UNDERWATER GEOMEMBRANES – TWO INSTALLATIONS A WORLD APART

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ABSTRACT

Case histories are presented of two underwater Geomembrane installations, one in Singapore and one in Baku, Azerbaijian, both public projects. Both projects had design influence from experiences gathered from construction techniques with underwater applications in the Netherlands.

The Geomembrane uses were in a near zero head differential leak environment, i.e. transmission of contaminants were minimized by placing a low permeability barrier against a berm to maintain a clean environment on the opposite wall.

Insitu installation of a Geomembrane barrier is obviously difficult and required special techniques using a material with a specific gravity >1.0. Material selection and subsequent deployment/installation are discussed for both projects.

1. INTRODUCTION

Landfilling capacity in the tiny tropical nation of Singapore became a concern in the 1980's. Land was scarce and growth was high. A unique solution, proposed by the Ministry of Environment of Singapore, called for an offshore waste disposal facility to contain inert incinerated residue for the next 30 years. Relying on land reclamation techniques long employed in Northern Europe, the facility called for the building of a 7 ½ km earth/aggregate berm in shallow ocean, resulting in an offshore waste pond, and subsequent filling area. The bund was to be lined with a Geomembrane and much of the installation would be underwater.

On the other side of the world, in Azerbaijian, a remediation project needed aggregate dams to isolate portions of a polluted lake as part of the project. The dams were in the lake, and as part of the effort to minimize cross flow, a Geomembrane was used as a component structure. Two dams were constructed, and both required the underwater installation of a Geomembrane along the face of the dams. The project was fast-tracked in preparation for the Baku European Games 2015, which faced the lake to be remediated.

2. UNDERWATER GEOMEMBRANE INSTALLATION TECHNOLOGY

Since the beginnings of the Geomembrane industry in North America in the 1950's, much attention, or curiosity, has been directed toward insitu installations. That is, the ability to line in the "wet", often correcting insitu problems. Initially, it was assumed that these engineered membranes could only be used as a direct replacement of hard shell or natural alternatives, and this could only be done in the "dry". For the most part, this has been true for all applications due to the inherit difficulty in designing, installing and securing a wet Geomembrane installation.

Underwater Geomembrane installations have historically been considered to be flow reduction features rather than absolute containment. As with the North American Geomembrane industry itself, methods were sought to install liners in water conveyance and containment structures, particularly along dam faces. The U.S. Army Corps of Engineers and the U.S. Bureau of Reclamation have been forerunners of these applications, but they have been limited due to installation techniques and project success. Mechanical sealing below the water surface is common but expensive and difficult. Often, edge securing has required divers and special apparatus to sink and secure. Higher specific gravity products such as PVC and specialized non-Polyethylene materials have been most common.

In the Benelux region of Europe, the technology of dewatering and underwater sealing has been more prominent. Dam face linings have been documented for 25 years, often with the same limitations of those elsewhere. However, some installations in the Netherlands have been successful in securing an underwater zone to allow sheet-pile installation and long term dry containment (van Regteren, 2005). These installations have been used in transportation applications where the primary purpose was as a hydraulic barrier, only. Here, hydraulic conductivity sought to be minimized understanding the limitations of the barrier concept. Further, these installations and those in North America presented a configuration where the Geomembrane was either 1) Under substantial head differential, or 2) was used as a component of a dewatering project. Water quality or chemical resistance has not been a prominent design consideration previously.

3. SITE DESCRIPTIONS

Two underwater Geomembrane installations are addressed in this paper. The following is a description of each.

The Palau Semakau Ash Disposal Site is located in Singapore and was constructed in 1995-1999. It was designed by Camp, Dresser and McKee Intl, Singapore and Specs Consultants Pte., Ltd, Singapore and is still operating in 2016. The site was 350 ha total with a 7 ½ km Perimeter Bund 7 ½ km. The Bund interior was to be lined with a low permeability barrier.

This project was a land reclamation effort to secure new disposal space for municipal solid waste incinerator ash generated within Singapore. Two small islands, Semakau and Seking were connected by constructing a 7 ½ km berm as shown in Figure 1. The area consisted of shallow reefs and lent itself well to marine construction with underlying marine clays overlaying rock with hydraulic permeabilies <10^{-8} cm/sec. The perimeter bund established the site area and allowed the ultimate dewatering process to occur. Interior dikes were built for operation of individual disposal cells.

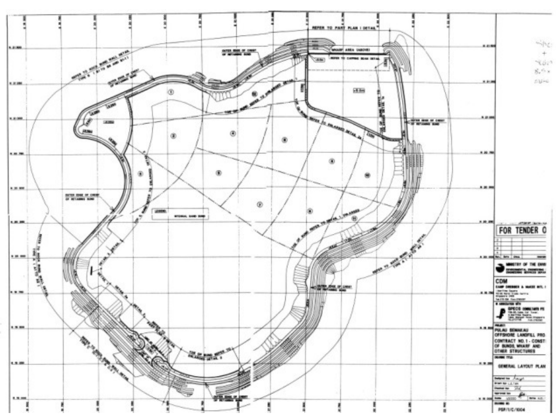

Figure 1: Palau Semakau Site Layout

The Boyukshore Lake Restoration Phase I is located in Baku City, Azerbaijan and was constructed in 2014-2015. It was designed by Witteveen + Bos, Deventer, Netherlands and was completed in 2015.The site is 1060 ha total, with dike (dam) lengths of1570 m and 1850 m. Rock dams were constructed and lined with a Geomembrane.

Boyukshor lake is the second largest lake in Azergaijan. It is oval shaped, 1060 ha surface area with an average depth of 3 ½ meters. It is fed primarily from groundwater and adjacent runoff. The lake has been heavily polluted from adjacent oil production and municipal/construction wastes on the Northern shore primarily, dating back to 1866. By 2004, the pollution of the lake, in conjunction with its central location (Figure 2) reached a new awareness as Baku was selected to be the host of the 2015 European Games. Further, the main venue site was proposed to be at the eastern shore of Boyukshor Lake. Site restoration required that portions of the lake be isolated, allowing the 300 ha closest to the proposed Olympic Stadium to be rehabilitated. Two dikes (dams) were to be constructed:

- North Dam: 1850 m along northern shore (most contaminated area)
- Road Dam: 1570 m connecting north and south shores and also serving as a 6-lane highway connector.

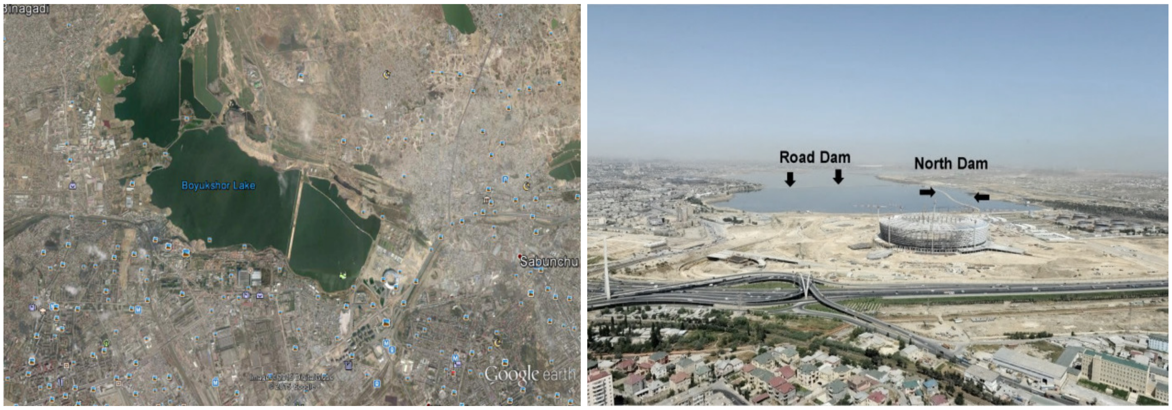

Figure 2: Boyukshor Lake Location with Dams

4. PROJECT DESIGN/INSTALLATION

4.1 Pulau Semakau/Geomembrane

The purpose of the perimeter bund was to establish site boundaries to allow eventual disposal cell construction within the bund area. Hydraulic modeling by Tan, et al, showed that significant leakage rate potential reductions could be achieved using a Geomembrane as opposed to a single clay layer of a clay layer and a GCL. Figure 3 illustrates the conclusions drawn as a result of this modeling effort.

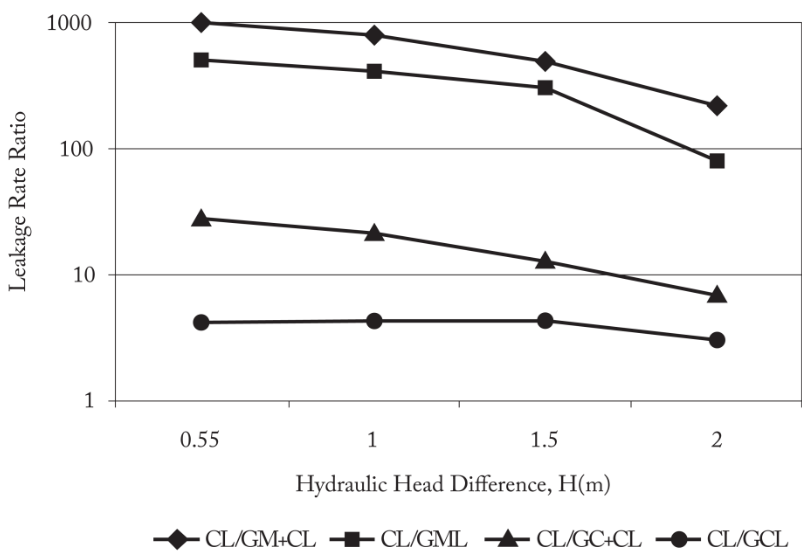

Figure 3: Results of Modeling with Various Lining Systems (Tan, et al)

This figure compares the lining alternatives on the basis of Leakage Rate Ratio, which is defined as:
Leakage Rate Ratio = $Leakage_{NO\ Liner}$ / $Leakage_{Liner}$
Note also the following designations:

CL/GCL – Clay liner/Geosynthetic Clay Liner
CL/GC + CL = Clay Liner/Geosynthetic Clay Liner + Clay Liner
CL/GML – Clay Liner/Geomembrane Liner
CL/GM + CL – Clay Liner/Geomembrane liner + Clay Liner

A GCL was shown to be 5-30 times better than clay alone, a Geomembrane liner 50-100 times better and a Geomembrane with clay was 200-1000 times better. The ranges are dependent on head conditions. The intended operating conditions for the facility was to keep water levels neutral on each side of the berm, i.e. the pond levels will be kept at or near sea level. Steady state conditions were assumed although Figure 3 does consider some amount differential head. By employing the selected barrier alternative of a Geomembrane in conjunction with a 2m dredged clay layer, it was assumed a bund could be constructed with very low permeability. The final cross-section design is shown in Figure 4.

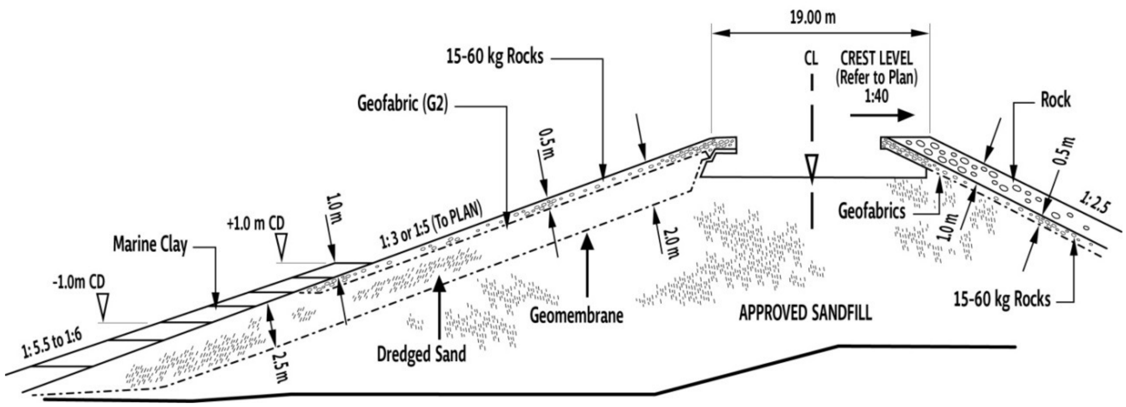

Figure 4: Palau Semakau Bund Site Plan and Cross-section with Geomembrane

With the Geomembrane/clay layer as the selected alternative, a material selection then concentrated on constructability. Field seaming and the use of large mechanical equipment for panel placement had to be minimized due to site constraints. There were two installation scenarios, one was a dry installation in the areas of existing land and the other involved a wet installation, where the Geomembrane would be installed from a barge into the ocean leading to the land. Three types of geomembranes were considered:

- Reinforced Coated Fabric: Ethylene Co-Polymer Alloy (EIA-RCF)
- Reinforced Laminates: Polypropylene and Chlorosulfonated Polyethylene (PPE/CSPE)
- Unreinforced Films, primarily High Density Polyethylene (HDPE)

In the evaluation of constructability, the weights of the panels, along with associated friction angles for the considered materials are contained in Table 1.

Table 1: Geomembranes Evaluated for Constructability Issues

Material Type	Thickness	Panel Weight	Friction Angle GM/Asphalt	Friction, Tan S GM/Asphalt
EIA-REC	1 mm	30.3 KN	22^o	0.404
PPE/CSPE	0.9 mm	32.6 KN	25^o	0.466
HDPE	2 mm	45.5 KN	18^o	0.325

The following is a description of the constructability concerns under both the Dry and Off Shore Deployment:

4.11 Case 1: Dry Deployment

In the first (dry) construction scenario, published friction angels were used to determine a theoretical safety factor when dragging the Geomembrane into place:

Assume: Impact Load Factor (Dynamic) = 1.1
1-meter clamp bar @ tug points (worst case)
F_{TP} = Force Tug Point = (Panel Weight x Tan S x Impact Load Factor) / No. of Tug Points
$F_{allowable}$ = Yield Tensile Strength
Calculate Factor of Safety (F.S.) in onshore dragging operation:
F.S. = $F_{allowable}$ /FTP

Table 2 summarizes the Force Tug Point/Allowable Force and Factor of Safety for each of the considered materials.

Table 2: Summary of Forces and Safety Factors for Dry Deployment Scenarios

Material Type	F_{TP}	$F_{allowable}$	F.S.
EIA-RCF	4473 N/m	96,300 N/m (550 lb/in)	21.5
PPE/CSPE	5570 N/m	35,000 N/m (200 lb/in)	6.3
HDPE	5422 N/m	16,800 N/m (100 lb/in)	3.1

All geomembranes considered in this dry scenario analysis have safety factors greater than unity. However the EIA Coated Fabric was 3 times as reliable as the laminated materials and 6 times as reliable as the HDPE film in this analysis. These conditions of course represent worst case, but are representative of the possible forces to be encountered in this field operation.

4.12 Case 2: Off Shore Deployment
Figure 5 illustrates the forces anticipated in deploying and placing the Geomembrane in the wet installation scheme:

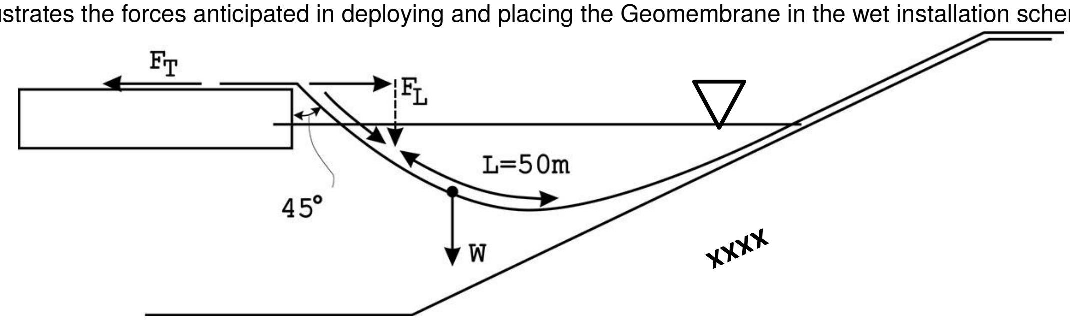

Figure 5: Forces Anticipated in Deploying and Placing Geomembrane in Wet Installation

F. S. =$F_{allowable}$ / F_{TP}
Where, $F_{allowable}$ = Yield strength of Geomembrane
F_{TP} = (w x Impact Load Factor) / (Tan 45^o x No. of Tug Points)
Where w =Buoyant Weight of Geomembrane = Geomembrane area (50 m x 20 m) x B_{wu}
Where B_{wu} = Buoyant Geomembrane Unit Weight
F_L = Force of Geomembrane in Water
F_T = Force of Geomembrane on Barge.

Note: Assume ballast is added to provide $HDPE_{SG}$ = 1.2
Table 3 summarizes the forces and theoretical safety factors for each material. While all exceed 1.0, The EIA-RCF Geomembrane exceeds the other materials.

Table 3: Summary of Forces and Safety Factors for Wet Deployment Scenario

Material	B_{wu}	F_{TP}	F. S.
EIA-RCF	21.5	1,050 N	91.7
PPE/CSPE	6.29	1,633 N	21.4
HDPE	3.1	544 N	30.9

Based on the constructability analysis, the following construction features were essential in the selection of the Geomembrane:

- A portion of the Geomembrane would be installed underwater and therefore a Specific Gravity >1 was needed.
- Ultimately clay and rock would overly the Geomembrane which could result in some damage. A material was needed which would be most resistant to puncture.
- Large panels were needed which could be custom pre-fabricated based on both width and length. Field preparation of the material for fitting was to be minimized or eliminated.
- Overlapping rather than field seaming was to be used and then covered with the marine clay layer. Width was to be maximized in order to minimize the amount of overlapping.
- Panel seams were to have maximum strength to withstand dragging and placement in the tropical environment, often under sustained loading. Abrasion strength was to be sufficient for installation.

The project designers created a specification that demanded the properties, listed in Table 4. Ultimately, the supplied Geomembrane was a Reinforced Ethylene CoPolymer (EIA-RCP), XR-5®, manufactured by Seaman Corporation, USA.

Table 4 summarizes the final Geomembrane project specifications.

Table 4: Project Geomembrane specifications

Property Material Type	Requirement Reinforced EIA-RCP Geomembrane
Yield Tensile Strength	250 Kg (550lbs) minimum
Dead Load Seam Strength	ASTM D-751 70 Deg C Pass @ 900 N (210lb), 4 hr. sustained load on seams at elevated temperature
Prefabrication Capability	Prefabrication capability
Fabricated Panel Width	20.5m (100ft) minimum
Fabricated Panel Size	1860 sm (20,000 sq ft) minimum
Specific Gravity	>1.2
Thickness	1 mm (0.040”) nominal

Figures 6 and 7 illustrate Dry and Wet Installation, respectively.

Figure 6: Geomembrane Dry Installation

Figure 7: Geomembrane Wet Installation

4.2 Baku Project/Geomembrane

The purpose of both dams was for separation of clean vs. contaminated lake water. The dams would serve as the separator. Negligible to zero hydraulic head differential was expected so a Geomembrane would serve as a barrier to lateral movement of both water and contaminants. The dams were to be constructed of Quarry run rock due to availability and cost. Dewatering occurred after initial construction of parallel dikes in the case of the Road dam and no dewatering occurred in the construction of the North dam.

For both the Road and North Dams, the design called for a maximum seepage of 100 m^3/day. When compared to the total inflow into the East Lake (that toward the main game site and the first portion of the Boyukshor Lake to be rehabilitated), this was considered acceptable. Because the dams were to be constructed of materials which could not guarantee that this permeability could be met, a Geomembrane was to be installed on the clean side of both dams.

The dams were composed of end-dumped quarry run that was graded into place. In order to isolate the clean/dirty areas, Geomembrane installation had to occur while water levels were neutral. That required a material and technique to install, sink, and secure. The riqours of installation along with Chemical resistance and strength were factors of selection.

Figure 8 illustrates the sequence of Geomembrane installation for both dams. The Road Dam was wider and had a more extensive cross-section as compared to the North Dam. Two parallel bunds were constructed and then the Geomembrane was installed. The Geomembrane had to be heavier than water, have a high modulus, be resistant to hydrocarbons, be able to withstand sustained loaded on the seams in an exposed condition, be able to be seamed into large panels, and be flexible. The selected product was a reinforced Ethylene Copolymer Alloy product, XR-5®, manufactured by Seaman Corporation, USA. The sequence of installation was a modification of a technique previously developed by Genap BV in the Netherlands. The membrane was floated from the berm, sunk and covered with small rocks. A geotextile overlaid the membrane. This technique was used for both the North Dam and the Road Dam. Large panels were brought to the site and field welded together along the berm. Figures 9 and 10 illustrate the final dam cross-sections. Figures 11-14 are photographs of Geomembrane installation for both dams.

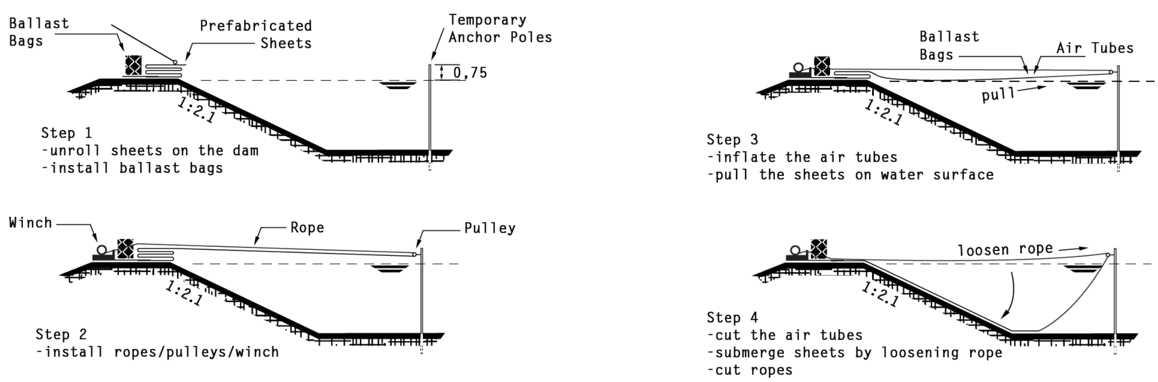

Figure 8: Sequence of Installation for Geomembrane (Genap NV, 2015)

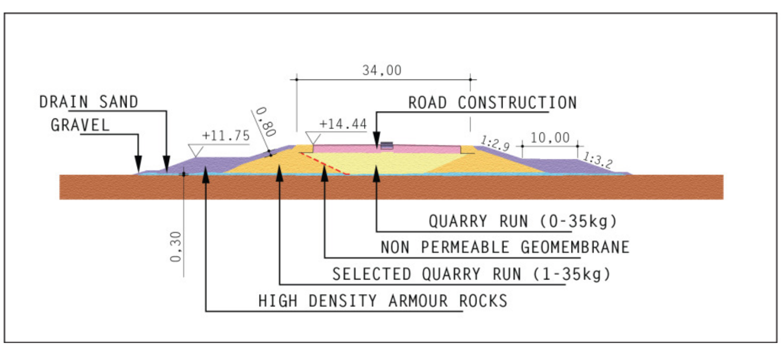

Figure 9: Completed Cross section for Road Dam (van de Enden, 2014)

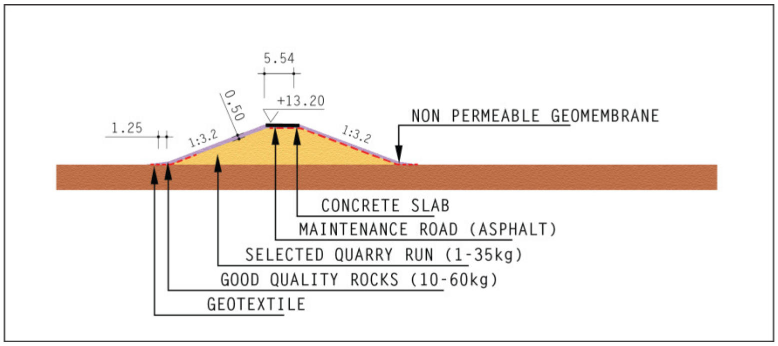

Figure 10: Completed Cross Section for North Dam (van de Enden, 2014)

Figure 11: Deployment of Fabricated panels on North Dam

Figure 12: North Dam Geomembrane Installation

Figure 13: Road Dam Geomembrane Installation

Figure 14: Road Dam Installation

5. PROJECTS COMPARISON/SUMMARY

The projects had more similarities than differences. Both proved that certain geomembranes can be successully integrated into a project where the minimization of cross flow is needed. It also shows that with proper techniques, underwater installation can be successful.

Table 5: Comparison of Palau Semakau and Boyukshore Lake Geomembrane Underwater Geomembrane Projects

PROJECT CHARACTERISTIC	PALAU SEMAKAU	BOYUKSHORE LAKE
Purpose	Minimize hydraulic movement into landfilling area	Minimize hydraulic movement from contaminated into clean enviroment
Location	Offshore	Fresh water lake
Head Differential	Neutral (limited tidal influence)	Neutral
Geomembrane component	Reinforced Ethylene CoPolymer	Reinforced Ethylene CoPolymer
Submerging Technique	Self weight	Self weight/Added Ballast
Placement Technique	Pulled along bottom from berm	Floated from berm and submerged
Overburden	Sand/rocks	Rocks
Field Seams	Overlap only	Heat welds
Geomembrane quantity (SM)	800,000	60,000 – Phase 1
Project Completion	1999	2015

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