Weber, C.T., and Zornberg, J.G. (2007). "Leakage through Geosynthetic Dam Lining Systems." *Dam Safety 2007 Conference*, ASDSO, Austin, Texas, 9-13 September, pp. 1-9 (CD-ROM).

LEAKAGE THROUGH GEOSYNTHETIC DAM LINING SYSTEMS

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Abstract

An experimental testing program was conducted to quantify leakage through a geomembrane liner system when subjected to high hydraulic heads. Leakage through geomembranes is mainly due to the presence of defects, which may occur during installation and operation. Previous studies focused on leakage through landfill liners (i.e., low hydraulic heads) have led to analytical models and simplified equations to estimate and predict the leakage rate through a geomembrane lining system. However, available methods used to estimate leakage are limited to a range of head that is experienced in landfills. The results of the experimental program presented herein are compared to available analytical models. A simplified equation was developed using an analytical model to predict leakage rates for a range of conditions representative of dams, including representative hydraulic heads and soil hydraulic conductivity of the soil. The new equation is compared with data from the experimental program and also with existing models. This paper discusses the advantages of using a geomembrane in tandem with a compacted clay liner as a redundant lining system for earth dams.

Introduction

Embankment dams are susceptible to internal erosion and piping. Geomembranes have been used in dam rehabilitation projects as a way to minimize degradation of the dam body due to seepage. These polymeric materials act as hydraulic barriers and have been placed on either the upstream face of the dam or in its core. Geomembranes have also been used in lining systems for new dams where low-permeability materials are not available or cost-effective. The hydraulic conductivity of a geomembrane (e.g. 10^{-15} m/s) is significantly lower than that of a compacted clay liner (e.g. 10^{-9} m/s).

In spite of their function as hydraulic barriers, geomembrane liners should not be considered to be fully impervious. Geomembranes are susceptible to damage during installation and over the service lifetime. These defects, typically punctures and seam imperfections, reduce the effectiveness of a geomembrane as a hydraulic barrier, especially under high hydraulic heads (Weber and Zornberg 2005).

Previous studies, both experimental and analytical, that were conducted to evaluate the flow through geomembrane defects involved hydraulic heads less than 7 m and focused on leakage through landfill liner systems. The components of flow through a geomembrane defect include the flow through the defect itself, flow across the interface between the geomembrane and soil, and flow into the soil layer. The interface flow can be characterized by the spacing of the gap between the geomembrane and the soil layer or by the transmissivity of the interface. Transmissivity is the product of the gap spacing and the hydraulic conductivity of the interface gap with units of [L^2/T]. The gap spacing, and thus the transmissivity, is affected by the roughness of the soil surface (e.g. indentations left by construction equipment) and the size of the soil particles at the interface. The gap spacing and the transmissivity of the interface are difficult to quantify experimentally and can vary greatly from location to location. However, these properties are typically approximated using analytical methods by assuming that the gap spacing (or transmissivity) is uniform. The existing methods used to approximate the interface properties have been calibrated for low heads.

In the previous experimental studies, variables affecting the flow were investigated, including subgrade material (soil type), geomembrane thickness, and defect characteristics (Fukuoka 1986; Brown et al. 1987; Walton et al. 1997; Benson et al. 1995; Barroso et al. 2006). Experimental studies have often been followed by analytical or numerical studies, in order to extrapolate the expected behavior in the field of the system simulated in the laboratory. Rowe (1998) and Touze-Foltz et al. (1999) developed analytical models to characterize flow through defects. Because the analytical solution is complex, Giroud (1997) established simplified equations to estimate the leakage rates through defects in geomembrane liners. Touze-Foltz and Giroud (2003) presented the most recent versions of these equations, which account for contact quality as well as hydraulic head, size of the defect, and hydraulic conductivity of the soil.

Despite the past studies on flow through geomembrane defects in landfill liners, there has been little information on the hydraulic performance of geomembrane liners in dams. Dams are subjected to significantly larger hydraulic heads than landfills liners. The maximum allowable head permitted by federal regulations for landfills is 0.3 m, whereas earth dams have a large range of heights. For example, Teton Dam (before it failed) was 13 m tall and the Lower San Fernando Dam had a height of over 43 m before the San Fernando earthquake in 1971.

An experimental program was conducted in this study to investigate flow through a geomembrane defect under high hydraulic heads, ranging from 7 to 42 m. A simplified equation, like the ones developed by Touze-Foltz and Giroud (2003), was developed using analytical methods for comparison with the experimental results.

Experimental Program

The objective of the experimental program conducted as part of this study is to quantify the leakage rate through a geomembrane liner with a defect under high heads. For this investigation, the geomembrane was placed in direct contact with a compacted layer of silty clay. The configuration could represent either i) a geomembrane in contact with the clay core of a dam or ii) when a compacted clay liner is placed beneath the geomembrane to minimize the leakage through the lining system. An example of the latter configuration is Terzaghi Dam (formerly Mission Dam) in Canada. The upstream face has a geomembrane liner installed over a 1.5 m-thick clay layer (Lacroix 1984).

A permeameter cell was constructed of clear acrylic to test the hydraulic performance of the barrier system (Figure 1). The cell was split into a bottom part which contains the soil layer, and a top part that provides a water reservoir and confines the hydraulic barrier circumferentially. The geomembrane was placed between the two sections and sealed using O-rings. A coarse porous stone was used to provide a free-draining at the bottom boundary. Both the inflow and outflow volumes were measured throughout testing. A pressure panel was used to control the hydraulic head in the system, which ranged from 7 to 42 m.

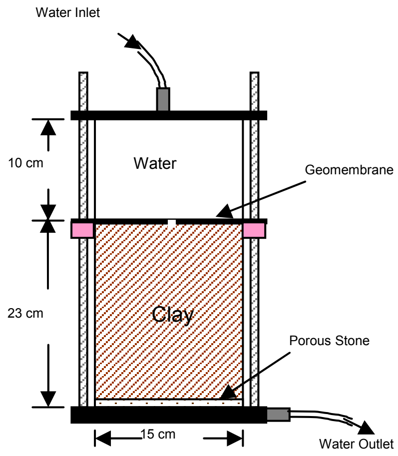

Figure 1: Permeameter cell used during experimental program.

The geomembrane used in the experimental program was a smooth linear low-density polyethylene (LLDPE) with a thickness of 1 mm. A circular defect with a diameter of 1.6 mm (area = 2 mm^2) was drilled at the center of the geomembrane specimen. The soil substrate used in this experimental program was a silty clay that classifies as CL according to the Unified Soil Classification System. The clay was compacted in five equal layers into the permeameter cell using water contents near optimum (w_{opt} = 11.9%) to obtain a relative compaction of 90% of the standard Proctor maximum dry unit weight ($\gamma_{d,max}$ = 18.6 kN/m^3). At these values, the silty clay has a saturated hydraulic conductivity of 1×10^{-8} m/s. However, the soil was not saturated at the beginning of the test and the degrees of saturation at the end of the tests were only about 70% to 80%. Table 1 provides details of the tests conducted for the experimental program.

Results

The flow into and out of the permeameter were monitored over the duration of each test. Steady-state flow was reached in each test. Steady-state flow was defined as the flow rate at the end of the test, when the flow reaches a constant value and inflow equals outflow. A typical set of inflow and outflow curves are shown in Figure 2.

The steady-state leakage (outflow) rates for six tests are shown in Figure 3. The leakage rates through the system increases as the hydraulic head increases. There is some scatter in the data. The discrepancy in the leakage rate for Test 2 (h = 14 m) is likely due to fines migration and clogging of the defect.

Simplified Equation

Touze-Foltz and Giroud (2003) detailed a method used to develop an equation to estimate the flow through a defect in a geomembrane liner. A simple mathematical equation form was originally selected by Giroud (1997), which includes parameters that affect the leakage rate, and extended by Touze-Foltz and Giroud (2003).

Table 1 – Details of the Experimental Testing Program

Test #	Hydraulic Head (m)	Unit Weight (kN/m^3)	Initial Water Content (%)	Measured Leakage Rate (m^3/s)
1	7	18.7	10.0	2.6×10^{-10}
2	14	19.1	13.7	8.1×10^{-11}
3	21	19.0	11.1	1.6×10^{-9}
4	28	19.4	12.0	5.4×10^{-9}
5	35	19.4	12.0	6.3×10^{-9}
6	42	19.4	12.0	3.8×10^{-9}

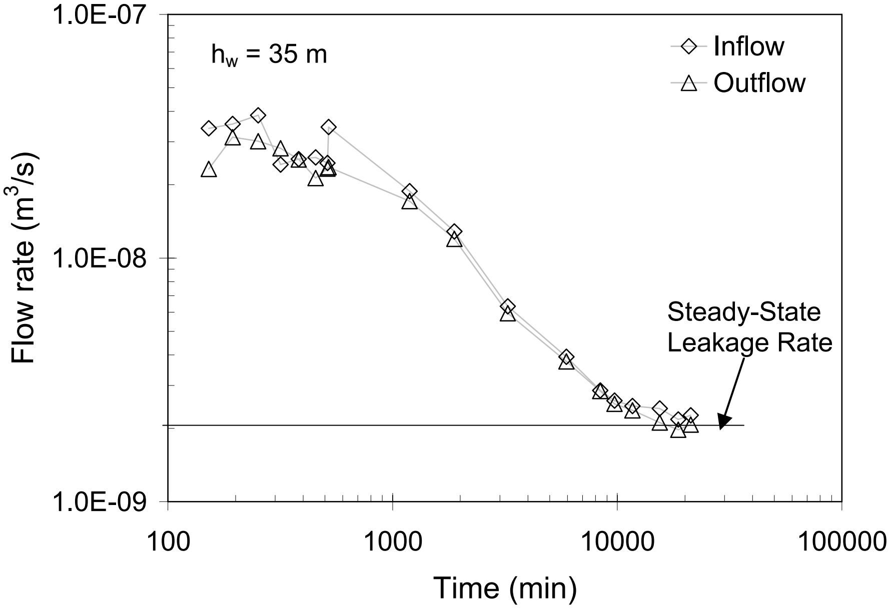

Figure 2: Typical flow measurements for permeameter tests.

Following the method laid out by Touze-Foltz and Giroud (2003), an equation was developed to estimate leakage through lining systems under high hydraulic heads. The equation takes the form of:

$$Q = C i_s^w h_w^x a^y k_s^z \tag{1}$$

where *C* is a coefficient relating to contact quality, h_w is the hydraulic head, *a* is the area of the defect, k_s is the hydraulic conductivity of the underlying soil layer, and i_s is the hydraulic gradient across the soil layer. This form was slightly altered from the mathematical form selected by Giroud (1997) by combining the hydraulic gradient into one term. Leakage rates were calculated using a range of values for the four parameters in Eq. 1. Touze-Foltz and Giroud (2003) used the contact coefficient C to characterize the change in leakage rate due to the quality of the interface contact.

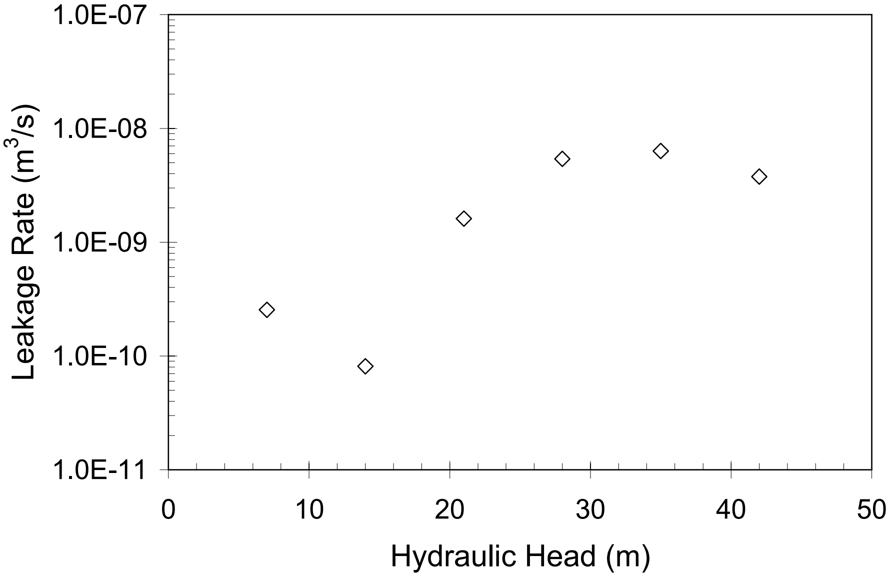

Figure 3: Leakage rates over a range of hydraulic heads.

The simplified equation was not calibrated using the experimental data. Instead, the exponents and constant in the equation were found using results obtained from the analytical solution presented by Touze-Foltz et al. (1999):

$$Q = \pi r_0^2 k_s \left(\frac{h_w + H_s}{H_s} \right) - 2\pi r_0 \theta \alpha \left[A I_1 \left(\alpha r_0 \right) - B K_1 \left(\alpha r_0 \right) \right] \tag{2}$$

where r_0 is the radius of the defect, θ is the transmissivity of the interface between the geomembrane and the soil and I_1 and K_1 are modified Bessel functions of the first order. The remaining variables are as defined above and the parameters α, A and B are defined by the following equations:

$$\alpha = \sqrt{\frac{k_s}{H_s \theta}} \tag{3}$$

$$H_s = H_L + H_f \tag{4}$$

$$A = \frac{\left(h_w + C \right) K_1 \left(\alpha R \right)}{K_1 \left(\alpha R \right) I_0 \left(\alpha r_0 \right) + K_0 \left(\alpha r_0 \right) I_1 \left(\alpha R \right)} \tag{5}$$

$$B = \frac{\left(h_w + C \right) I_1 \left(\alpha R \right)}{K_1 \left(\alpha R \right) I_0 \left(\alpha r_0 \right) + K_0 \left(\alpha r_0 \right) I_1 \left(\alpha R \right)} \tag{6}$$

where H_L is the thickness of the soil layer, H_f is the thickness of the foundation layer (porous stone, in this case), the I_0 and K_0 are modified Bessel functions of the zero order, and R is the radius of wetted area. The radius of wetted area is the radius at which the hydraulic head at the interface between the geomembrane and the soil is zero and can be found by solving the following equation for R (Touze-Foltz and Giroud 2003):

$$AI_0(\alpha R) + BK_0(\alpha R) - C = 0 \tag{7}$$

As shown in Eqs. 2 and 3, the transmissivity at the interface between the geomembrane and the underlying soil layer is needed to solve the analytical equation. The transmissivity of the interface is dependent on the hydraulic conductivity of the soil and the size of the interface gap. The transmissivity of the interface is difficult to measure directly but can be back-calculated using leakage rates measured in the laboratory.

For a range of soil hydraulic conductivities, Brown et al. (1987) back-calculated the transmissivity from their experimental data using the analytical model. Similarly, the transmissivity for each of the six tests shown in Figure 3 was back-calculated using Eq. 2. The transmissivity was varied until the calculated leakage rate was equal to the leakage rate measured in the laboratory. The back-calculated values for transmissivity for all six tests are shown in Figure 4. The transmissivity increases as the head increases slightly for the range of heads used in the study.

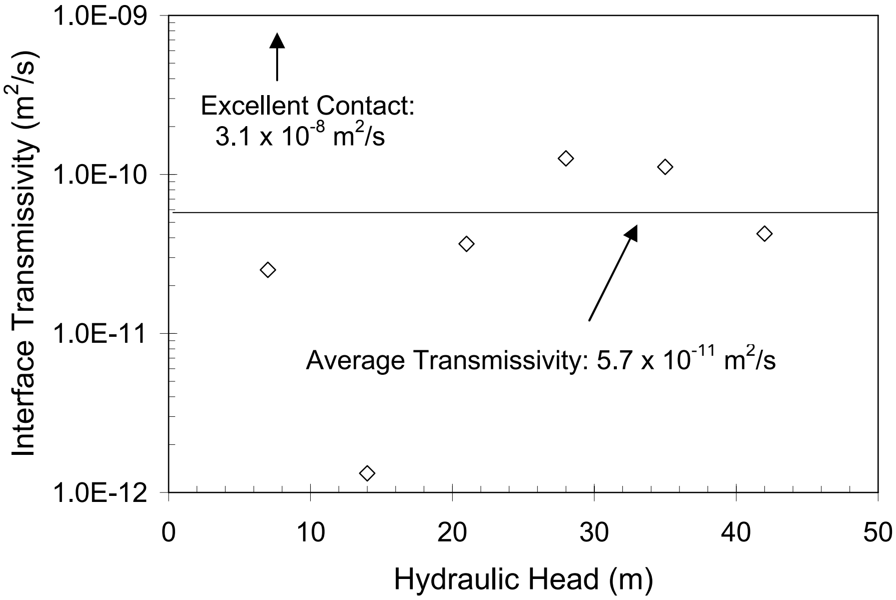

Figure 4: Back-calculated transmissivity for a range of hydraulic heads.

In order to perform the calculations required to develop the simplified equation, Touze-Foltz and Giroud (2003) used the values back-calculated by Brown et al. (1987) to develop the following equation to approximate the transmissivity based on the hydraulic conductivity of the soil, k_s:

$$\log\theta = -1.7476 + 0.7155\log k_s \qquad (8)$$

The estimated transmissivity for the hydraulic conductivity of the silty clay used for the experimental testing program is shown in Figure 4 and is about two orders of magnitude larger than the back-calculated values.

` By using Eq. 8, Touze-Foltz and Giroud (2003) could vary the transmissivity in the analytical calculations by changing the values of the hydraulic conductivity used for their analysis. This equation was developed to estimate flow through defects for excellent contact conditions. The empirical equation developed by Touze-Foltz and Giroud (2003) that corresponds with Eq. 8 is:

$$Q = 0.096a^{0.1}h_w^{0.9}k_s^{0.74}\left[1+0.1\left(h_w/H_s\right)^{0.95}\right] \qquad (9)$$

Eq. 9 yields leakage rates that are four orders of magnitude larger than the leakage rates measured in experimental program presented in this paper. Eqs. 8 and 9 were developed for landfill conditions, which would account for the discrepancy. However, this means that Eq. 8 is not valid for use in this study so a new relationship must be used to develop a new equation to estimate leakage under high heads.

The average transmissivity for the back-calculated values in Figure 4 is about two orders of magnitude lower than the hydraulic conductivity. Thus, the following relationship was used to calculate the leakage rates for this analysis:

$$\theta = 0.01k_s \qquad (10)$$

Table 2 lists the range of for each of the four parameters in Eq. 1 that were used to develop the new equation. One parameter was varied over the range of values listed in Table 2 while the rest of the parameterss were kept constant to determine the sensitivity of the leakage rate for each variable. Linear regression was used to determine the exponents for the changing parameter. The new equation for estimating leakage through geomembrane defects under high heads is:

$$Q = 1.07a^{0.20}h_w^{0.95}i_s^{-0.33}k_s \qquad (10)$$

Eq. 10 was developed by using the values in Table 2 to solve for the exponents in Eq. 1. The leakage rates calculated by Eq. 10 can be compared with the measured leakage rates from the experimental program (Figure 5). Neglecting the outlier at a head of 14 m, Eq. 10 effectively estimates the leakage through a defect in a geomembrane over a clay layer under high hydraulic heads. However, the study presented herein only investigated leakage through one size of defect over one type of soil (e.g., hydraulic conductivity). Further experimental studies should be conducted to verify the equation before it can be used in design. Defect sizes and shapes that are commonly found in the field should be included in the study, as well as soils that have less desirable hydraulic conductivities (i.e., sand).

Table 2 – Range of Values Used to Develop Eq. 10

Variable	**Range (Units)**
Area of Defect, a	0.02 - 1.3 (cm^2)
Hydraulic Head, h_w	7 - 50 (m)
Hydraulic Gradient, i_s	1 - 100
Hydraulic Conductivity, k_s	$1x10^{-9}$ - $5x10^{-8}$ (m/s)

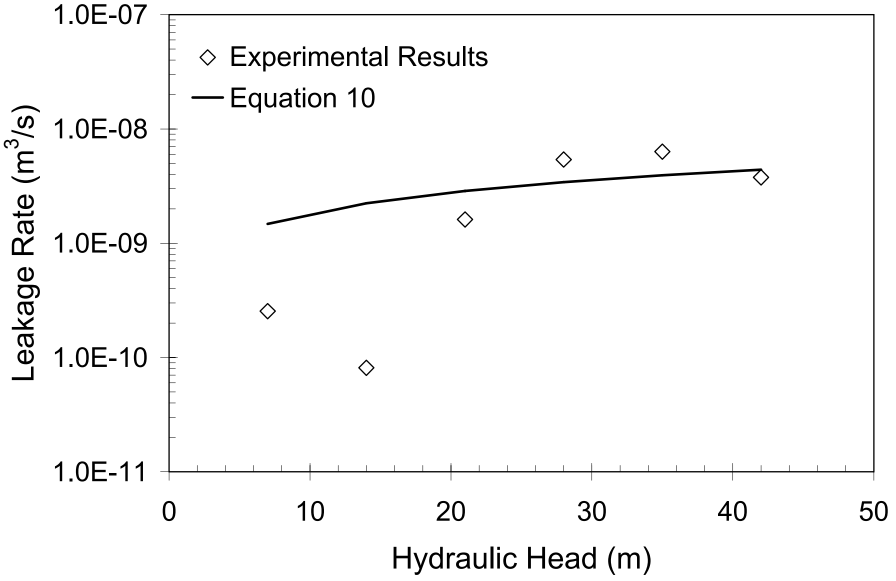

Figure 5: Comparing measured and calculated leakage rates.

Conclusions

A study was conducted to quantify leakage through a geomembrane in contact with soil for dam projects. Existing equations do not accurately estimate the leakage rates due to high hydraulic heads, because they were developed for a range of heads that is representative of landfill conditions. The simplified equation developed in this study provides a preliminary basis for estimating leakage through a geomembrane liner under conditions representative of dams.

While there is good agreement between Eq. 10 and the experimental results from this study, further investigation will be required to verify the validity of the equation for a wider range of variables (e.g., defect size, hydraulic conductivity). Since geomembranes are sometimes used when materials with undesirable hydraulic properties are available, future testing will focus on this aspect. Also, tests will be conducted to measure the transmissivity between the geomembrane and the soil layer to verify the values back-calculated in this study.

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