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ADVANCES ON THE USE OF GEOSYNTHETICS IN HYDRAULIC SYSTEMS

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ABSTRACT

Geosynthetic have been used as impervious barriers in dams since 1959 (Contrada Sabetta dam). The use of geosynthetics in hydraulic systems has the potential to grow significantly when compared with the expected growth of the industry in other well established areas such as transportation and environmental systems. While significant advances have taken place in geosynthetics engineering since geomembranes were first used in hydraulic structures, ongoing research and field performance evaluations continue to provide valuable insight. This paper focuses on the current status of the use of geosynthetics in dams both worldwide and in the US as well as on recent advances on the research in this area. Regarding ongoing research, emphasis in this paper is on studies being conducted as part of the Center for Polymers in Hydraulic Systems (CPHyS). This includes evaluation of the durability of geomembranes and the hydraulic performance of geosynthetics under high hydraulic heads.

INTRODUCTION

Many advances have taken place in geosynthetics technology since the first use of geomembranes for waterproofing dams in 1959. However, there are still significant research needs that should be addressed to optimize the design, installation, and performance evaluation of geosynthetics in hydraulic structures. Durability, lifetime prediction, and quantification of leakage through geomembranes under high heads are among the topics that would benefit from additional research. Experimental studies are being conducted on these topics as part of the activities of the Center for Polymers in Hydraulic Systems (CPHyS) of the Geosynthetic Institute (GSI). In addition, field information on the areas of durability and leakage continues to be collected from a growing number of projects worldwide.

An overview of the use of geosynthetics in hydraulic systems was provided by Zornberg and Weber (2003). The present paper initially provides an update on the use of geosynthetics worldwide and some recent applications in the US. Subsequently, this paper summarizes recent results form ongoing research on the lifetime prediction of geomembranes and on the performance of geosynthetic barriers under high hydraulic heads.

UPDATE ON THE USE OF GEOSYNTHETICS IN DAMS

According to the World Commission on Dams (2000), over 45,000 large dams have been constructed worldwide. The International Commission on Large Dams (ICOLD) defines a large dam as a dam with a height of at least 15 m or a dam that retains more than 3,000,000 m^3 of water. The average dam is 35 years old (World Commission on Dams, 2000). Deterioration and structural damage due to ageing are the major concern associated with hydraulic structures in developed countries.

Geosynthetic barriers have been used as alternative solutions to mitigate deterioration processes in existing dams, to prevent the onset of seepage-induced degradation in new dams, and as the main hydraulic barrier in cases where low-hydraulic conductivity soils are not readily available.

Geomembranes were first used in a dam constructed at the Contrada Sabetta dam (Italy), in 1959. The structure involves a rockfill and rubble masonry dam, where two 2 mm-thick polyisobutylene geomembranes were installed during construction (Sambenelli and Rodriguez 1996). The geomembrane continues to function as intended after over 45 years since its installation. The Contrada Sabetta dam is 32.5 meters high and has 1H:1V slopes on the upstream face. The geomembrane system was installed as a hydraulic barrier underneath concrete slabs placed on the upstream face. Porous concrete was installed underneath the geomembrane during construction of the dam.

The hydraulic conductivity of geomembranes ($\underset{\sim}{~}$ 10^{-15} m/s) is significantly smaller than that of typical clays ($\underset{\sim}{~}10^{-9}$ m/s). However, the main mechanism of water infiltration through geomembranes involves flow through defects. Drainage systems have been installed to collect water permeating the geomembrane liner in order to minimize infiltration into the dam structure. Specifically, geonets and geotextiles have been used in drainage applications. A good example is the use of geonets installed behind the geomembrane in the Lost Creek Dam project (Onken et al. 1998), the first underwater installation of a geomembrane in a dam project.

Geomembranes have been often placed on the upstream face of the dam, minimizing water infiltration and subsequent degradation of the dam materials. However, geomembranes have also been used in place of, or in addition to, clayey soil used as an impervious barrier in the core of a dam. For example, a rock-fill dam of the Zhushou Reservoir (Sichaun Province, China) was constructed using a geotextile/geomembrane composite placed as an additional hydraulic barrier over the clay core of the dam (Tao, et al. 2002). Use of a geosynthetic liner was triggered by the shortage of the originally specified core clay material. The uses of geomembranes within fill dams represent a new, yet very promising application.

The updated ICOLD report from the Committee on Materials for Fill Dams (Scuero, et al., 2005) reports on 250 dams that have incorporated geomembranes. This includes 174 fill and 75 concrete dams. Out of the 250 dams, 47 are in China, 38 in the US, 37 in France, 35 in Italy, 9 in Austria, 8 in Germany, 6 in Czech Republic, 3 in Portugal and in the UK, 2 in Switzerland, Belgium, Romania and Slovakia, 6 scattered in other European countries. Europe and the US account for over 75% of the total (153 dams).

Regarding the type of dams, geomembranes have been successfully used to provide a watertight facing on new RCC dams up to 188 m high, to repair old masonry and concrete dams up to 174 m high, and have been used as the main impervious component on fill dams up to 110 m high. Figure 1 provides the current total (and percentage) of dams in each category.

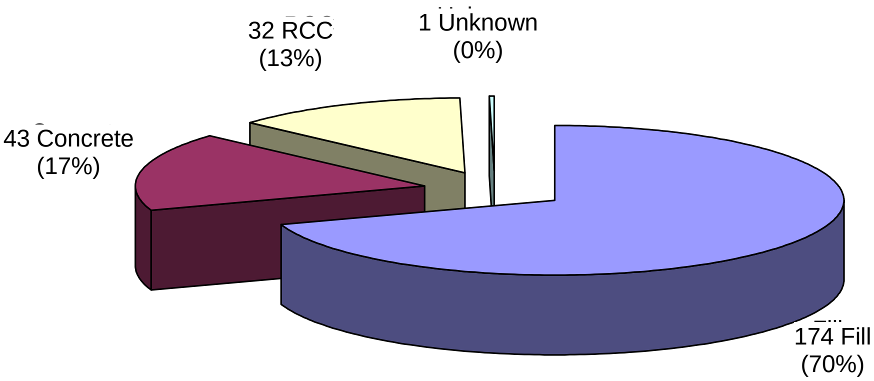

Figure 1. Types of dams with geomembranes.

Figure 2 provides a summary of the type of geomembrane used in 237 of the dams for which the type of geomembrane is reported (Scuero, et al. 2005). Polyvinyl chloride (PVC) has been used in most of the projects, although various forms of polyolefins (LLDPE, HDPE, fPP) have also been used in a number of applications. A representative number of projects have used geotextiles impregnated with polymers (in situ membranes, 9 projects) as well as butyl rubber, polysobutylene, ethylene-propylene-diene monomers (IIR, PIB, EPDM, 9 projects), Chlorosulphonated polyethylene (CSPE, 8 projects), and chlorinated polyethylene (CPE, 3 projects). Bituminous materials have been used either as oxidized bitumen (prefabricated geomembrane, 17 projects), polymeric bitumen (1 project), or oxidized bitumen (in-situ membrane, 3 projects).

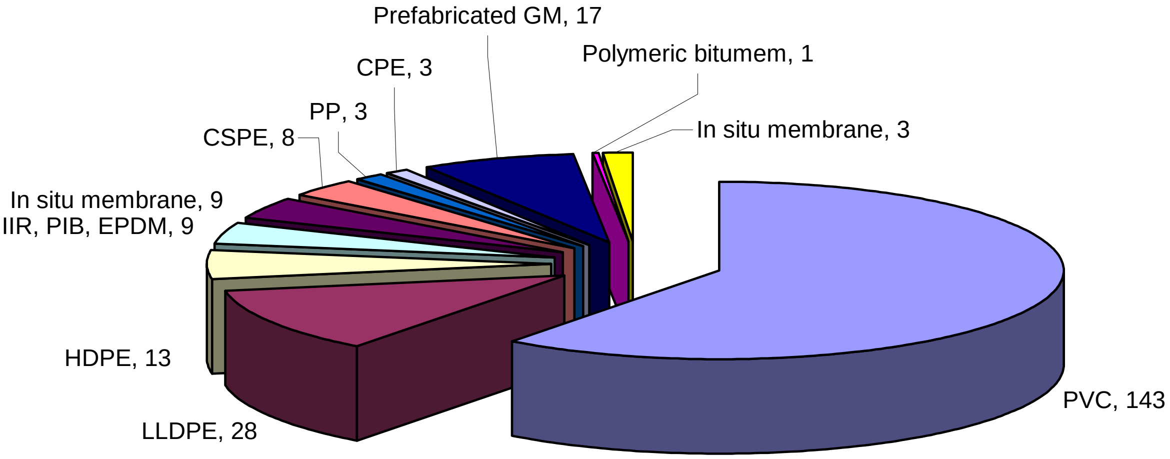

Figure 2. Type of geomembranes used in dam projects worldwide.

Some major projects involving the use of geomembranes have been completed recently in the US. These include the Olivenhain Dam and the Salt Spring Dam, both in California. The Olivenhain Dam (Figure 3) is a recently completed dam involving use of a PVC geomembrane as an impervious barrier. Located in San Diego, California, this dam is the largest roller-compacted concrete dam in North America. Construction was completed in August 2003 for the purpose of emergency water storage for the city of San Diego. The dam can store over 30 million m^3 of water. A 2.5-mm PVC geomembrane was installed during construction, attached to the upstream face. An important basis for selection of a geomembrane liner was that the integrity of a flexible geomembrane barrier would not be compromised for the design earthquake.

The dam was designed as a concrete gravity dam constructed using roller-compacted concrete (RCC) placing methods. RCC methods allowed a quicker and more economical dam construction (as compared to conventional concrete placing methods) using limited forming on the upstream and downstream faces, only. The zero-slump concrete was placed in one foot “lifts” and compacted with a 10-ton vibratory roller, much like conventional earth fill embankment dam construction. RCC gets its economy from a fast placement schedule, as the zero-slump concrete will support heavy construction equipment immediately after placement. Each subsequent lift was placed as quickly as possible. RCC was placed 24-hours a day, seven days a week. The Olivenhain Dam is the first RCC gravity dam permitted by the state of California and, with a height of 318 feet (97 meters) and RCC volume of 1.44 million cubic yards (1.1 million cubic meters), is the tallest RCC dam in the North America. The Olivenhain Dam has the typical geometry for concrete gravity dams with a vertical upstream face and a 0.8:1 sloping downstream face with the point of intersection with the upstream face at the dam crest. The crest width is 20-feet (6.1 meters) with a crest length of about 2,570 feet (783 meters). The vertical face of the gravity dam was formed using precast concrete panels that were fabricated on-site. These upstream face panels were lined with the PVC membrane, which was bonded directly to the precast panels.

Another recent use of geomembrane lining in the US is the Salt Springs Dam, which is owned by Pacific Gas & Electric Co. (PG&E), see Figure 4. This dam is the 5th oldest concrete-faced rockfill dam (CFRD) in the world and the first CFRD to reach 100 meters in height (Larson et al. 2005). The dam is located in California, southeast of Sacramento, high in the Sierra Nevada Mountain Range. Construction of the dam was halted at mid-height in the 1930s. When the rock placement resumed, a zone of differential settlement resulted in the dam where the concrete face has required continual repairs over its 70 year history.

A leak occurred in this zone in 2001, which resulted in a significant increase in seepage beyond the level set by the California Department of Safety of Dams (CA DSOD). As a temporary measure, PG&E undertook immediate repairs involving divers at considerable expense to decrease the seepage. The permanent fix of the upstream face at Salt Springs eventually included installation of a PVC geomembrane system over the upstream face. The overall goal was to reduce seepage to 12 cfs.

Phase I repairs began in the spring of 2004, with the installation of a PVC geomembrane system over the center of the face in the transition zone, in order to mitigate the risk of significant seepage increases. The membrane system arrested seepage in this zone during the filling of the reservoir from snow runoff in 2004. At the same time, seepage analyses were conducted for subsequent remediation using various geomembrane configurations. The study results showed that in order to maximize the seepage reduction from a geomembrane installation, the area of the membrane system installation should be extended down the face (Figure 4). The geomembrane installation was completed in the spring of 2005, encompassing approximately 200,000 square feet on the face of the dam.

Figure 3. Olivenhain dam, an RCC Dam in California.

Figure 4. Installation of geomembrane at Salt Springs Dam, a CFRD dam in California.

The geomembrane system installation included placement a 59 oz/sy geotextile for rough surface areas of the dams. This was placed directly on surface to smooth irregularities of dam face and decreasing surface preparation costs. A tri-planar geonet was placed along and above the lower perimeter seal for drain collection. The geocomposite used in this project involved a PVC geomembrane (100 mils) with a 14.7 oz/sy geotextile. The geomembrane system installation began with surface preparation. The surface of Salt Springs Dam was frequently described as a "moonscape," as it was extremely rough with craters in the face from deterioration over 70 years of service. Additionally, shotcrete patches had been applied on the face that had offsets of up to approximately 6 inches (Figure 5). Originally, it was considered to remove these shotcrete patches. However, the shotcrete was sound and the cost to remove was prohibitive. The solution was to chip off the vertical edges of the shotcrete patches and then add extra layers of geosynthetic material as sacrificial layers before application of the thick geotextile that was installed over the entire face. The surface preparation of the surface took considerable time and represented a significant portion of the overall installation time.

Figure 6 shows the geomembrane system following dewatering after the geomembrane system had been in service for one season. The picture shows how the geocomposite conformed to the subgrade. The picture also shows how the surface preparation was limited, as significant voids did not have to be completely backfilled, but rather just smoothed with concrete and extra layers of geosynthetics. Seepage at Salt Springs over the last five seasons (2001-2005) has been successfully reduced by over 47% to the target seepage.

Figure 5. Typical section of the concrete face at Salt Springs Dam after 70 years of service and repairs.

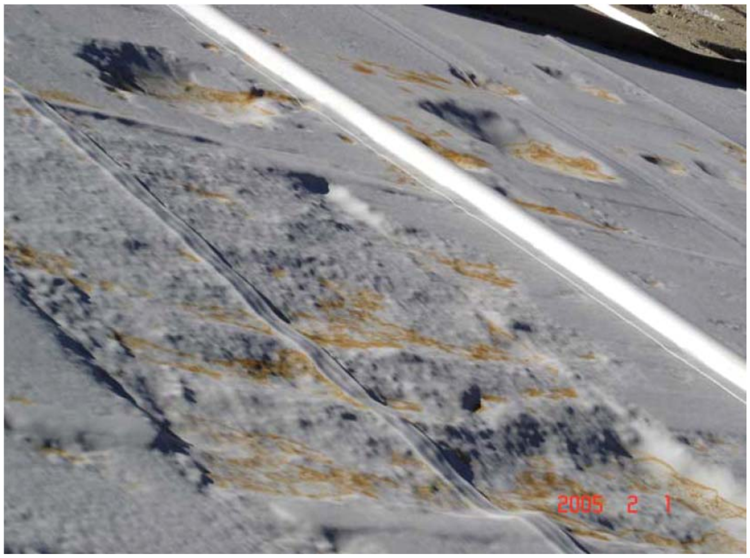

Figure 6. View of geomembrane conditions after dewatering following one year of operation.

DURABILITY OF GEOSYNTHETICS

Project-based knowledge

As previously discussed, it is already 46 years that the first geomembrane was placed in a dam (Contrada Sabetta, Italy, 1959). Geomembranes have now been incorporated in the design of hydraulic barriers both for new dams and for repair of existing dams. The composition and the quality of the geomembrane dictate its performance over time. Table 1 summarizes the oldest geomembranes (as of 2005) installations by type of geomembrane (Scuero et al. 2005).

As shown in Table 1, significant evidence is now available for evaluation of the field performance of the various types of geomembranes. Cazzuffi (1998) reported the results from samples of exposed PVC geomembranes retrieved from six of the Italian dams, where they had been in service for different periods of time, ranging from 2 to 19 years. The retrieved samples have been tested for plasticizer content, hardness, tensile properties, and hydraulic conductivity. The decrease in plasticizer content resulted in slightly higher modulus and tensile strength. The functionality of the geomembranes was not affeacted, as evaluated by the measured hydraulic conductivity. Recovery of exposed PVC geomembranes installed in canals owned by Italian authorities led to similar conclusions.

Experimental-based knowledge

Studies on lifetime prediction of geomembranes have been a central focus of research at GRI (Koerner, et al. 2005). The studies initiated at Drexel University under U. S. EPA contract from 1991 to 1997, have continued under GSI consortium funding since that time. Focus to date has been on HDPE geomembranes beneath solid waste landfills due to its common use in this particular challenging application.

Incubation of the coupons has been in landfill simulation cells (Figure 7) maintained at 85, 75, 65 and 55°C. This experimental information is suitable for evaluation involving covered geomembranes for dam applications. The specific conditions within these cells are oxidation beneath, chemical (water) from above, and the equivalent of 50 m of solid waste mobilizing compressive stress. Results have been forthcoming over the years insofar as three distinct lifetime stages:

- Stage A - Antioxidant Depletion Time
- Stage B - Induction Time to Onset of Degradation
- Stage C - Time to Reach 50% Degradation (Half life)

Table 1 - Oldest Geomembrane Installations by Type of Geomembrane (after Scuero, 2005)

Type	Basic material	Abbreviation	Total exposed	Total covered	Oldest exposed	Oldest covered
Polymeric	Polyvinyl chloride	PVC-P	73	70	1974	1960 (Terzaghi Dam, Canada)
Polymeric	Polyolefin	LLDPE	0	28	-	1970 (Atbashinsk, Kirgizistan)
Polymeric	Polyolefin	HDPE	2	11	Not known	1978 (Bitburg, Germany)
Polymeric	Elastomeric	Polysobutylene IIR	5	4	1982	1959 (Contrada Sabetta, Italy)
Polymeric	Chlorosuflonated Polyethylene	CSPE	3	5	Not known	1981 (Kolnbrein Austria)
Polymeric	Polyolefin	PP	1	2	Not known	Not known
Polymeric	Chlorinated Polyethylene	CPE	0	3	-	1970 (Odiel-Perejil, Spain)
Bituminous	Oxidized bitumen	Prefabricated GM	7	10	1973 (Banegon, France)	1978
Bituminous	Polymer bitumen	SBS	0	1	-	1996

Details on the characteristics of these three stages are provided by Koerner, et al. (2005) and Koerner and Hsuan (2003). Stage A, that of antioxidant depletion for HDPE geomembranes as required in the GRIGM13 Specification, has been well established by GSI research and corroborated by others (e.g. Sangram and Rowe, 2004). The GRI data for Standard and High Pressure Oxidative Induction Time (OIT) is given in Table 2. Also, as expected, the lifetime is strongly dependent on the service temperature; with the higher the temperature the shorter the lifetime. Stage “A” in the table corresponds to measured values from Hsuan and Guan (1997).

Stage “B,” that of induction time, has been obtained by GRI after comparing 30-year old polyethylene water and milk containers (containing no long-term antioxidants) with currently produced containers. The data shows that degradation is just beginning to occur as evidenced by slight changes in break strength and elongation, but not in yield strength and elongation. The lifetime for this stage is also given in Table 2.

Figure 7. View of incubation cells at GSI, maintained at various constant temperatures.

Table 2 - Lifetime prediction of HDPE (nonexposed) at various temperatures (after Koerner et al. 2005).

In service Temperature (°C)	Stage "A" (yrs.)		Stage "B" (yrs.)	Stage "C" (yrs.)		Total lifetime (ave. values)
	Std OIT	HP-OIT	Field Data	Max.	Min.	
20	200	215	30	255	149	449
25	135	144	25	132	77	270
30	95	98	20	70	41	173
35	65	67	15	38	22	111
40	45	47	10	21	12	73

Notes: Stage "A" measured values from Hsuan and Guan (1997) research via GRI (Koerner et al. 2005)
Stage "B" estimated values from field samples by GRI (Koerner et al. 2005)
Stage "C" literature values from Gedde, et al. (1994)

Stage "C", the time for 50% change of mechanical properties depends on the activation energy (i.e. the slope of the Arrhenius curve), which is very sensitive to material and experimental techniques. The data shown in the table is from Gedde, et al. (1994), which is typical of the HDPE resin used for gas pipelines.

As also indicated in Table 2, the half life of covered HDPE geomembranes (formulated according to the current GRI-GM13 Specification) is estimated to be 449 years under a temperature of 20°C. The half life decreases with temperature and is expected to be lower for resins other than HDPE. Yet, particularly when compared with the half life that could be attributed to materials such as concrete, the longevity of geomembranes is considered exceedingly adequate for hydraulic applications. Deterioration of exposed concrete after 70 years of service, as described for the Salt Springs Dam, is clear evidence that traditional materials in dam construction are possibly less durable than geosynthetics (recall Figure 5).

PERFORMANCE OF GEOSYNTHETICS UNDER HIGH HYDRAULIC HEADS

Project-based knowledge

An important objective in projects involving the use of geomembranes in dams has been to minimize the progressive deterioration of concrete. Unlike this area, where technology is becoming well established, additional breakthroughs are expected to take place on the use of geomembranes in fill dams. As shown in Figure 1, a total of 174 dams that involved the use of geomembranes correspond to fill dams. This indicates that there is a significant potential for new developments regarding the use of geosynthetic barriers in fill dams. The geomembrane sealing system in fill dams has been as follows:

- Upstream system
    - Exposed
    - Covered
- Internal system

Table 3 shows the number of reported uses of geomembranes in fill dams (Scuero et al. 2005). Only 18 dams have used geomembranes in an internal position (out of a total of 162 dams for which the position of geomembrane is invariably upstream). The concept of composite liners, that is, taking advantage of the synergism between geomembranes and clay liners (e.g. GCLs) needs additional insight regarding its application for high heads representative of dam projects. The use of composite liners, which has led to significant confidence regarding the use of geosynthetic barriers in environmental applications, would be applicable both for upstream covered and internal systems in dams. In geomembrane-only approaches, while geomembranes alone can provide the decrease of flow through dams, but additional redundancy provided by a composite liner is expected to prompt significant new applications in hydraulic systems.

The new construction of dams provides the possibility of installing the geomembrane seal inside the dam fill. It should be noticed that the geosynthetic barrier system can include the following possible systems resting on fill material:

- geomembrane alone
- geomembrane/clay layer
- geomembrane/drainage layer
- geomembrane/GCL/drainage layer

Table 3 - Reported Uses of Geomembranes in Earth and Earth/Rock Fill Dams

	Total	Upstream		Internal
		Upstream exposed	Upstream covered	
Total number of fill dams	162	44	100	18
Total number of new constructions	77	14	49	14
Total number of rehabilitation	55	20	31	4
Unknown if new construction or rehabilitation	30	10	20	0

The presence of a clay layer or a GCL provides the system with the ability to deal with the main mechanism of leakage, which is leakage through defects in the geomembrane. Drainage layers have been used to avoid problems associated with rapid drawdown when the geomembrane system is used in the upstream face. In internal systems, drainage layers can additionally provide the opportunity of internal monitoring of the dam. Figure 8 shows a number of configurations in which internal geomembranes have been used in fill dams. Figure 8(a) shows a geomembrane in inclined position, as used in Valence d'Albi Dam (France). Figure 8(b) shows a geomembrane in vertical position, as used in Atbashinks Dam (Kirgizistan). Figures 8(c) and 8(d) show two configurations including a geomembrane system in zig-zag (differing in the height of the lifts) as used in the Fencheng Dam (China) and Wantuzhou Dam (China). The advantage of the 'internal system' is the protection of the geomembrane against external mechanical, physical, biological and chemical actions, as well as against vandalism. The quantity of geomembrane installed is less when compared to the upstream option. Disadvantages include the risk associated with placement of the upstream and downstream fill. The use of composite systems would help alleviating concerns associated with the potential damage of the geomembrane during construction.

Experimental-based knowledge

An ongoing experimental testing program at the University of Texas aims at evaluating the performance of geosynthetic barriers under hydraulic heads that are high and representative of dam projects. Weber and Zornberg (2005) report on the feasibility of using geosynthetic clay liners (GCLs) in lining systems that incorporate a geomembrane under hydraulic heads. This approach would be feasible for systems illustrated in Figure 8 as well as for covered geosynthetic barriers in the upstream face of dams. Another aspect being investigated involves assessment of the quality of the contact between geomembrane and the underlying fill. The quality of such contact is of major relevance in the quantity of leakage through geomembrane defects for the case of low hydraulic heads (Koerner 2005). A good example is the case of the design of drainage systems in landfills, which are typically limited to a maximum hydraulic head of 1 ft. This section reports results on the evaluation of the quality of the contact between geomembrane and underlying fill, where the geomembrane is under high heads representative of dam conditions.

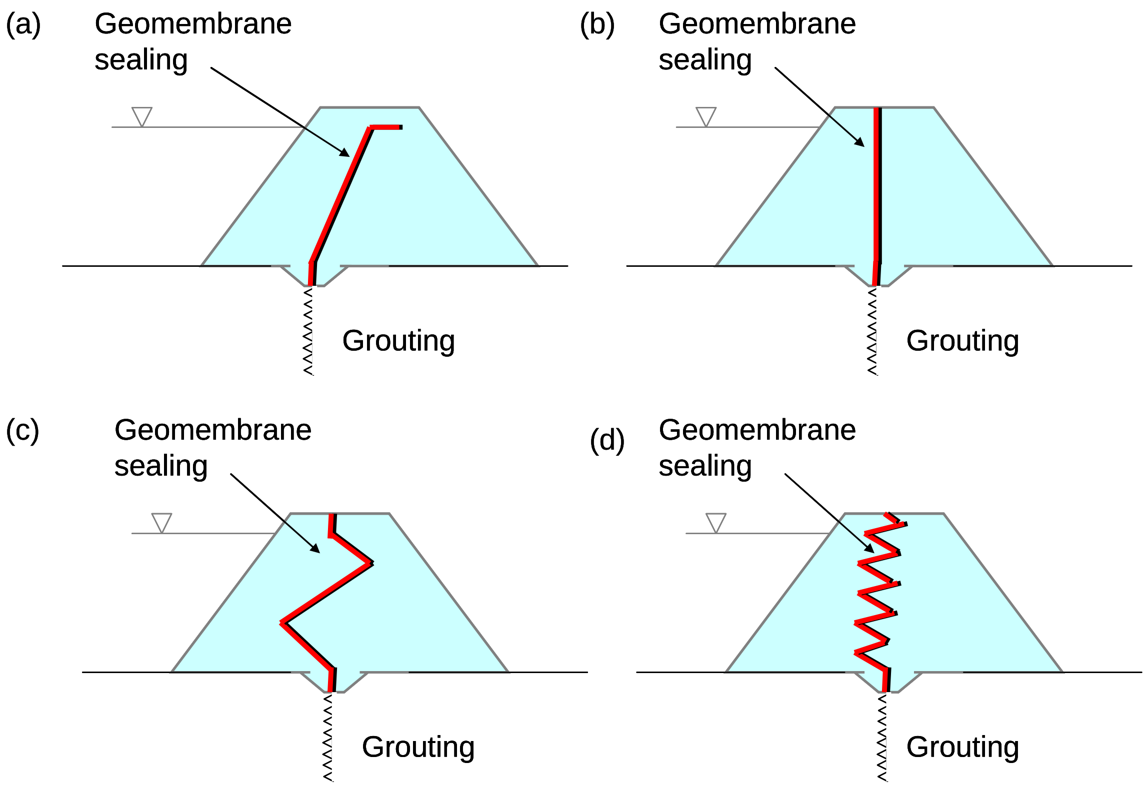

Figure 8. Internal geomembrane configurations: (a) inclined, (b) vertical, (c) zig-zag with large lifts, (d) zig-zag with small lifts.

A permeameter cell was constructed of clear acrylic to test the hydraulic performance of the barrier system (Figure 9). 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 was placed between the two sections and sealed using O-rings. A coarse porous stone is used to provide a free-draining bottom boundary. Both the inflow and outflow volumes are measured throughout testing. A pressure panel is used to control the hydraulic head, ranging from 7 m to 42 m. The permeameter cell setup for the geomembrane/clay test series is shown in Figure 9.

Tests were conducted on systems involving a geomembrane with a circular defect placed over a compacted clay layer. 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 to deformations of the dam as well as those due to thermal contraction and expansion. A circular defect with a diameter of 1.6 mm was drilled at the center of the geomembrane specimen. The soil used in this study was a low-permeability clay. The variables in these tests include contact quality of the geomembrane-clay interface, soil density and hydraulic head. Test details are listed in Table 4.

Table 4 - Details for Geomembrane/Clay Test Series

Test	Unit Weight (kN/m^3)	Head (m)	Contact Quality
1	13.8	0.5	Poor
2	14.7	0.5	Good
3	18.0	35	Good
4	18.7	7	Good
5	17.9	35	Poor

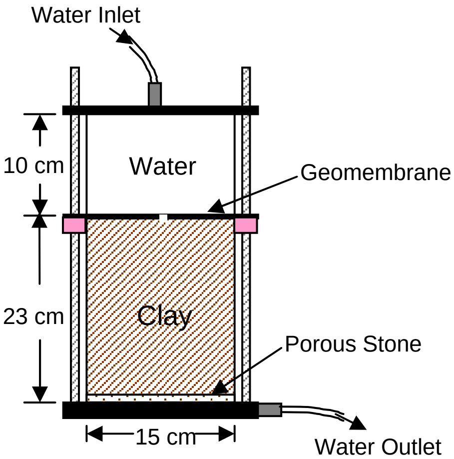

Figure 9. Cell setup for geomembrane/clay test series.

The volume of water flowing into and out of the permeameter cell was monitored and recorded throughout the duration of each test. An example of these measurements is shown in Figure 10. As indicated in this figure, the volume of water flowing into the cell is greater than the volume of water flowing out of the bottom of the cell. This is because the underlying soil was initially unsaturated. The water flowing into the cell begins to fill the pores of the soil and increases its storage. Therefore, the total volume of water leaving the cell is less than the water flowing into the cell. The difference between the total volume that flowed into the cell and the total volume out of the cell equals the volume of water stored in the clay. Flow rates into and out of the cell were determined from the volume measurements (Figure 10). An indication that steady state has been reached is obtained when the slope of the volume curve stabilizes, which should occur in both influx and outflux curves. As shown in the figure, both influx and outflux curves show the same flux rate when reaching steady state.

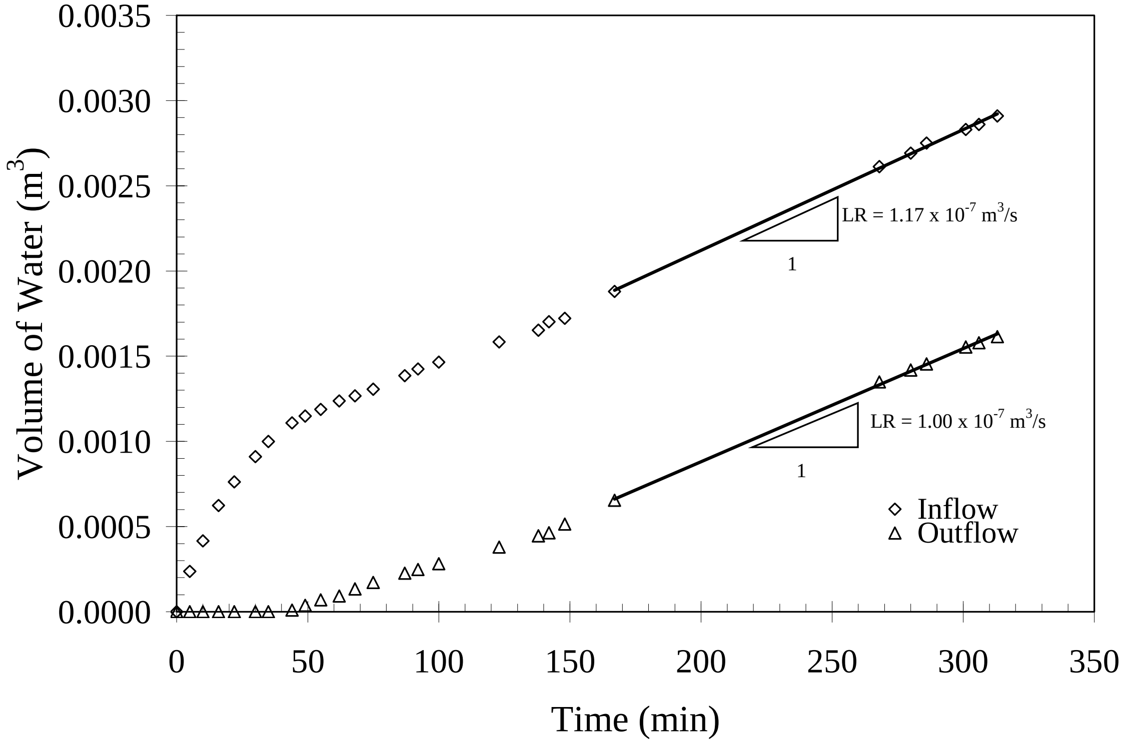

Figure 10. Volume measurements and flow measurements into and out of the permeameter cell for Test 5 (Head = 35 m).

The experimental results for Tests 1 and 2 are compared in Figure 11. The hydraulic head for these tests was the same (comparatively low, 0.5 m) and they have the same soil density and placement water content. However, Test 1 had a poor interface contact quality and Test 2 had a good contact quality. As shown in the figure, the slope of the volume curve for Test 1 is steeper than that for Test 2. Specifically, the leakage rate for Test 1 exceeds that for Test 2 by at least two orders of magnitude. These results are consistent with the expected effect of the quality of the contact between geomembrane and underlying soils for the case of environmental liners (i.e. those dealing with comparatively small heads). Good contact quality minimizes the amount of fluid that diverts laterally through the interface and reduces the radius of wetted area. These results confirm that the quality of the contact interface between the geomembrane and the soil is important for low heads (0.5 m in this case).

Experimental results for Test 5 are presented in Figure 12, where they are compared with those from Test 3. These tests were conducted using a hydraulic head of 35 m and soil samples compacted to the same density and using the same placement water content. Test 5 had poor contact quality between the geomembrane and the soil, while Test 3 had good contact quality. There is not a significant difference in the measured leakage rates once the tests reached steady state. Indeed, the leakage rates under steady state conditions are considered to be very similar. The small difference is attributed to differences in the soil placement conditions. This is a strikingly different response than that observed in Figure 11 for tests conducted under low hydraulic head. Specifically, these results suggest that the quality of the contact between geomembrane and the underlying soil does not play a significant role in the leakage through geomembrane defects when the hydraulic heads are comparatively high. These results may have important practical implications both regarding the placement and quality control operations. These results would also suggest that one of the most important aspects responsible for the poor performance of composite liners (i.e. poor contact) may not play a significant role in leakage calculations through geomembrane defects in dams.

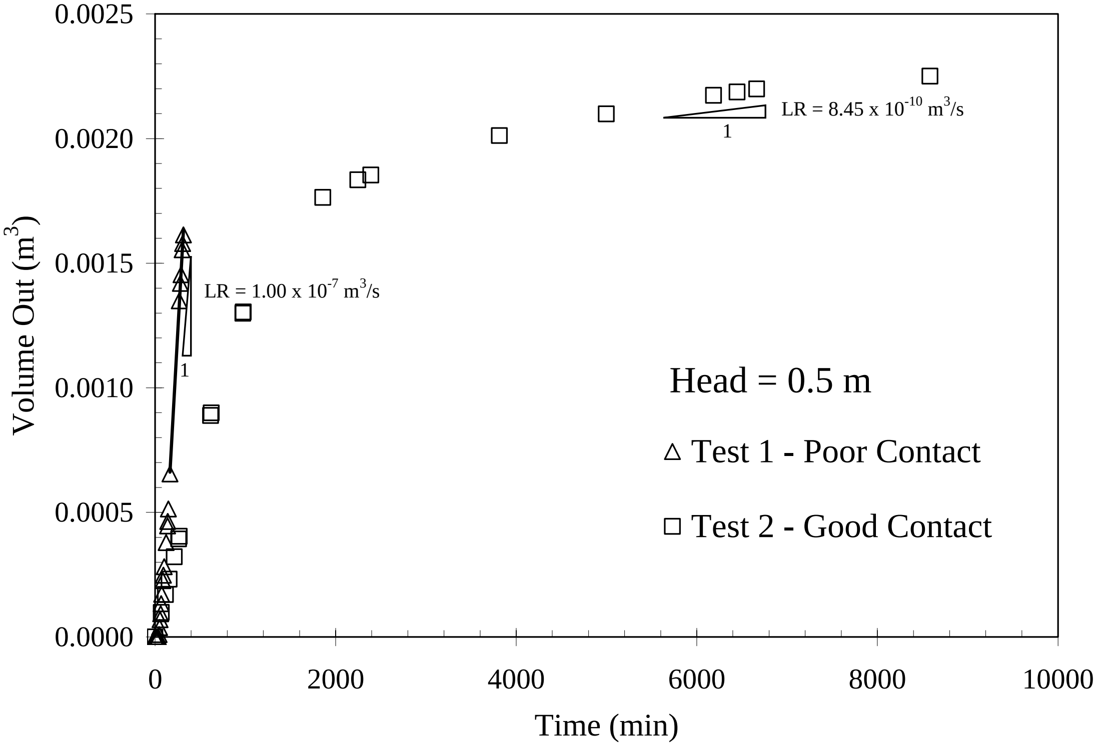

Figure 11. Volume curve for Tests 1 & 2, conducted under low head.

CONCLUSIONS

The current status of the use of geosynthetics in dams both worldwide and in the US was briefly discussed in this paper. The number of projects using geomembranes in dams has been steadily increasing in the US, with two major projects being recently completed using PVC geomembranes. This paper summarizes recent research activities that have been the focal point of ongoing research conducted as part of the Center for Polymers in Hydraulic Systems (CPHyS).

In the area of durability of geomembranes, ongoing monitoring results estimate that the half life of covered HDPE geomembranes is approximately 450 years under a temperature of 20°C. The half life decreases with temperature and is expected to be lower for resins other than HDPE. Yet, particularly when compared with the halflife that could be attributed to materials such as concrete, the longevity of geomembranes is considered exceedingly adequate for hydraulic applications.

In the area of leakage through geosynthetic barriers under high hydraulic heads, this paper summarizes the results of one of the various aspects currently under investigation. Namely, the significance of the quality of the contact between geomembrane and underlying soils for the case of composite liners under high hydraulic heads. Available results indicate that the quality of the contact, which is a very important parameter when predicting the leakage under low hydraulic heads, is not a significant parameter when predicting the leakage under high hydraulic head systems.

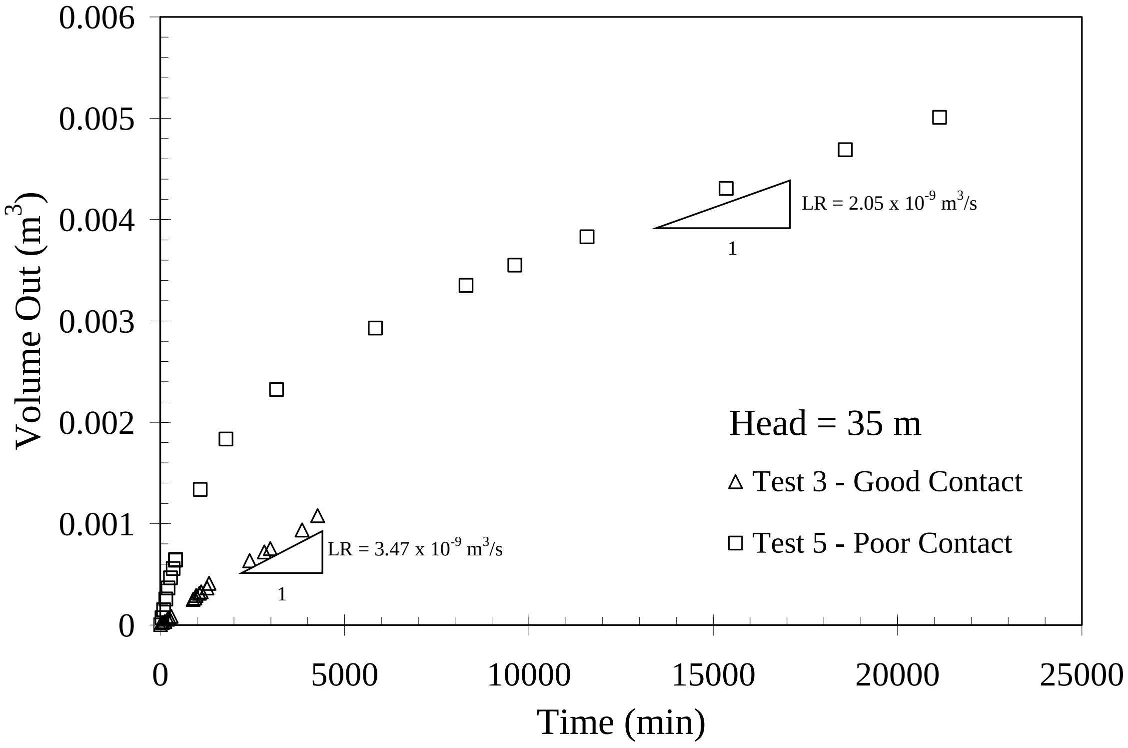

Figure 12. Volume curve for Tests 3 & 5, conducted under high head.

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