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USE OF GCLS TO CONTROL LEAKAGE THROUGH GEOMEMBRANE DEFECTS UNDER HIGH HYDRAULIC HEADS

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ABSTRACT

This paper presents the results of an experimental testing program conducted at the University of Texas at Austin that involves the quantification of leakage through defects in geosynthetic liners under conditions representative of dams (i.e., high hydraulic heads). Specifically, the objective of this study is to investigate the feasibility of using geosynthetic clay liners (GCLs) in dam lining systems. Tests were performed on geomembranes in direct contact with a pervious sand substrate as well as on geomembranes placed over GCLs in direct contact with a pervious sand substrate. The impact of the quality of interface contact, hydraulic head, and GCL hydration procedures on the leakage rate were considered. Comparison of the experimental results allows quantification of the improved performance of barriers that include a GCL. Beyond the comparison of the experimental results, analyses were conducted using available leakage models. Overall, the use of GCLs in combination with geomembranes was found to be a suitable alternative to control leakage rates in dam hydraulic liners, even under very high hydraulic heads.

INTRODUCTION

Many of the earthen and concrete dams in the United States have been in service for extended periods of time. Accordingly, a growing number of them are in need of hydraulic retrofitting. Earthen dams, for example, are susceptible to degradation resulting from cracks on the upstream face, erosion of the facing materials, piping of fines from the dam core, all of which may result in unacceptable amounts of water leakage through the dam. Internal erosion of the dam body due to seepage forces is a significant concern due to the potential piping and structural instability that could lead to catastrophic failure.

A feasible solution to prevent structural damage in dams involves the use of geosynthetics to line the upstream face of the dam or its core. Specifically, geomembranes have often been used in lining systems for dams where low-permeability materials are not available or cost-effective. In spite of their function as hydraulic barriers, it should not be expected that the geomembrane liner will be fully impervious, as they are susceptible to damage during installation and long-term service. This damage, typically punctures and tears, impacts the effectiveness of a geomembrane as a hydraulic barrier, especially under high hydraulic heads (Weber and Zornberg 2005). To protect the geomembrane, geotextiles have been used as a cushion between the geomembrane and the dam facing. In addition, geotextiles and geocomposites have been used to provide interface drainage in the case of concrete dams, as the main objective for lining systems in these structures is to minimize exposure of the concrete to water, avoiding its long-term degradation. Also, drainage prevents the buildup of pore pressures underneath the liner in case of a rapid drawdown. However, these protection measures do not minimize the leakage of water through a damaged hydraulic barrier. Accordingly, an experimental program was conducted as part of this study to evaluate the use of geosynthetic clay liners (GCLs) in dams, in tandem with geomembranes, as a protection layer and also as an additional hydraulic barrier.

GCLs are manufactured using a layer of bentonite clay sandwiched between carrier geosynthetics, typically geotextiles. Bentonite has a very low hydraulic conductivity when saturated, often less than 10^{-11} m/s, depending on the pore water, confining pressure, and conditioning procedures. Due to its swelling capabilities, bentonite provides self-healing to the lining system at the location of defects (e.g., puncturing of geomembrane). GCLs have been used extensively in association with geomembranes (i.e., composite liners) in landfills, often as a replacement for compacted clay liners. Federal regulations limit the hydraulic head permitted on composite liner systems in landfills to 0.3 m. Accordingly, there is good experience on the hydraulic performance of GCL-GM composites under low hydraulic heads. However, there is little experience on the hydraulic performance of these liners in dams, and thus dam liners, which must withstand significantly higher heads.

GCLs have already been used in dam rehabilitation projects. A good example is the Idaho Springs Dam, an earth dam in central Colorado built in 1978 to control flooding and provide local water supply (NID 2005). By 2000, significant seepage was observed from the downstream face of the dam embankments. This was attributed to deterioration of the dam, so a rehabilitation project was undertaken to improve the long-term dam performance. A GCL, consisting of a bentonite core sandwiched between two carrier geotextiles and with a 0.5 mm geomembrane laminated to the outer surface, was installed on the upstream face of the dam. A soil layer and rip-rap cover were placed over the GCL (Olsta and Carine 2005). The project was completed in 2001, and no evidence of seepage on the downstream face has been observed since that time.

EXPERIMENTAL PROGRAM

The objective of the experimental program conducted as part of this study is to investigate the feasibility of using geosynthetic clay liners (GCLs) in lining systems that incorporate a geomembrane under hydraulic heads that are comparatively high and consistent with dam conditions. Tests were conducted with and without the presence of a geomembrane, with and without the presence of a GCL, and under a variety of GCL hydration conditions, geomembrane contact quality of the interface, and hydraulic heads.

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

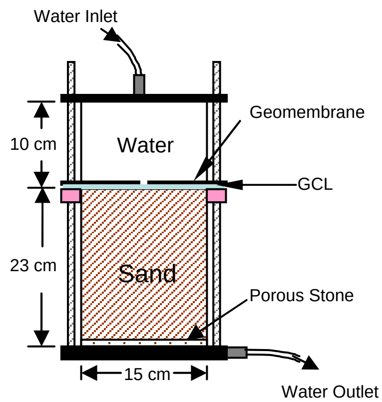

Figure 1: Permeameter cell used during experimental program.

The geomembrane used in the experimental program was a smooth linear low-density polyethylene (LLDPE) with a thickness of 1 mm. The flexible nature of LLDPE allows the geomembrane to accommodate deformations of the system. A circular defect with a diameter of 1.6 mm was drilled at the center of the geomembrane specimen. The GCL used in the experimental program was a Bentofix NWL®, which consists of bentonite sandwiched between two non-woven carrier geotextiles. The GCL has a hydraulic conductivity of approximately 10^{-11} m/s (GSE 2003). Both hydrated and unhydrated GCLs were used in the testing program. Hydrated GCLs were soaked in water for at least 48 hours under a normal stress of 20 kPa. In addition, a set of tests was conducted on a GCL hydrated under 2 kPa to evaluate the effect of hydration normal stresses on the hydraulic performance. No defects were imposed on the GCL. The sand substrate used in this experimental program was Monterey #30, a medium to fine sand. The sand was densified in the permeameter cell using a shaking table to reach a relative density (D_R) of 75%. The sand was saturated from the base of the cell before placing the hydraulic barrier system. The sand at this density has a saturated hydraulic conductivity of $8x10^{-7}$ m/s.

Most of the tests in the experimental program included a geomembrane. Four test series were conducted as part of the experimental program: (1) without a GCL, (2) with unhydrated GCLs, (3) with GCLs hydrated under a normal stress of 20 kPa, and (4) with GCLs hydrated under a normal stress of 2 kPa. Subsets within these test series evaluated the effects of hydraulic head, interface contact quality and the presence of a geomembrane. Table 1 provides details of the individual tests in each series.

Table 1 – Scope of the Experimental Testing Program

Test Set	Subseries*	Tests	Hydraulic Head	Details
1	B	GM-1 GM-2 GM-3 GM-4 GM-5	7 m 14 m 21 m 28 m 35 m	Geomembrane in direct contact with sand (no GCL).
2	B	UGCL-1 UGCL-2 UGCL-3 UGCL-4 UGCL-5 UGCL-6	7 m 14 m 21 m 28 m 35 m 42 m	Geomembrane placed over unhydrated GCL, which was placed in direct contact with sand.
	P	UGCL-Poor	7 m	Geomembrane placed over unhydrated GCL, which was placed over sand with poor interface contact
	O	UGCL-NoGM	14 m	Unhydrated GCL in direct contact with sand (no geomembrane).
3	B	GCL20-1 GCL20-1 GCL20-2 GCL20-3 GCL20-4 GCL20-5	7 m 14 m 21 m 28 m 35 m 42 m	Geomembrane placed over GCL hydrated under 20 kPa normal stress. GCL in direct contact with sand.
	P	GCL20-Poor	7 m	Geomembrane placed over GCL hydrated under 20 kPa normal stress. GCL placed over sand with poor interface contact.
4	B	GCL2-1 GCL2-2 GCL2-3 GCL2-4 GCL2-5	14 m 21 m 28 m 35 m 42 m	Geomembrane placed over GCL hydrated under 2 kPa normal stress. GCL in direct contact with sand.

* B: Baseline; P: Poor contact; O: Without geomembrane

RESULTS & ANALYSIS

All tests were run until steady-state flow was achieved. The steady-state leakage rate for each test was defined as the flow rate at the end of the test. Table 2 summarizes the average steady-state leakage rates of the Baseline tests conducted as part of Test Series 1 to 4. The B-subseries involve the presence of a geomembrane and good interface contact quality. Each test in the B-subseries was conducted under a different hydraulic head. The average steady-state leakage rate in the unhydrated GCL tests (Test Series 2) is approximately three orders of magnitude smaller than that measured in the geomembrane-only tests (Test Series 1). Consequently, the use of a GCL in the lining system may have a significant impact on the leakage rate through a damaged geomembrane in projects where the leakage rate through the dam (e.g., earth dams) is a key aspect in the design. Test Series 3 has an average steady-state leakage rate that is approximately one order of magnitude lower than that measured for Test Series 2. This comparison indicates that GCL hydration plays a relevant role in the effectiveness of the system in decreasing leakage through defects in geomembranes. However, hydrating GCLs in the field may not be cost-effective. The average leakage rate for Test Series 4 was essentially the same as that for Test Series 3. These results show that the effect of hydration normal stress is negligible with respect to leakage rates.

Table 2 – Average Steady-State Leakage Rates for B-Subseries in Test Series 1-4

Baseline Test Series	Average Leakage Rates (m^3/s)
1	1.61×10^{-5}
2	1.36×10^{-8}
3	1.29×10^{-9}
4	1.28×10^{-9}

Additional aspects such as effect of contact quality, GCL hydration conditions, and the presence of a geomembrane were investigated (see Table 1) but will not be discussed herein due to space constraints. Only the results of Test Series 1 and 4 are discussed further in this paper.

Tests Series 1 involved geomembrane-only tests conducted using heads ranging from 7 to 35 m. In these tests, steady-state flow was reached almost immediately. This is because of the comparatively high hydraulic conductivity of the sand used for this study. The steady-state leakage rate increased as the hydraulic head was increased for each test in Test Series 1. Giroud and Bonaparte (1989) recommend using Bernoulli's equation for flow through an orifice to estimate the flow through a defect in a geomembrane placed over a permeable soil. The orifice equation is as follows:

$$Q = Ca\sqrt{2gh}$$

where Q is the flow rate, C is an empirical coefficient that accounts for the geometry of the orifice, a is the area of the orifice (in this case, the defect in the geomembrane), g is the acceleration due to gravity, and h is the hydraulic head. The measured leakage rates (steady-state rates reached for each head) for Test Series 1 were compared with Bernoulli's orifice equation, using different values for the empirical coefficient, C (Figure 2). Giroud and Bonaparte (1989) suggest a value of C = 0.6 for use with flow through defects in geomembranes. Instead, a coefficient value of C = 0.4 was found to yield flow rates that are very similar to those measured in Test Series 1. However, as shown in Figure 2, a coefficient of C = 0.6 gives leakage rates that are slightly larger than the measured value. The better comparison obtained using a lower C-value than the previously suggested value can be attributed to the high hydraulic heads in this study than those used by Giroud and Bonaparte (1989) (heads less than 3 m). The difference can also be attributed to the sharpness of the orifice edges, roughness of the defect interior and diameter of the defects. The comparison reveals that the equation for flow through an orifice can be used to estimate leakage for flow through a small defect in a geomembrane in good contact with sand. Although the good match depends on the selection of the proper flow coefficient, C, the basic trend of the orifice equation is consistent with the experimental data is consistent, indicating that the use of this equation and properly calibrated C-coefficients for high heads can be useful in predicting the leakage through the geomembrane for dam systems.

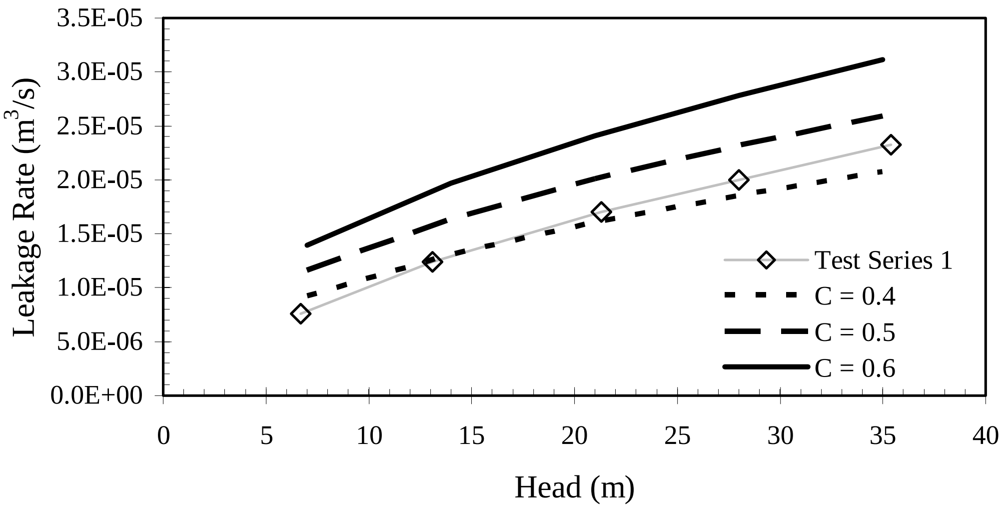

Figure 2: Comparing leakage rates for Test Series 1 with Bernoulli's orifice equation

Test Series 4 involved tests that included a GCL between the geomembrane and sand specimen. The GCL was hydrated under 2 kPa of normal stress. These tests were conducted using hydraulic heads ranging from 14 to 42 m. The leakage rates (measured flow rate exiting the permeameter cell) for each head over the duration of each test are shown in Figure 3. Each test was allowed to reach steady-state flow, which was identified in Figure 3 by the constant leakage rate achieved towards the end of the test. Unlike the tests in Test Series 1, steady state was not reached immediately in the tests conducted as part of Test Series 4.

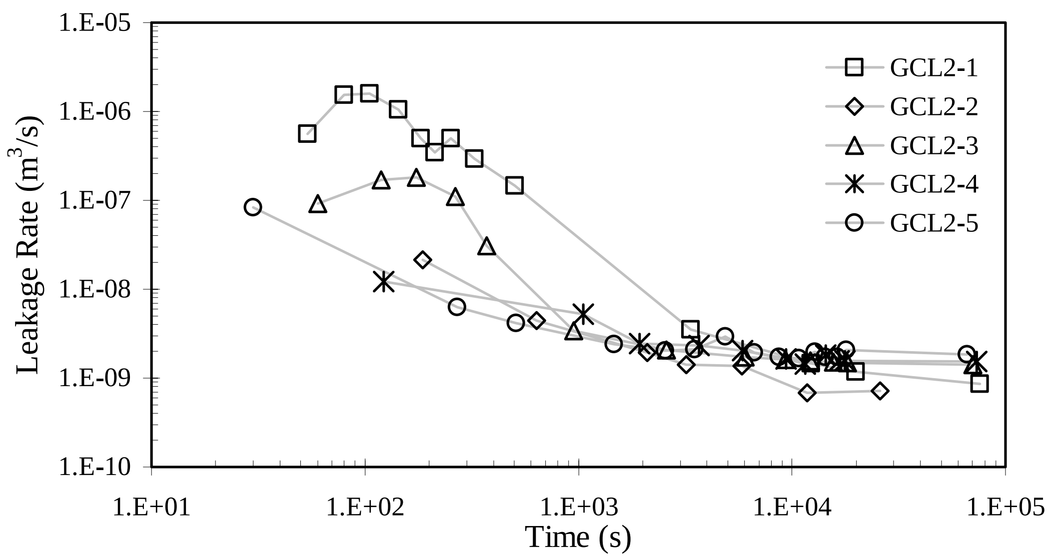

Figure 3: Leakage rates with time for Test Series 4

The steady-state leakage rates obtained in Test Series 4 are summarized in Figure 4. The leakage rate increases as the hydraulic head is increased for each test. This trend is evident despite the scatter in the data. Bernoulli's equation for flow through an orifice can no longer be used because the material beneath the geomembrane is no longer permeable. Accordingly, methods of analysis suitable for composite liners were used to evaluate the data obtained from Test Series 4.

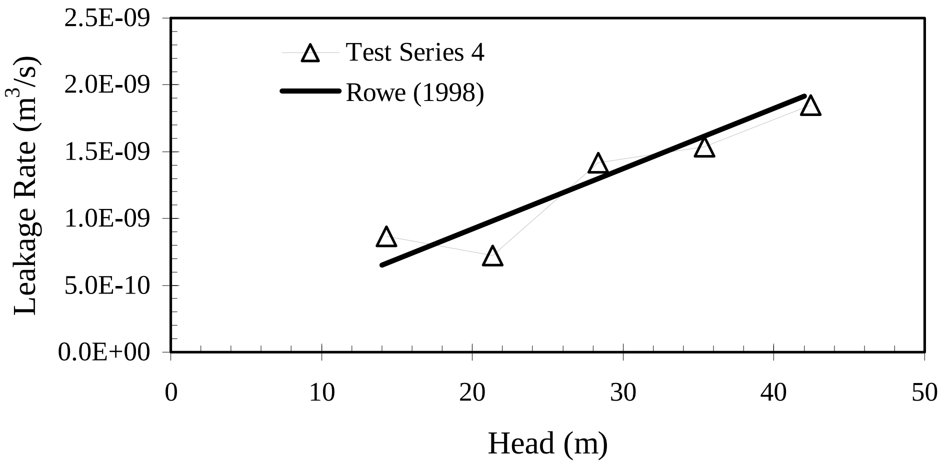

Figure 4: Comparing leakage rates for Test Series 4 with Rowe (1998) analytical model

Giroud and Bonaparte (1989) developed an empirical equation to estimate leakage rates through geomembrane defects when the geomembrane is placed over low-permeability soil. However, this model did not provide a good fit for the experimental data obtained in Test Series 4. This can be attributed to the fact that the model was developed for and calibrated with data obtained from tests conducted under low hydraulic heads.

Rowe (1998) developed an analytical model for predicting leakage rates through defects in geomembrane liners that are placed over low-permeability underlying soils. The model corresponds to the solution of differential equations for flow solved using Bessel functions and results that are independent of experimental constraints, such as hydraulic head, unlike empirical equations. The model is presented in detail in Rowe (1998). The predicted leakage rates are compared in Figure 4 with the steady-state values measured in Test Series 4. The good comparison indicates that the suitability of Rowe's model to predict leakage rates measured through the geomembrane-hydrated GCL lining systems. The predicted radius of wetted area for Test Series 4 ranged from 2 to 3 cm which is well below the radius of the permeameter (15 cm). Rowe's model is dependent on the transmissivity of the interface. In fact, the good match between experimental and predicted results was obtained when the transmissivity of the interface is very small (5×10^{-11} m^2/s). The transmissivity of the interface is dependent on the contact quality and the transmissivity of the carrier geotextile of the GCL. Nonetheless, the good comparison reveals that Rowe's model can be used to predict leakage rates through defects in geomembranes for high heads representative of dam scenarios.

CONCLUSIONS

An experimental program was conducted to evaluate the suitability of using GCLs along with geomembranes in lining systems under high hydraulic heads. Some of the results obtained in this program were presented herein. The main conclusions of this study are:

1: Tests that incorporated GCLs, hydrated or unhydrated, yielded steady-state leakage rates that were over three orders of magnitude lower than the leakage rates measured in systems without GCLs. In turn, hydrated GCLs led to leakage rates that were approximately one order of magnitude lower than unhydrated GCLs.

2: The C-coefficient in Bernoulli's equation for flow through an orifice was found to be dependent on the range of hydraulic heads. If the appropriate value is used, the orifice equation can provide a good estimate of the leakage rates through a defect in a geomembrane under high hydraulic heads.

3: The analytical model developed by Rowe (1998) was found to provide a good estimate of the leakage rate through defects in geomembranes placed over GCLs. However, the prediction depends on the selected transmissivity of the interface. Nonetheless, expected trends in the leakage rates with respect to head can be evaluated using this model.

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