SELECTING A GEOMEMBRANE SYSTEM FOR A LINED EMBANKMENT DAM AND RESERVOIR PROJECT

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ABSTRACT

Several geomembrane systems are available for use at reservoir and dam projects. Choosing the right system is not always a straight forward decision. Selecting a geomembrane is site and project specific, and must consider many factors including: the exposure conditions, installation configuration, intended purpose of the facility, operation and maintenance performance criteria, material availability, project size, service life of the facility, and owner preferences. This paper provides a summary of currently available geomembrane systems used to line embankment dams and reservoirs, discusses their general properties, and presents a screening process to help designers and owners select a geomembrane for different types of dam and reservoir projects.

The selection of the geomembrane for two recent upland pumped-storage projects are presented including the rehabilitation of the Tampa Bay Reservoir in Florida, and the construction of the new Bel Air Reservoir in Maryland. A different geomembrane was selected for each project. Nine different geomembrane systems are presented and described with their performance on similar existing projects. The geomembrane systems were evaluated based on appearance, history of performance, constructability, water tightness, strength, durability, and cost. The cost evaluation included a life-cycle cost analysis. Lessons learned from the evaluation of the geomembrane systems for the Tampa Bay Reservoir and Bel Air reservoir projects will be shared.

INTRODUCTION

Geomembranes have been used on dams for nearly 60 years. There are many different types of geomembranes installed on dams today, for which research and performance testing is available for many of these geomembranes. Selecting a geomembrane for a dam project however, is not only about analyzing the performance testing results. The designer must also consider the exposure conditions, installation configuration, intended

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purpose of the facility, material availability, project size, service life of the facility, owner preferences, ease of repair and project history.

The term geomembrane is used generically within this paper to replace the many other terms often used to describe lining systems. A geomembrane is basically an impermeable barrier comprised of one or more layers of a synthetic sheet. The United States Bureau of Reclamation indicates polymeric geomembranes are typically produced in roll form between 6 feet and 33 feet wide, up to 1,000 feet long, and between 30-100 mil thick. [USBR 2014]. Bituminous geomembranes can be over 200 mils thick.

The International Commission of Large Dams (ICOLD) maintains a database documenting geomembrane systems used on dams [ICOLD 2010]. As of 2006, eight different types of geomembranes have been used in the construction or rehabilitation of 265 dams, 183 of which are installed on fill. Geomembranes can be either left exposed to the elements or covered if conditions are warranted. Specially formulated polyvinyl chloride (PVC) is the most prevalent geomembrane material for both exposed and covered applications. A summary of selected geomembrane materials and dam type for this evaluation is provided in Figures 1 and 2.

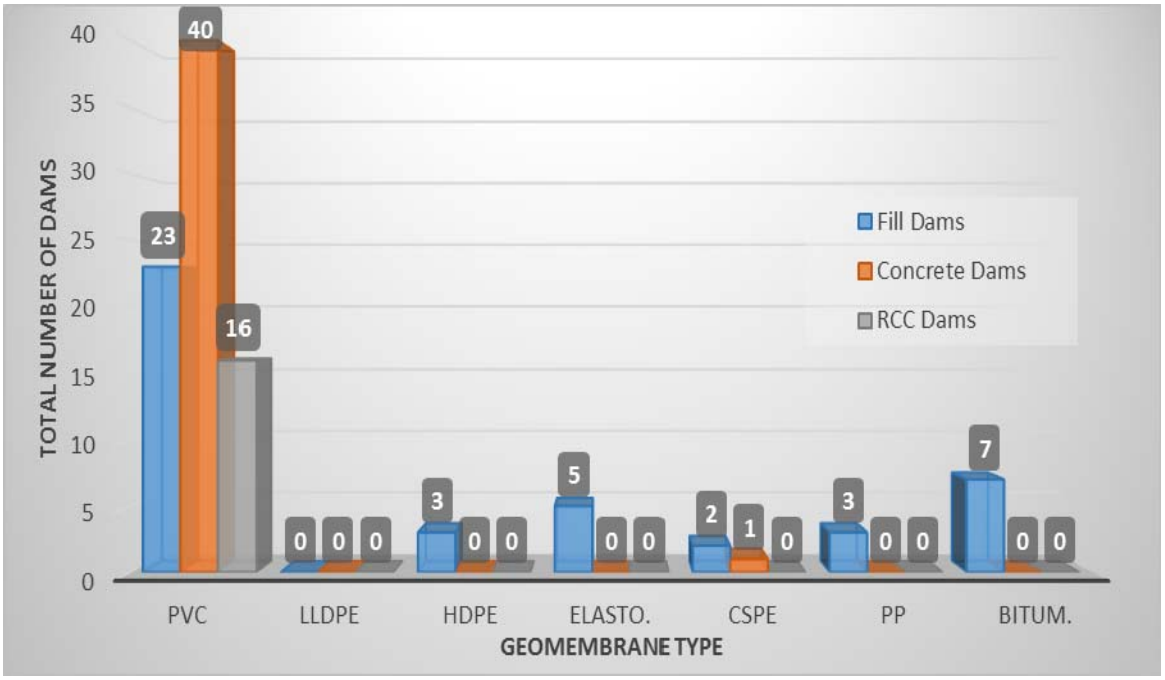

Figure 1. Applications of Exposed Geomembranes on Dams

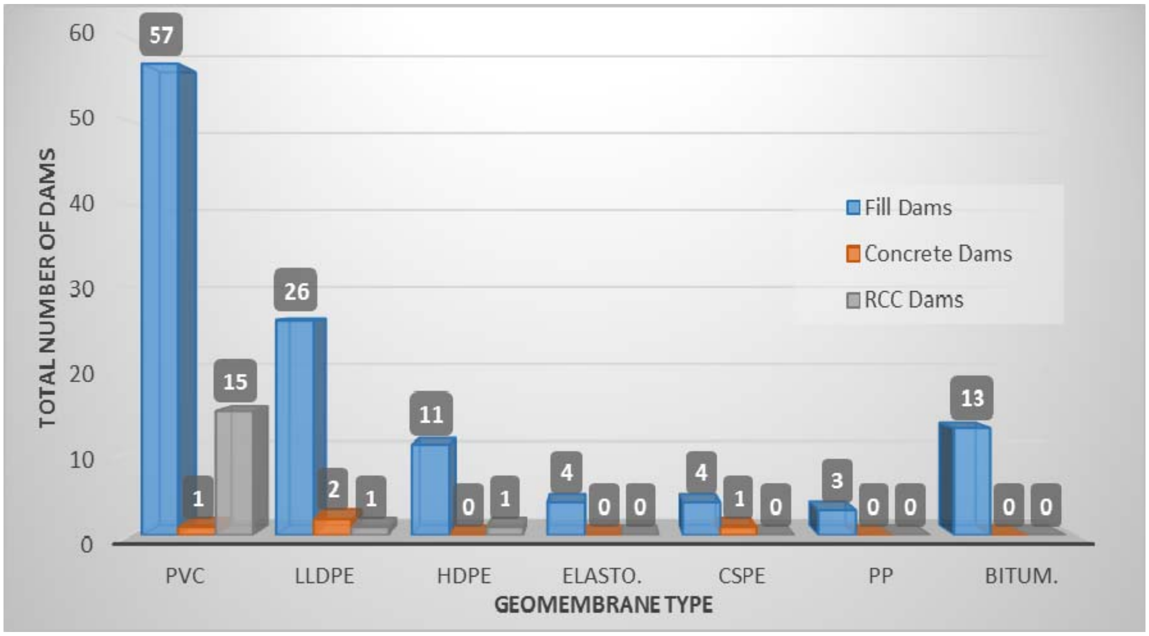

Figure 2. Applications of Covered Geomembranes on Dams

The United States Army Corps of Engineers (USACE) has developed a rating system for polymeric geomembranes for evaluation of underwater installations on concrete hydraulic structures [1995]. Although this paper does not cover all the types of geomembrane systems available for use on embankment dams, it is a reliable resource for permeability, strength, and durability of polymeric geomembranes. It is however, important to consider non-polymeric lining systems for embankment dams, as well. A selection process was recently developed by the authors for geomembrane systems for embankment dams and is discussed below.

COMMON GEOMEMBRANE SYSTEMS FOR EMBANKMENT DAMS

Polyvinyl Chloride (PVC)

The specially formulated PVC liner material by CARPI is a thermoplastic and the most common geomembrane material used on fill dams, which includes both earth fill and rock fill. The oldest PVC geomembrane application on a dam dates back to 1960. The oldest exposed application dates back to 1974. Some exposed PVC geomembranes have exhibited a 30-year service life without a required replacement [ICOLD 2010]. Recent advances in polymer science suggest that PVC may have a service life greater than 100 years. USACE [1995] testing indicates PVC is a superior product among available polymeric geomembranes.

Advantages: PVC geomembranes have a proven record of successful performance on many fill dams worldwide. Their use provides a high degree of confidence and allows visual inspection with the possibility of future repairs if left exposed. PVC conforms well to the underlying substrate and exhibits good elastic recovery and puncture resistance [USACE 1995]. PVC geomembranes have good tensile, elongation, and puncture and abrasion resistant properties and can be easily seamed [USBR 2014]. Exposed geomembrane provides a uniform appearance free of defects. Special PVC liners are available with heat bonded non-woven geotextiles on one or both sides of the PVC membrane to increase frictional resistance and puncture resistance.

Disadvantages: Potential degradation from UV radiation depends on composition. Polymer formulation can be adjusted to add UV protection if required. The exposed surface, even when textured, is slippery and often requires special construction features to provide egress for persons or animals that accidently enter the reservoir if left in the exposed condition. Installation may require a proprietary system.

Bituminous

In the simplest form, bituminous geomembranes are comprised of non-woven geotextile dipped in elastomeric bitumen. Reinforcing materials are often added to provide strength. Bituminous geomembranes used for dam applications are not very prevalent in the United States, but are beginning to show signs of increased use on dam projects. Bituminous geomembranes have also been used to line canals and secondary containment lagoons. Most dam applications of bituminous geomembranes to date have been in Canada and Europe.

Oxidized bituminous geomembranes were predominantly used prior to development of elastomeric bitumen. The oldest known exposed application of an oxidized bituminous geomembrane on a dam occurred in 1973 in Banegon, France. Superficial micro-cracks only affecting the physical appearance have been observed [Daly 2017]. Elastomeric bituminous geomembranes have a longer service life estimated to be 35-40 years. Approximately 20 dams worldwide are known to use a bituminous geomembrane as of December 2006 [ICOLD 2010]. Vendor literature indicates this number has recently grown substantially (e.g., One vendor has provided bituminous geomembranes for more than 15 dams between 2006 and 2018).

Advantages: Good appearance, seepage control and strength characteristics. Routine constructability that can be performed by local work crews and does not require a specialty contractor. Vendor literature and case studies indicate conformance to underlying substrate and good resistance to puncture and tearing. Very good friction angle on exposed surface providing a suitable surface for egress. It is a relatively heavy material with better resistance to wind uplift.

Disadvantages: Installations on dams in the United States are limited. Relatively little third-party performance testing is available. May be susceptible to "mud curling", a phenomenon that affects physical appearance but maintains strength and water-tightness [ICOLD 2010].

Elastomeric

The term “elastomeric” is used in this evaluation to group several thermoset rubber geomembranes due to limited dam applications and evaluations. Published literature indicates that ethylene-propylene diene monomer (EPDM) is the most popular elastomeric membrane for dam applications, but butyl rubber and polyisobutylene (PIB) have also been used as well. Only eleven dams worldwide are known to use an elastomeric geomembrane system as of 2006. The oldest covered application dates back to 1959 (the first application of a geomembrane on a dam) and the oldest exposed application dates back to 1982 [ICOLD 2010].

Advantages: Elastomeric geomembranes have good appearance, seepage control, and strength characteristics. They conform to an irregular substrate with good elastic recovery and puncture resistance [USACE 1995].

Disadvantages: Installations on dams have been very limited in number. Little data is available regarding service life and durability for dam projects. In general, the service life, especially when exposed, is believed to be less than that of PVC and Bituminous liners. USACE [1995] indicates fair repairability. Seams may require several days of curing before exposure to mechanical stresses and may become more rigid with age.

Compacted Clay Liner (CCL)

CCLs have historically been the primary means of reducing seepage using a soil material. CCLs are composed of clay-sized particles obtained onsite or from a local borrow source. The design thickness of a given CCL is often governed by its hydraulic conductivity as determined during an extensive laboratory testing program. CCLs are typically on the order of three feet thick and yield a permeability around $1x10^{-7}$ cm/sec depending on the percentage of clay and compaction effort. CCLs have been used extensively as liners for dams. Many modern earth embankment dams are configured with a compacted clay core or core trench to reduce through and under seepage.

Advantages: Good seepage control characteristics. Very easy to construct using common earth-moving equipment. Good resistance to freeze/thaw and puncture.

Disadvantages: The proposed reservoir slopes may need to be flattened to allow the use of a relatively low strength CCL. The critical criterion is availability and proximity of suitable clay material. Exposed CCL is prone to desiccation cracking and requires soil cover.

Polypropylene (PP)

PP is a thermoplastic and geomembrane application. PP is a fairly new material used in dam design and rehabilitation. PP geomembranes are often formulated with additives to make the material more flexible, often depicted as fPP or reinforced with a non-woven geotextile scrim reinforcement depicted as RPP or PP-R. Only six dams worldwide are known to incorporate PP geomembranes as seepage reduction devices as of 2006, the oldest of which was installed in 1995 [ICOLD 2010].

Advantages: PP geomembranes have good appearance, seepage control, durability and are relatively easy to install. Vendor literature indicates good resistance to freeze/thaw and UV radiation.

Disadvantages: Installations on dams have been limited in number. Little service life data is available. Seaming of PP sheets is relatively more difficult due to the high crystallinity of the material. Testing indicates PP conforms to underlying substrate, but exhibits moderate puncture resistance and poor elastic recovery [USACE 1995].

Chlorosulfonated polyethylene (CSPE)

CSPE is commonly marketed under the trade name “Hypalon™”. CSPE is a thermoplastic rubber comprised of blended materials that can be heat seamed during initial installation but vulcanizes as it ages, and becomes more rigid. Floating covers formulated from CSPE are often used for potable water reservoirs. Only nine dams worldwide are known to use covered or exposed CSPE geomembranes. The oldest covered application dates back to 1986. The oldest exposed application dates back to 1981 [ICOLD 2010].

Advantages: CSPE geomembranes have good appearance, seepage control and strength characteristics; very good resistance to oxidation, UV radiation, and freeze/thaw.

Disadvantages: Installations on dams have been limited in number. Installation and repairs are relatively more difficult as sheets are joined via chemical fusion with solvents. Thermal seaming is also possible during initial installation. Exposure to excess solvents during installation weakens adjoining sheets. USACE [1995] testing indicates CSPE conforms to underlying substrate but has moderate puncture resistance and poor elastic recovery.

Geosynthetic clay liner GCL

GCLs consist of powdered or granulated bentonite clay bonded between two non-woven geotextiles. GCLs are most popular in design of solid-waste containment systems where a 4.0 mm - 6.0 mm thick GCL yields a permeability equal to or greater than a traditional three-foot thick compacted clay geomembrane. GCLs are typically used in covered applications as the bentonite can be prone to desiccation and subsequent loss in ability to retard seepage. Use of GCLs in dams has been limited. In 2001, a GCL treatment was used on the downstream embankment slope of Idaho Springs Dam in Colorado.

Advantages: Good seepage control characteristics. Relatively simple to install. Sheets are joined by overlapping adjacent pieces and spreading loose bentonite to seal. Loose bentonite should be hydrated during seaming to ensure watertight seal. Adequate puncture resistance. GCLs have the ability to "self-heal" due to additional hydration of the bentonite.

Disadvantages: Installations on dams in the United States are limited. GCLs must be used in conjunction with cover soil layer to prevent desiccation and reduce shrink-swell concerns.

Linear Low-Density Polyethylene (LLDPE)

LLDPE is a thermoplastic geomembrane commonly used in landfill applications but has also been used for seepage reduction on several fill dams. For the purpose of this evaluation, the term LLDPE includes all flexible PE geomembranes that have a lower density than HDPE and includes very low-density polyethylene (VLDPE) and low-density linear polyethylene (LDLPE). LLDPE is not as rigid as HDPE and typically exhibits higher elongation properties. However, use of LLDPE geomembranes in dams have been limited to covered applications. No dams are known to have used an exposed LLDPE geomembrane. The oldest covered LLDPE geomembrane application on a dam dates back to 1970 [ICOLD 2010].

Advantages: LLDPE geomembranes have a proven record of performance regarding seepage control and resistance to UV degradation.

Disadvantages: No known exposed installations on dams. Sheets are joined via thermal seaming and require little set time before exposure to mechanical stresses. Seaming can be difficult due to chemical stability when exposed to heat. The stiffness of LLDPE promotes folding during installation. Vendor literature indicates that experienced specialty contractors should be used to install. Lower strength is a factor that may need to be considered.

High Density Polyethylene (HDPE)

HDPE is a thermoplastic geomembrane most commonly used in landfill applications. HDPE has also been used for seepage reduction on several fill dams. Use of HDPE geomembranes are typically in covered applications due to susceptibility to folds, thermal expansion and contraction of the material, and stress cracking, however exposed applications exist. The oldest covered HDPE geomembrane application on a dam dates back to 1978. The oldest exposed application dates back to 1994 [ICOLD 2010].

Advantages: HDPE geomembranes have a proven record of performance regarding seepage control, good durability and resistance to UV degradation [USACE 1995].

Disadvantages: Seaming can be difficult due to chemical stability when exposed to heat. HDPE is prone to folds and waves during installation, which can cause excess stresses and reduce geomembrane durability [ICOLD 2010]. Vendor literature indicates that experienced specialty contractors should be used to install. USACE [1995] testing indicates HDPE does not conform to substrate, has no elastic recovery, poor puncture resistance, poor repairability and may not be the best choice for some dam applications. Thermal expansion and contraction of the material when exposed can be a problem.

SELECTION PROCESS

It can be difficult to determine the best geomembrane system for a project given the different types of systems and the project specific criteria to consider. USACE [1995] previously developed a rating system for underwater installation of geomembrane systems on concrete structures. A similar rating system was developed by the authors in conjunction with a lifecycle cost analysis to select a geomembrane system for two embankment dam projects. This selection process was recently used for the Bel Air Impoundment located in Bel Air, MD for Maryland American Water. The Bel Air project will be used to demonstrate the liner selection process.

The Bel Air Impoundment is an off-stream pump-storage project that will provide water supply. The dam site has ample fill to construct the reservoir, however the in-situ soils were not conducive to retaining water. A geomembrane system was therefore required for both the interior embankment slopes and the reservoir bottom. Since the geomembrane system is a significant cost to the project, justification of the selected geomembrane system was warranted.

Figure 3. Bel Air Impoundment Rendering.

It was imperative to first determine if the project would have an exposed or covered geomembrane system. Some geomembrane systems perform differently depending on if they are exposed or covered, thus affecting their rating. Exposed systems are often less expensive than covered systems. Selection of an exposed or covered system should be based on technical criteria. An exposed system was selected for the Bel Air Impoundment.

Evaluation Criteria

The general criteria for evaluating geomembrane systems for use as a seepage reduction measure in most dams include the following factors:

1. Appearance
2. Constructability
3. Seepage control
4. Strength
5. Durability
6. Cost

The importance or weight that each factor has on the selection of the geomembrane depends on the exposure conditions, installation configuration, intended purpose of the facility, operation and maintenance performance criteria, material availability, project size, service life of the facility, and owner preferences. A brief discussion of each of the evaluation criteria is presented below. The weighting factors assigned to each of the evaluation criteria are discussed in more detail later in this section.

Appearance. Appearance is normally a standard established to satisfy aesthetic requirements set by owners or local agencies. Geomembrane systems can be used in either exposed or covered applications; appearance only plays a part with exposed geomembranes. Exposed geomembranes are advantageous due to easier access for repairs and lower construction costs, whereas covered geomembranes are often used when geomembrane durability is a concern. The exposed surface frictional resistance should be considered for an exposed application as other means of egress within the reservoir may impact appearance as well. The appearance of the geomembrane system can be very important where public perception of the condition, stability, and safety of the structure is essential. For screening purposes, appearance is categorized as “Good”, “Fair” and “Poor”.

Constructability. Constructability includes an assessment of: (1) the availability of the construction materials and specialized labor required to perform the installation, (2) the impacts that the installation/construction of the geomembrane system has on the overall construction schedule, (3) the complexity of the construction techniques needed to install the geomembrane system and (4) the complexity of the construction techniques required to connect two dissimilar geomembrane types in the event that the reservoir side slopes warrant a different geomembrane than the reservoir bottom. For screening purposes, constructability is categorized as “Routine”, “Moderate” and “Difficult”.

Seepage Control. Geomembranes are not fully impermeable and cannot be installed on a large area without flaws. Seepage must be evaluated as part of the design and addressed with seepage collection and/or detection. USBR [2014] provides guidance for seepage evaluations. Key factors related to seepage control include strength characteristics, the permeability of the geomembrane, whether or not the geomembrane is drained or undrained, and the performance of the geomembrane should the embankment experience minor movements or settlement. For screening purposes, seepage control is categorized as “Good”, “Fair” and “Poor”. Details of the seepage collection system for Bel Air Impoundment is presented in Scrafford et al (2018).

Strength. The loading on a geomembrane system is governed by the surface friction of the geomembrane and adjacent materials, moisture content and water pressure within the underlying embankment, and resistance to bending. The anticipated fluctuation of a reservoir pool will inflict variable stresses on the exposed geomembrane. Any irregularities in the underlying substrate may concentrate those stresses and cause a puncture failure. A geomembrane’s puncture resistance, conformance to the underlying and overlying substrate, and elastic recovery are the main considerations when evaluating the strength criterion. For screening purposes, strength is categorized as “Good”, “Fair” and “Poor”.

Durability. Durability can be influenced by a number of site specific factors including (1) chemical attack, (2) solar radiation, (3) thermal expansion and contraction, (4) wave and ice loading, (5) freeze/thaw cycles, (6) resistance to wind uplift, (7) suitability for potable water use over the project’s life (NSF/ANSI 61 certified) and (8) vandalism. Other durability considerations include maintenance requirements and the anticipated service life of the geomembrane. Durability includes an assessment of what would be involved to repair or replace the geomembrane system should a defect in, or failure of, the geomembrane occur. For screening purposes, durability is categorized as “Good”, “Fair” and “Poor”.

Cost. The cost of the various geomembrane systems was not evaluated as part of the initial screening. Preliminary cost estimates for the top-rated geomembranes were developed and analyzed.

Evaluation Criteria Weighting Factors

The weighting factors should be project specific and modified based on a project’s specific requirements. For example, the importance of the appearance can easily vary depending on the projects location. The primary function of the Bel Air Impoundment was to maintain dependable water supply during a period of prolonged drought. The reservoir is expected to experience numerous cycles of filling and emptying for which the duration is extremely variable. Therefore, the most important selection criteria for selecting a geomembrane system for this project are seepage control, strength and durability. Although important, constructability was considered a secondary criterion. Appearance was judged to be the least important selection criteria. Cost was not included in the preliminary screening. The weighting factors and rating system selected for screening the geomembrane systems for the Bel Air Impoundment are summarized in Table 1.

Table 1. Point Rating System Used to Evaluate Geomembrane Systems

Evaluation Criteria	Weighting Factor	Point Rating
Appearance	1	Good = 3 pts., Fair = 2 pts., Poor = 1pt.
Constructability	2	Routine = 3 pts., Moderate = 2 pts., Difficult = 1 pt.
Seepage Control	3	Good = 3 pts., Fair = 2 pts., Poor = 1pt.
Strength	3	Good = 3 pts., Fair = 2 pts., Poor = 1pt.
Durability	3	Good = 3 pts., Fair = 2 pts., Poor = 1pt.

Numerical Screening of Geomembrane Systems

The numerical screening approach applies a point rating to each evaluation criteria, and the applicability of each criteria is then weighed against its overall importance. The total points for each criterion are summed to obtain a final score. The geomembrane systems with the highest scores represent those systems that are judged to be the best candidates for that particular project. A total of nine geomembrane systems listed previously were screened by this approach. This includes non-polymeric geosynthetic clay liner (GCL) and compacted clay liner (CCL) systems. Table 2 presents a numerical screening example.

Table 2. Numerical Screening Example

Evaluation Criteria	Weighting Factor	Point Rating	Point Total
Appearance	1	Fair = 2	2
Constructability	2	Routine = 3	6
Seepage Control	3	Good = 3	9
Strength	3	Good = 3	9
Durability	3	Poor = 1	3
Total	-	-	**29**

Based on the evaluation and criteria established for the Bel Air project, the PVC and bituminous geomembranes were the highest scoring geomembrane systems. Both systems are proven effective and durable seepage barriers. Consideration was also given for combining one of these geomembrane systems with one or more of the other geomembrane systems (e.g., installing a PVC geomembrane on the embankment slopes and a GCL on the reservoir bottom).

LIFECYCLE COST ANALYSIS

Costs must be considered before making a final selection. Initial installation costs should be considered as well as lifecycle costs. Manufacturers of the top scoring geomembrane systems were contacted to obtain details of their systems and obtain costs to develop initial installation costs and to perform a lifecycle cost and value comparison. It is important to collaborate with the owner to complete the lifecycle cost analysis to determine the importance of cost, expected service life of the facility and maintenance expectations.

The service life of the Bel Air Impoundment was selected by the owner to be 100 years. Therefore 100-year lifecycle costs for the PVC and bituminous geomembranes were estimated for comparison. The service life of each geomembrane system is unique. Performing a lifecycle cost analysis is a good way of comparing life cycle costs of geomembranes with different service lives. It is necessary to include an initial installation cost and periodic replacement costs of the geomembrane system over the service life of the project if the service life of a geomembrane is less than 100 years.

Replacement should consider costs associated with draining and cleaning the reservoir, removing the existing geomembrane, system warranties and performance guarantees, engineering, bidding, and construction management. These assumptions and replacement costs will vary for each project. Replacement costs may require draining and cleaning the reservoir, which may be an unacceptable operating condition as the reservoir would be out of service during the liner replacement work.

Since the lifecycle cost analysis and present worth calculations are dependent on the assumed inflation rate and interest rate, an inflation rate is assumed along with a range of interest rates. This approach shows the sensitivity that the assumed inflation rate and interest rate can have on the analysis. The results of a sample analysis are presented graphically on Figure 4.

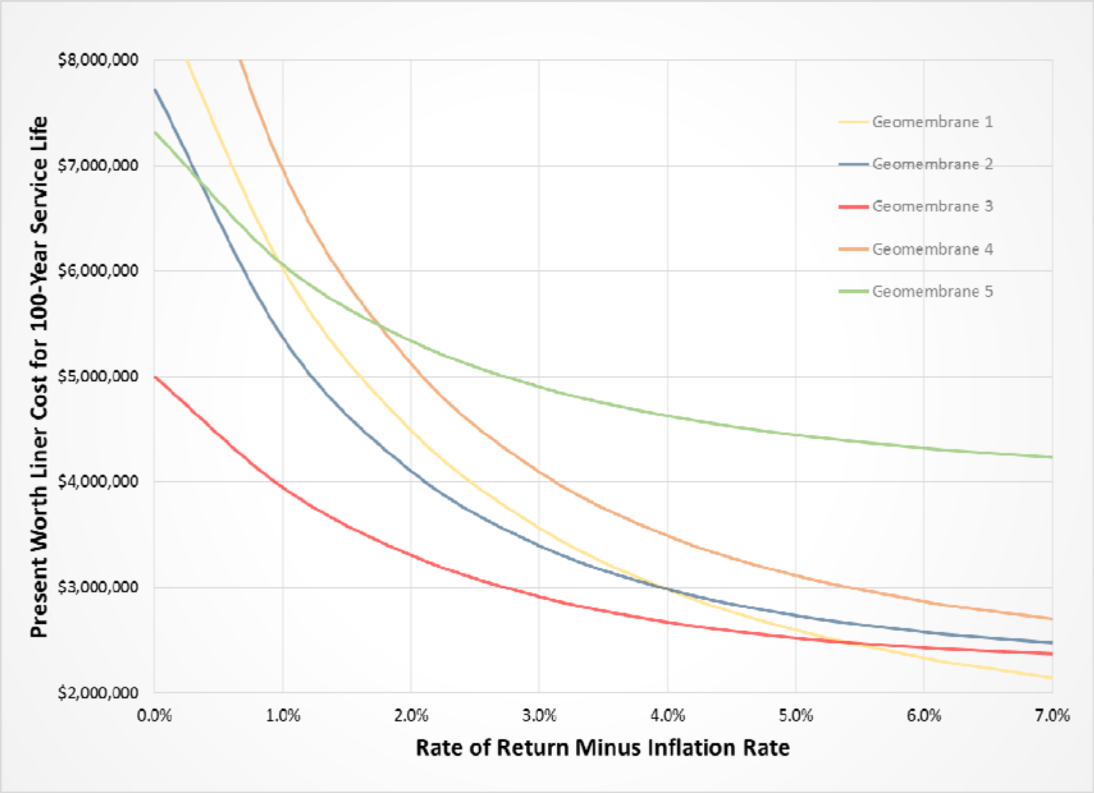

Figure 4. Lifecycle Cost Analysis for the Bel Air Impoundment

As shown in Figure 4, the cost varies depending on the interest rate or rate of return. It is essential to recognize that the lifecycle cost analysis is unique to each project and results can vary greatly between them. As a result of the life-cycle cost analysis for the Bel Air Impoundment, the owner selected a bituminous geomembrane manufactured by Axter Coletanche Inc..

C.W. BILL YOUNG REGIONAL RESERVOIR EXAMPLE

The C.W. Bill Young Regional Reservoir owned by Tampa Bay Water is a pump-storage reservoir located near Tampa Bay, Florida. While this project is very similar to the Bel Air Impoundment in some ways, the project and site conditions are vastly different. A covered geomembrane system was selected at this site. Project and site conditions such as hurricane-force winds, wave action, and alligator activity warranted a covered application. A PVC geomembrane manufactured by Carpi USA Inc. was selected for this reservoir through a similar selection process as previously discussed.

The geomembrane installation included an anchor trench at the top of the embankment and an anchor trench to tie into a soil bentonite cutoff wall at the toe of embankment. The covering over the geomembrane system included a gravel drain installed directly on the PVC geomembrane followed by an application of stair-step soil cement. As a result, the PVC geomembrane included a geotextile on each side to provide sliding resistance and improved puncture resistance during construction. Critical requirements of this geomembrane system were durability, service life, strength, and seepage control.

Figure 5. Aerial View of C.W. Bill Young Reservoir

Figure 6. Aerial View of C.W. Bill Young Reservoir Geomembrane Installation

Figure 7. Photographs Showing C.W. Bill Young Reservoir Geomembrane Installation.

CONCLUSION

There are many features and conditions to consider when selecting a geomembrane. Initially understanding the project and owner requirements up front is imperative. This is essential in determining the evaluation criteria and weighing factors. The initial screening and rating of geomembranes should be based on the technical requirements of the project whereas cost is considered afterwards.

Based on the author’s recent experience with both PVC and bituminous geomembranes, Carpi USA Inc. and Axter Coletanche Inc. provide quality geomembrane products that are used to line reservoirs world-wide and do not appear to have any fatal flaws regarding constructability, durability, and strength.

ACKNOWLEDGEMENTS

It should be recognized that each project should be analyzed individually and that the rating system and lifecycle cost analysis can vary significantly depending on the site conditions and the owner’s requirements. This paper is not intended to cover or represent every geomembrane system available for use on dams.

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