates of water through 0.08cm HDPE with and without a geotextile below the liner at two heads

Flaw	Flow rate ($cm^3 s^{-1}$) at head			
	50 cm		100 cm	
	without geotextile	with geotextile	without geotextile	with geotextile
15.2 cm slit	122.6 ± 106.6a*	52.6 ± 28.5a	178.3 ± 96.0a	95.1 ± 41.2a
15.2 cm seam	149.1 ± 83.6a	30.9 ± 20.1b	229.7 ± 149.5a	58.5 ± 29.7b

*Values in a given row at a given head (mean ± s.d.) followed by the same letter do not differ significantly at $P = 0.05$.

thick soil liner with a hydraulic conductivity of 1.1×10^{-5} cm s^{-1} when subjected to the same head.

A single round hole with a diameter of 0.16 cm (approximately 1/16 inch) could easily be created by an underlying stone and under a 50 cm head would leak 1120 m^3 y^{-1} (approximately 29,000 gal/y). By combining the leakage rates reported in this study with estimates of the number and type of defects observed by others as reported in the literature [3], designers should be able

TABLE 5

Flow rates of water through various thickness liners with a 0.64 cm diameter round hole over gravel subbase

Thickness (cm)	Material	Flow rate ($cm^3 s^{-1}$) at head	
		50 cm	100 cm
0.08	HDPE	48.0 ± 4.8b*	72.7 ± 12.7a
0.20	HDPE	89.5 ± 27.6a	123.2 ± 49.7a
0.25	HDPE	71.1 ± 31.1a	145.2 ± 82.0a
0.05	PVC	24.9 ± 17.3a	33.8 ± 20.9a
0.08	PVC	26.3 ± 14.8a	40.3 ± 21.5a
0.09	CSPE	25.4 ± 8.7a	42.3 ± 26.7a
0.11	CSPE	49.3 ± 17.9a	83.5 ± 38.4a

*Values in a given column at a given head for a given material followed by the same letter do not differ significantly at $P = 0.05$.

TABLE 6

Maximum anticipated leakage in $m^3\ y^{-1}$ from a single slit, seam flow or round hole in 0.08 cm thick HDPE liner at two liquid heads

Holes size and shape	Leakage ($m^3\ y^{-1}$) at head (cm)	
	50	100
5 cm slit	No data	80
15 cm slit	3870	5620
5 cm seam	400	330
15 cm seam	4702	7240
0.16 cm diameter	110	150
0.64 cm diameter	1480	2210
1.27 cm diameter	4260	6780

to better estimate and design for the volumes of leachate that will need to be managed.

The data also show the need for an effective quality control and assurance program (EPA, [7]) during FML installation since even small flaws can result in significant leaks.

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