RECLAMATION
Managing Water in the West

Design Standards No. 13

Embankment Dams

Chapter 20: Geomembranes
Phase 4 (Final)

U.S. Department of the Interior
Bureau of Reclamation

March 2014

Mission Statements

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Design Standards Signature Sheet

Design Standards No. 13

Embankment Dams

DS-13(20)-16: Phase 4 (Final)
March 2014

Chapter 20: Geomembranes

Foreword

Purpose

The Bureau of Reclamation (Reclamation) design standards present technical requirements and processes to enable design professionals to prepare design documents and reports necessary to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public. Compliance with these design standards assists in the development and improvement of Reclamation facilities in a way that protects the public's health, safety, and welfare; recognizes needs of all stakeholders; and achieves lasting value and functionality necessary for Reclamation facilities. Responsible designers accomplish this goal through compliance with these design standards and all other applicable technical codes, as well as incorporation of the stakeholders' vision and values, that are then reflected in the constructed facilities.

Application of Design Standards

Reclamation design activities, whether performed by Reclamation or by a non-Reclamation entity, must be performed in accordance with established Reclamation design criteria and standards, and approved national design standards, if applicable. Exceptions to this requirement shall be in accordance with provisions of *Reclamation Manual Policy*, Performing Design and Construction Activities, FAC P03.

In addition to these design standards, designers shall integrate sound engineering judgment, applicable national codes and design standards, site-specific technical considerations, and project-specific considerations to ensure suitable designs are produced that protect the public's investment and safety. Designers shall use the most current edition of national codes and design standards consistent with Reclamation design standards. Reclamation design standards may include exceptions to requirements of national codes and design standards.

Proposed Revisions

Reclamation designers should inform the Technical Service Center, via Reclamation's Design Standards Web site notification procedure, of any recommended updates or changes to Reclamation design standards to meet current and/or improved design practices.

Chapter Signature Sheet
Bureau of Reclamation
Technical Service Center

Design Standards No. 13

Embankment Dams

Chapter 20: Geomembranes

DS-13(20)-16:[1] Phase 4 (Final)
March 2014

Chapter 20 – Geomembranes is an existing chapter within Design Standards No. 13 and was revised to include the addition of:

- State-of-the-practice design and construction considerations
- Bureau of Reclamation geomembrane installation case histories
- Removal of extraneous polymeric manufacturing discussion and dated installation techniques

[1] DS-13(20)-16 refers to Design Standards No. 13, chapter 20, revision 16.

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Contents

Contents (continued)

Page

Contents (continued)

Page

Tables

Table ***Page***

Figures

Figure ***Page***

Figures (continued)

Figure ***Page***

Figures (continued)

Figure ***Page***

Chapter 20

Geomembranes

20.1 Introduction

Since the end of World War II, the development of synthetic polymers has allowed a significant amount of new construction materials to become available. These include materials such as geomembranes, geotextiles, geogrids, and plastic pipes. The Bureau of Reclamation (Reclamation) has conducted extensive laboratory and field research on many of these engineered synthetic materials, specifically geomembranes used as seepage barriers in embankment dams or as canal linings.

Since the 1990s, the use of geomembranes has grown dramatically, including applications in water retention dams, water conveyance, tailing dams, hazardous waste containment, solid waste landfills, and heap leaching operations. Although geomembranes provide an effective barrier to seepage, there can still be performance issues due to poor installation, instability of soil covers, faulty connections with appurtenant structures, and strain incompatibility at abutments. The designer should always consider the critical nature of the application and the consequences should the geomembrane fail to perform as intended.

Geomembranes are vulnerable to installation damage, and they can have a finite, useful life. If left uncovered, they typically have a useful life of between 10 and 20 years. If covered, their performance is increased dramatically, but they still may not last indefinitely because of issues associated with degradation due to oxidation and post-installation damage due to root penetration or burrowing animals. They are often not used by Reclamation in critical locations or used as the sole line of defense for controlling or reducing seepage.

20.1.1 Purpose

This chapter is intended to provide design guidance for the use of geomembranes in embankment dams. Geomembranes can be used as seepage barriers in embankment dams or for complete containment of reservoirs. This chapter is not intended to be all encompassing in regard to discussing the different methods used to manufacture geomembranes, their use and applications in other industries, or identifying every geomembrane type currently available on the market.

This chapter does not apply to geotextiles, which are covered in chapter 19 of these design standards.

20.1.2 Scope

The scope of this chapter is limited to (1) providing the reader with a basic understanding of geomembranes and their use for embankment dams and reservoirs, (2) presenting various applications that can be utilized for new and existing embankment dams, (3) presenting typical design considerations, and (4) providing guidelines for specifications and construction considerations.

20.1.3 Deviations from Standard

All Reclamation designs of geomembranes associated with embankment dams or reservoirs should conform to this design standard. If deviations from the standard are required for any reason, the rationale for not using the standard shall be clearly presented in the technical documentation for the geomembrane design. The technical documentation is to be approved by the appropriate line supervisors and managers.

20.1.4 Revisions of Standard

Comments or suggested revisions to this standard should be forwarded to the Chief, Geotechnical Services Division, Bureau of Reclamation, Denver, Colorado 80225 for review and incorporation in this design standard.

20.1.5 Applicability

This design standard is applicable to the use of geomembranes as an impermeable element in embankment dams or reservoirs. The standard covers geomembrane properties, applications, design, construction, and monitoring.

20.2 Geomembrane Materials

Geomembranes are manmade, low-permeability membrane liners or barriers formed into thin sheets used to control the migration of a fluid. A common application of geomembranes includes seepage barriers for geotechnical structures constructed essentially with soil and/or rock such as embankment dams. Geomembrane is a generic term that has been proposed to replace many terms such as synthetic membranes, polymeric membranes, plastic liners, flexible membrane liners, impermeable membranes, and impervious sheets. Compacted earth linings incorporating various types of manufactured or natural additives, and hard surface linings such as steel, concrete, gunite, asphaltic concrete, and soil cement, are not considered geomembranes for the purposes of this design standard.

The types of geomembranes that adhere to the aforementioned definition include those composed primarily of polymeric materials made in a factory, either nonreinforced or reinforced (composite) with a fabric. American Society for Testing Materials (ASTM) D4439 outlines a geomembrane as an "essentially impermeable geosynthetic composed of one or more synthetic sheets." Geomembranes can also include those composed of bituminous products. However, because of their limited use throughout the United States and within Reclamation, they are not discussed in this chapter. For more information related to bituminous geomembranes, refer to the International Commission on Large Dams (ICOLD) Bulletin 135 [1]. Additionally, liners/barriers that are manufactured onsite, such as impregnated geotextiles and sprayed liners, are not discussed in this chapter because of their limited use and requirements for favorable weather conditions during installation. Additional information related to these types of geomembranes can be referenced in ICOLD Bulletin 78 [2]. This chapter focuses primarily on polymer type geomembranes that are manufactured in a factory because of their common use in the United States and Reclamation.

20.2.1 Common Geomembrane Types

The design and specification of a geomembrane requires an understanding of the properties of the polymer used to manufacture the material. For example, the flexibility of the polymers can vary and impact the ease of installation. Polymers degrade with exposure to ultraviolet (UV) light. Therefore, carbon black and other additives are added to the polymer to enhance its resistance to degradation due to exposure to sunlight. Also, a greater thickness increases the expected service life.

Table 20.2.1-1 presents a brief summary of the more commonly used polymeric geomembranes.

20.2.1.1 Covered Geomembranes

Many geomembranes are only intended for covered applications, and when buried, are predicted to last hundreds of years. One report cites a service life in excess of 950 years [1]. Furthermore, covered geomembranes are protected from the numerous elements that may damage exposed liners such as oxidation, abrasion, UV degradation, freeze/thaw, animal intrusion, wind uplift, and vandalism.

20.2.1.2 Exposed Geomembranes

Geomembranes that have been formulated for exposed applications have a typical service life of about 30 years. However, some geomembranes have been in operation for over 30 years on dam faces with little to no loss in the original physical properties.

Table 20.2.1-1. General comments on polymers used in geomembranes [1]

Geomembrane type	Abbreviation	Polymer type	Approximate resin formulation (Percent of total weight)	Comment
High-density polyethylene	HDPE	Thermoplastic	95–98	High resistance to UV and chemical degradation. Can be susceptible to stress cracking.
Linear low-density polyethylene	LLDPE	Thermoplastic	94–96	LLDPE has less resistance to UV and chemical degradation. Slightly more flexible than HDPE. Excellent elongation properties.
Polyvinyl chloride	PVC	Thermoplastic	30–40	Good flexibility at all temperatures. Could degrade quickly depending on plasticizer.
Chlorosulphonated polyethylene	CSPE	Thermoplastic rubber	40–60	Difficult to repair once installed because of vulcanization.
Ethylene propylene diene terpolymer	EPDM	Thermoset	25–30	Excellent flexibility. Seams must be glued and may not be as durable as other membranes.
Polypropylene (flexible)	fPP	Thermoplastic	85–96	Fairly new product and service life not well known, but considered to be flexible and easy to install.

20.2.1.2.1 Plasticized Polyvinyl Chloride

Geomembranes are typically manufactured in rolls with dimensions of width ranging between 6 and 33 feet, lengths of up to 1,000 feet, and a weight of up to 2 tons. Geomembrane rolls can be fabricated to any shape and thickness (30–100 mil). Their size is usually limited by handling or weight considerations. Fabricated panels of flexible geomembranes (such as polyvinyl chloride [PVC] and chlorosulphonated polyethylene [CSPE] geomembranes) can be accordion-folded or rolled for transportation. Stiffer geomembranes (such as high-density polyethylene [HDPE] and linear low-density polyethylene [LLDPE]) are shipped in rolls.

20.2.2 Manufacturing Processes

Smooth or textured geomembranes can be manufactured to be relatively homogenous and are constituted primarily of polymeric materials mixed with other additives as required. Additionally, geomembranes can be manufactured in multiple layers, in different colors, with varying degrees of texturing (single or double-sided), or with reinforcement that can be external or internal to the membranes. The primary purposes for the differing configurations are to either enhance the mechanical properties (e.g., tensile strength) of the geomembranes under consideration or, in the case of multilayered products, to reduce the costs by enhancing the properties of the outer layers only. Additional information can be referenced in ICOLD Bulletin 135 [1] or in Scheirs [3].

The three most common ways of manufacturing geomembranes are listed below:

- Extrusion
- Calendaring
- Spread coating

The manufacturing processes are described briefly in sections 20.2.2.1 through 20.2.2.3. More detailed descriptions regarding the manufacturing process and composition of geomembranes can be referenced in published literature or by visiting manufacture's Web sites.

20.2.2.1 Extrusion

The extrusion process is most commonly used to produce HDPE, LLDPE, and polypropylene (fPP) geomembranes. A molten polymeric compound is extruded through a die to form a sheet of polymeric compound. The molten polymeric compound is driven through the die either by applying pressure on the molten polymeric compound or by using a circular die to form a tube and blowing air inside it.

The extrusion process can also be used to produce textured geomembranes (i.e., geomembranes with a rough surface), which can create a higher friction surface. The four methods used to texture geomembranes include coextrusion, impingement, lamination, and structuring. The most common methods used in the United States are coextrusion and structuring. Either method produces a textured surface that improves the sliding resistance along the interface of a geomembrane and soil. For more information regarding the coextrusion process, refer to Koerner [4].

20.2.2.2 Calendaring

The calendaring process is most commonly used to produce PVC, CSPE, and scrim reinforced (-R) geomembranes, including CSPE-R and fPP-R [4]. A hot polymeric compound passes through a series of heated rollers to form a sheet of polymeric compound. Several sheets of polymeric compound can be calendared simultaneously and associated to form a "multi-ply" geomembrane. This is mostly used to associate polymeric sheets having complementary properties. However, in the 1970s, nonreinforced calendared geomembranes were often composed of two identical plies. The purpose of this process was to minimize the risk of having a pinhole through the entire thickness of the geomembrane.

Pinholes are small holes that can exist in a sheet of polymeric compound as a result of grit or from the manufacturing process. The rollers are usually smooth. However, rollers with a patterned surface are sometimes used to produce geomembranes with a textured surface.

20.2.2.3 Spread Coating

The spread coating process is typically used for producing geomembranes reinforced with geotextiles (a type of geocomposite). With this process, a uniform coating of molten polymeric compound is spread on a woven or nonwoven geotextile. This manufacturing process is rarely used.

20.2.3 Comparison of Geomembranes

20.2.3.1 High-density Polyethylene

HDPE geomembranes are composed of thermoplastic crystalline polymers that are highly resistant to chemicals such as acids, oils, and solvents. Most HDPE geomembranes have between 2 and 3 percent carbon black content to provide UV resistance. They are used extensively in the United States and are very resistant to tearing and puncturing. HDPE geomembranes can be manufactured in numerous dimensions, thicknesses, and colors to facilitate ease of installation.

Conversely, because HDPE geomembranes are semicrystalline, they can be very stiff, especially during cold weather, and could be difficult to install in tight corners. Wrinkles are common due to their high coefficient of expansion. HDPE can expand due to solar heat exposure during installation, which can inhibit seaming operations and placement of protective cover materials. HDPE geomembranes perform well when left uncovered; however, they can be susceptible to stress cracking if the resin is not appropriate. HDPE geomembrane seams must be thermally welded.

20.2.3.2 Linear Low-density Polyethylene

LLDPE, sometimes referred to as very flexible polyethylene (VFPE) geomembranes, is similar to HDPE except that it has a lower density (typically less than 0.94 grams per cubic centimeters). As a result, LLDPE geomembranes are more flexible than HDPE geomembranes and have greater puncture resistance when elongated, but have lower tensile strength [3]. LLDPE has excellent elongation properties, which are critical when differential settlements or rough subgrade conditions are anticipated. They are commonly used in the United States and are somewhat resistant to environmental degradation. LLDPE is often selected rather than HDPE for applications in northern climates due to HDPE's difficulties in cold weather installation and issues with stress cracking. LLDPE is also available in numerous sizes, texturing, and thicknesses to accommodate design and construction needs.

Even though LLDPE is more flexible than HDPE, it is still somewhat stiffer than other products such as PVC, fPP, and EPDM. Therefore, LLDPE could be more difficult to install in tight areas than PVC or fPP. LLDPE geomembrane seams must be thermally welded.

20.2.3.3 Polyvinyl Chloride

PVC geomembranes can also be produced in various widths and thicknesses. Most are unreinforced, but fabric reinforcement has been used. Most PVC geomembranes manufactured in the United States are not formulated for exposed applications such as they are in Europe. PVC geomembranes contain up to 40 percent of one or more plasticizers to make the sheeting flexible [3]. Different plasticizers can be used in PVC geomembranes depending on the application and required service life. Plasticizer loss is the primary reason for PVC geomembrane deterioration. Plasticizer loss results from volatilization due to high temperatures. However, based on observation and testing of PVC geomembranes installed at some Reclamation facilities, PVC geomembranes have performed satisfactory, when covered, with very little loss of plasticizers over time. Also, increased awareness of this problem has resulted in the production of higher quality PVC geomembranes by incorporating high molecular weight plasticizers with low migration rates [5].

PVC geomembranes have good tensile, elongation, and puncture and abrasion resistance properties. PVC geomembranes can be readily seamed by solvent welding, adhesives, and heat or dielectric methods. Due to the flexible nature of PVC and possibly the manufacturing process, the interface friction angle with underlying or overlying soils is generally higher than other smooth geomembranes. PVC geomembranes are widely used in both the United States and Europe. In fact, they are the most widely used geomembrane product in the world in embankment dam applications [1]. Specifically formulated PVC geomembranes (using the highest quality UV stabilizers) are used in exposed dam facings when incorporating additives commensurate with European standards.

20.2.3.4 Chlorosulphonated Polyethylene

CSPE geomembranes are thermoplastic rubbers and are a relatively new class of geomembranes. CSPE geomembranes are processed and shaped at relatively high temperatures when they are plastic; when they are cooled to normal ambient temperatures, they behave like vulcanized rubbers [6]. As with HDPE and LLDPE geomembranes, their seams can be thermally welded. However, their long-term durability is related primarily to floating covers for the last 25 years, and they can be more difficult to repair because of cross linking or vulcanization of the thermoplastic rubber with age.

20.2.3.5 Ethylene Propylene Diene Terpolymer

EPDM geomembranes have excellent resistance to weather and ultraviolet exposure and resist abrasion and tearing. EPDM can tolerate temperature extremes and maintain flexibility at low temperatures. EPDM geomembranes are thermoset polymers; therefore, they require the use of special cements and careful application to assure satisfactory field seaming. Good quality control testing and observation procedures should be in place to assure long-term durability.

20.2.3.6 fPP

fPP geomembranes are made from polypropylene and a thermoset rubber and are flexible, similar to PVC and EPDM geomembranes. They are also considered durable, but can be susceptible to degradation due to organic acids and could potentially crack at sharp bends where exposed [4]. Since they are flexible, they are easier to install than LLDPE and HDPE geomembranes. Similar to HDPE, LLDPE, and CSPE geomembranes, they are thermally welded. However, as opposed to CSPE geomembranes, fPP geomembranes are generally easier to repair.

20.3 Geomembrane Applications for Embankment Dams

The applications of geomembranes for use in embankment dams include the following:

- Impervious facing of embankment dams
- Impervious embankment elements
- Dam raises
- Reservoir lining (commonly referred to as upstream blankets)
- Cutoff walls
- Repair of leaking dams
- Temporary applications (cofferdams and limiting seepage into excavations)

There are a number of other uses for geomembranes in other industries that are not discussed in this chapter and can be referenced in associated textbooks [4, 7, 8, 9].

The performance of a geomembrane depends on the materials in contact with it. Together with the protective cover, drainage layers, and support layer (which may be a drainage layer or a low permeability material), one or several types of geomembranes can be used to form a lining system or seepage barrier. Selection of the lining system is the first phase of leakage control design. In selecting the lining system and its location, the potential leakage rate is the primary consideration, but other considerations, such as impacts to embankment stability, puncture resistance, long-term durability, ease of installation, and long-term maintenance are also very important. These various considerations for designing new embankment dams and for rehabilitating existing embankment dams are discussed below with reference to specific Reclamation projects.

20.3.1 Embankment Facing

Geomembranes can be used to line the upstream face of embankment dams to minimize migration of water through the dam. Figure 20.3.1-1 illustrates two types of applications in which geomembranes were used on the face of embankment dams.

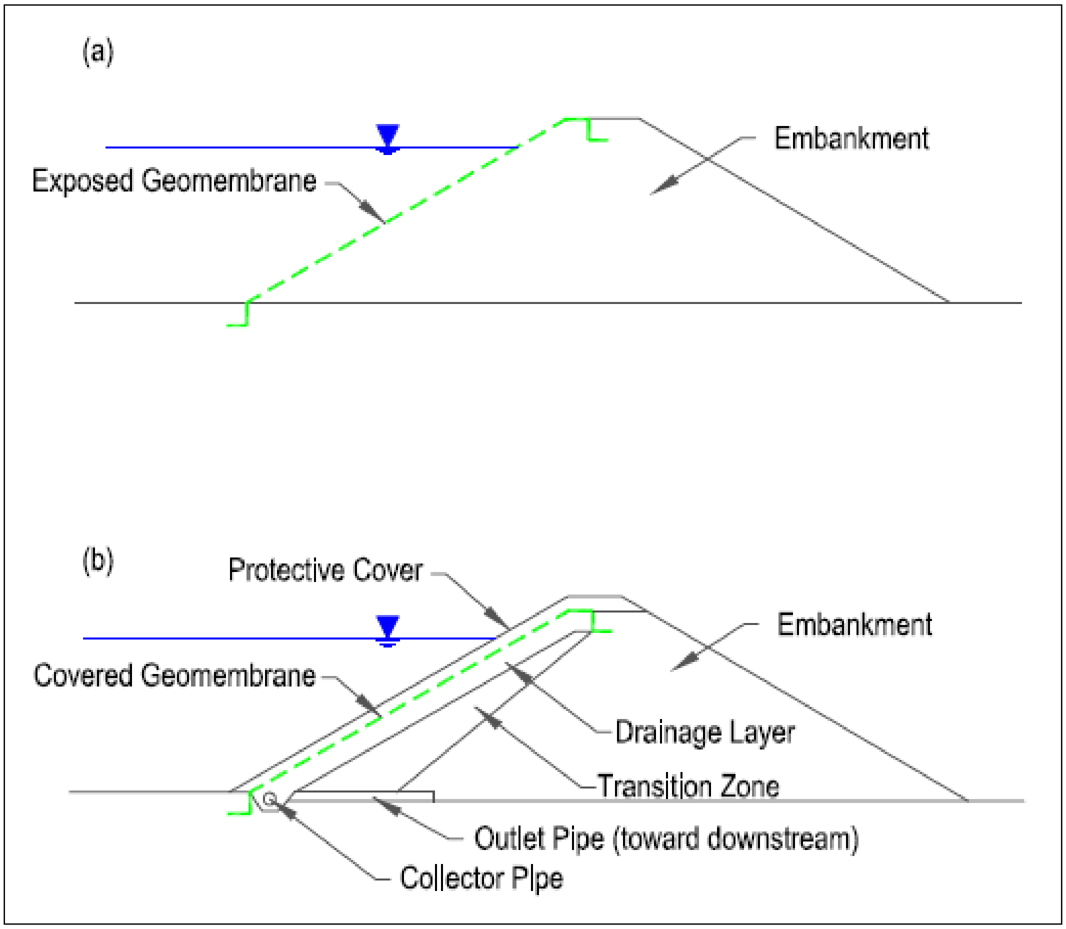


Figure 20.3.1-1. (a) Seepage barrier basic exposed concept and (b) geomembrane system incorporating protective cover and drainage elements.

A negligible amount of leakage occurs through geomembranes as a result of diffusion. A much greater amount of leakage occurs because of defects in the geomembrane. Defects can be due to improper manufacturing (which is now very rare), improper seaming (which is difficult to eliminate totally), and accidental puncture (which is always possible). Leakage due to potential defects must always be considered in the design; however, tie-in to the abutments and upstream toe is typically the major source of leakage. Therefore, the material underlying the geomembrane must be permeable enough to evacuate water that migrates through the geomembrane. If water were allowed to accumulate under the geomembrane, it could uplift the geomembrane during rapid drawdown of the reservoir. The presence of a protective soil layer overlying the geomembrane can minimize uplift, but may not be sufficient to prevent it completely.

On figure 20.3.1-1a, the geomembrane is used as a single liner on the upstream face of the dam. At the crest and toe of the upstream face, the geomembrane is either anchored in a trench backfilled with compacted soil or connected to a concrete beam or simply ran out horizontally (the concrete beam at the toe of the dam may be underlain by a cutoff wall). The advantage of runout versus anchoring is that the geomembrane is subject to less tensile stress. This basic cross section has been used in many dams in the United States and Europe [1].

Many installations utilize a geomembrane underlain by a drainage layer and overlain by a protective cover. A typical cross section of a dam with a covered geomembrane at the upstream face is shown on figure 20.3.1-1b. One or more transition layers (filter zones) may be required between the drainage layer and the embankment. In some cases, a double liner may be desired to monitor leakage or to provide a redundant seepage barrier. This is considered more of a preference rather than a requirement, and the benefits versus cost should be carefully evaluated.

20.3.1.1 McDonald Dam

The McDonald Dam modification was designed by Reclamation for the Bureau of Indian Affairs (BIA) and is an example of the utilization of a geomembrane for upstream facing. The homogeneous earthfill embankment is 1,500 feet long at crest elevation 3604, has a structural height of 49 feet, and impounds 8,225 acre-feet of water. A seepage barrier system was constructed on the upstream slope of the earthfill embankment between elevations 3545 and 3601. The system consisted of a primary barrier (geomembrane) underlain by a secondary barrier (compacted clay liner). The seepage barrier is shown on figure 20.3.1.1-1 and consists of, from top to bottom: (1) riprap, (2) geomembrane cover material, (3) textured geomembrane (60-mil [VFPE]), (4) geotextile (10 ounce per square yard [oz/yd^2] nonwoven), (5) bedding material, (6) compacted clay liner (impervious earthfill), and (7) filter material.

Installation of the seepage barrier system is shown on figure 20.3.1.1-2.

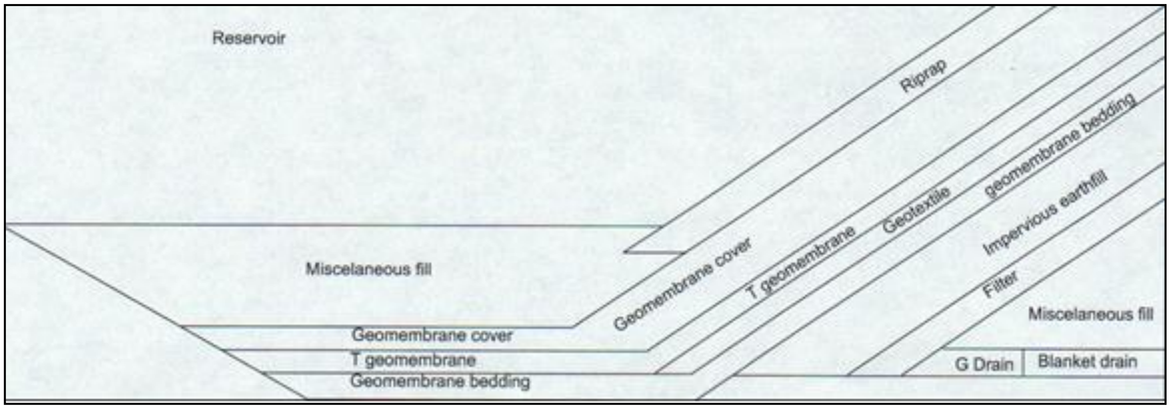


Figure 20.3.1.1-1. McDonald Dam upstream seepage barrier facing components.

Figure 20.3.1.1-2. (a) Geomembrane deployment, (b) geomembrane and cover material, (c) geomembrane cover placement, and (d) completing pre-welds (or test welds) prior to installation of geomembrane sheets.

20.3.2 Embankment Core

Geomembranes can replace or augment impervious cores (zone 1). This can be achieved by placing the geomembrane inside the dam instead of on the upstream face. In other words, the geomembrane serves as a substitute to the impervious element of an embankment dam. Four possible applications are shown on figures 20.3.2-1 through 20.3.2-4. The geomembrane core shown on figure 20.3.2-1 is constructed after completion of the embankment by excavation of a trench supported by bentonite slurry followed by insertion of geomembrane panels connected by a special technique. This technique is described in section 20.3.4 for the design and construction of cutoff walls.

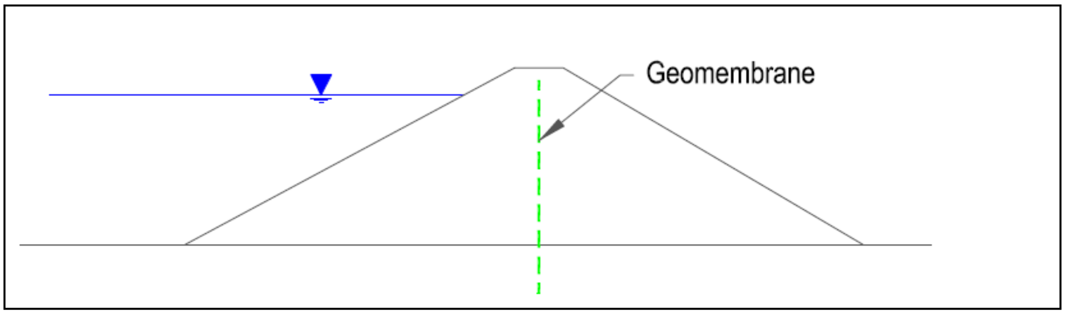


Figure 20.3.2-1. Vertical seepage barrier using geomembrane panels.

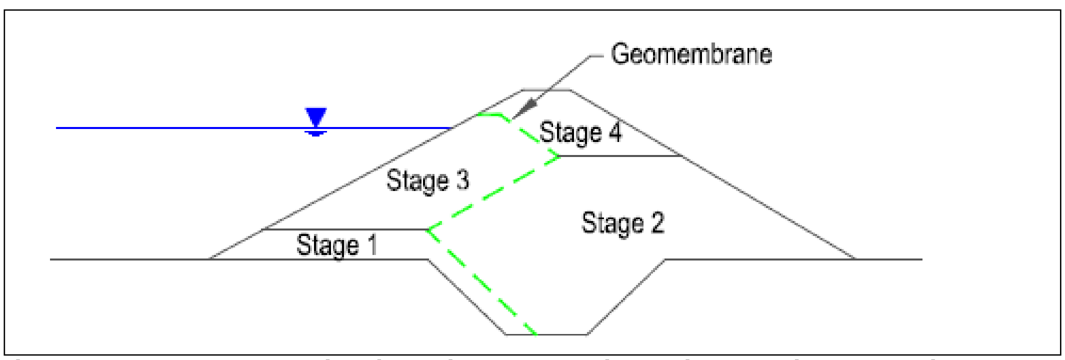


Figure 20.3.2-2. Seepage barrier using geomembrane in staged construction.

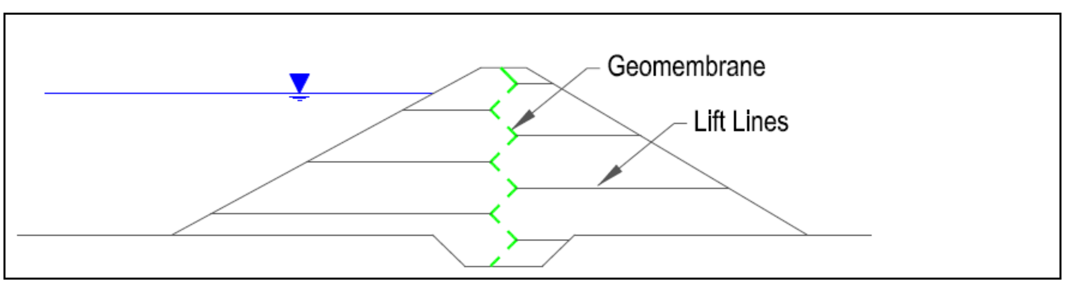


Figure 20.3.2-3. Seepage barrier using geomembrane in lift construction.

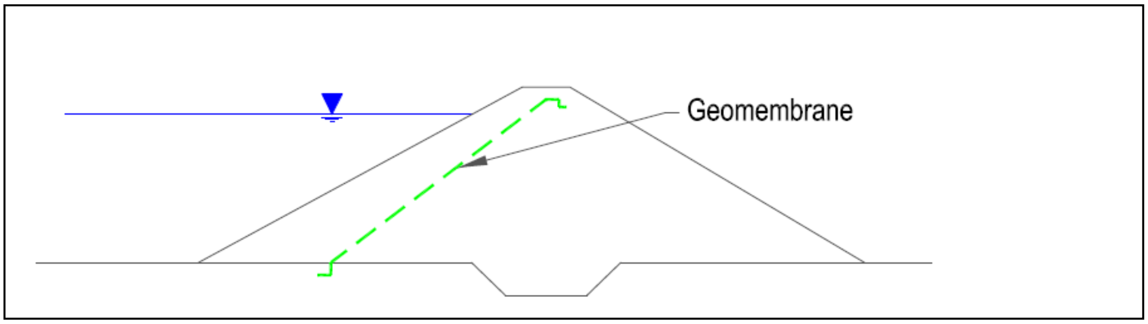


Figure 20.3.2-4. Seepage barrier using geomembrane in the upstream shell.

Alternatively, the geomembrane core can be constructed as the embankment construction progresses. A typical cross section is shown on figure 20.3.2-2. The embankment is constructed in several stages and, at the end of each stage, the geomembrane is placed and seamed to the geomembrane in the previous lift. The location of the geomembrane should be such that it does not create a slip surface for the upstream as well as the downstream slope. A textured geomembrane should be considered if this is an issue. A zig-zag shape such as that shown on figure 20.3.2-3 is sometimes considered to minimize the surface area of a geomembrane and allows for embankment settlement with minimal stress to the geomembrane. However, it is not recommended because it can be difficult to construct and does not significantly decrease the geomembrane surface area compared to the cross section shown on figure 20.3.2-4. It should be noted that all of these types of installations make it very difficult to repair the geomembrane once embankment construction is complete. It is recommended that redundancies such as filters and drains or other impervious elements be included with these types of installations to mitigate potential internal erosion concerns and that the geomembrane not be relied upon to be the sole line of defense. Depending on site-specific conditions and consequences, additional engineering controls may be required.

Geomembranes can also be used with traditional construction techniques to raise the crest of embankment dams. Two examples are illustrated on figure 20.3.2-5. In any of these cases, it is essential that the geomembrane does not promote the development of a slip surface. Therefore, stability analyses (section 20.4.10) must be performed to properly select the location and type (e.g., textured versus smooth) of geomembrane.

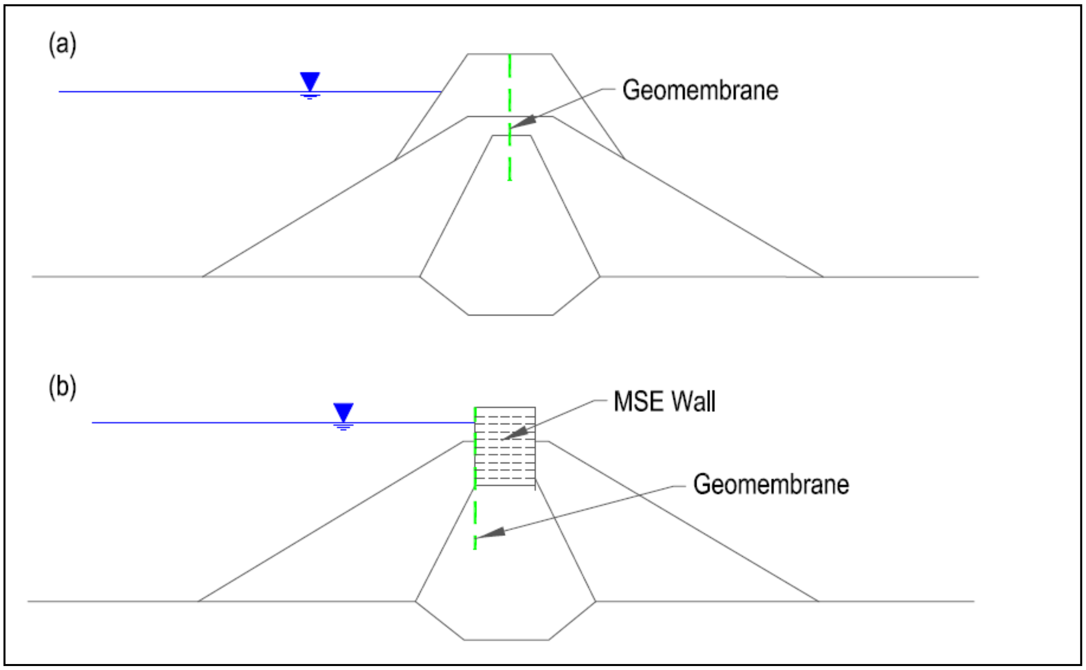


Figure 20.3.2-5. Dam raise using geomembrane: (a) vertical geomembrane installed into existing zone 1 core and (b) mechanically stabilized earth wall with vertical geomembrane facing installed into existing zone 1 core.

20.3.2.1 Pactola Dam

Pactola Dam is an example of a Reclamation dam that integrates a geomembrane into a dam raise. The zoned earthfill embankment is 2,236 feet long at crest elevation 4655, has a structural height of 245 feet, and impounds 99,000 acre-feet of water. A portion of the earthfill embankment was raised approximately 15 feet and incorporated an inclined 40-mil HDPE geomembrane, which tied into the existing zone 1 core material as shown conceptually on figure 20.3.2.1-1.

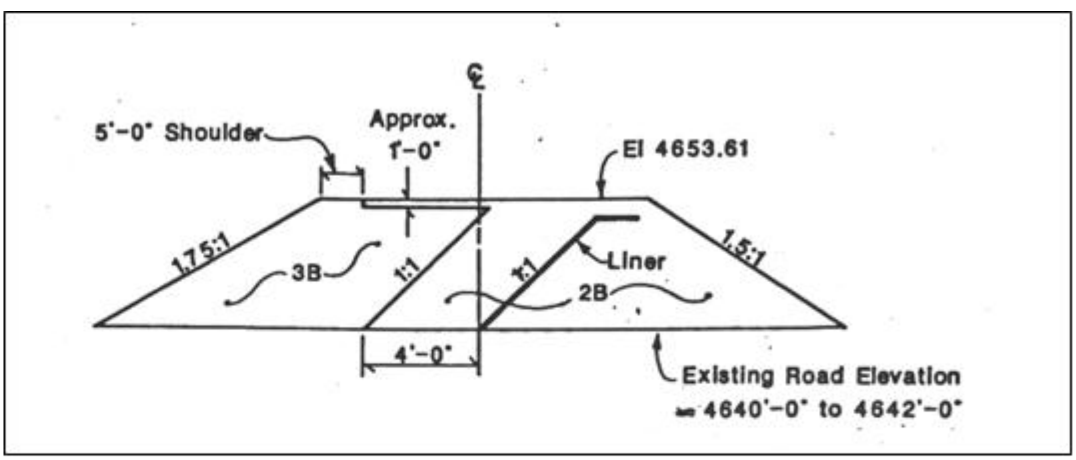


Figure 20.3.2.1-1. Pactola Dam raise with HDPE geomembrane.

The geomembrane seepage barrier was incorporated from elevation 4652.5 down into the crest of the existing zone 1 core. The geomembrane was underlain with a nonwoven geotextile to protect the geomembrane from damage due to puncture caused by the underlying zone 2B material. One foot of cover material (zone 2A) was placed over the geomembrane to protect the geomembrane from damage caused by placement of the zone 2B material. The upper anchor trench had dimensions of 2 feet by 2 feet and incorporated 2 feet of runout of the geomembrane prior to backfilling of the trench. The lower anchor trench (or key trench) connection details between the geomembrane and existing zone 1 core are shown on figure 20.3.2.1-2, and the concrete anchor detail tying into bedrock is shown on figure 20.3.2.1-3.

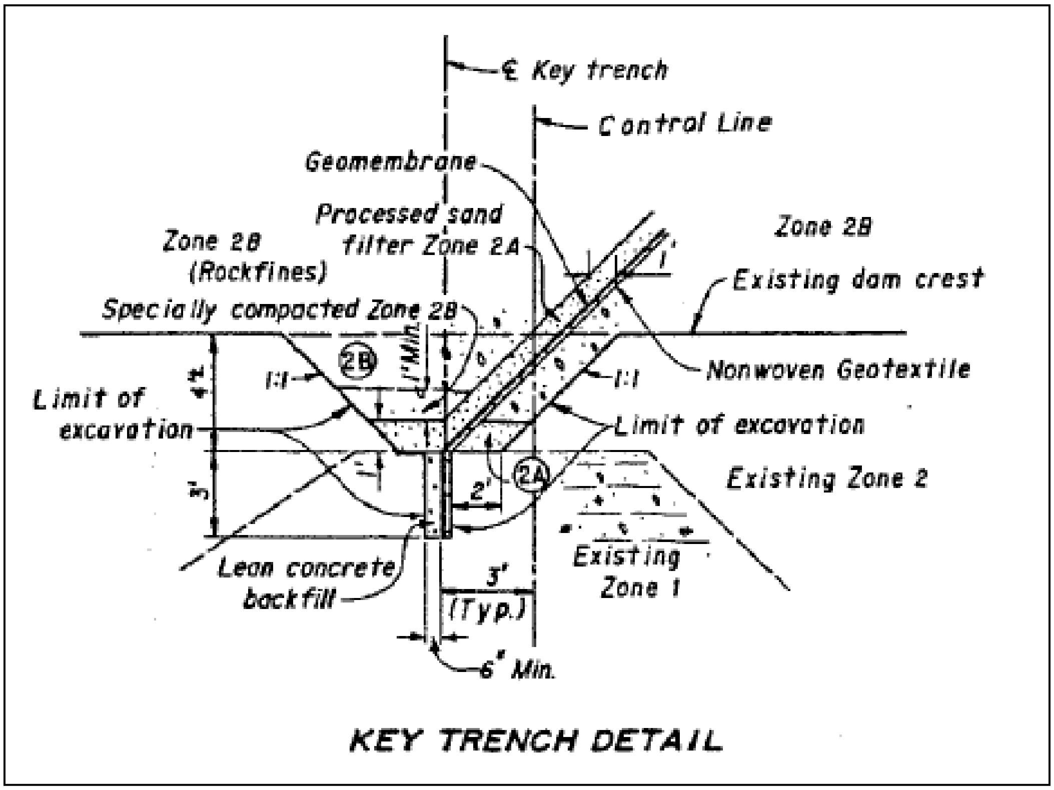


Figure 20.3.2.1-2. Pactola Dam geomembrane key trench tying into existing core zone.

Construction of the dam raise is shown on figure 20.3.2.1-4.

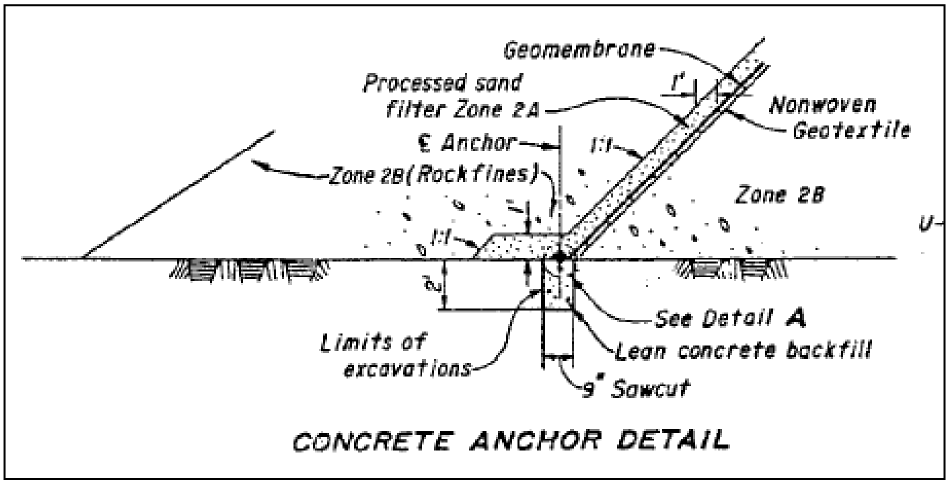


Figure 20.3.2.1-3. Pactola Dam geomembrane key trench tying into bedrock.

Figure 20.3.2.1-4. Pactola Dam raise construction photos:
(a) geotextile and geomembrane placement, (b) key trench,
(c) extrusion welding HDPE seam, (d) placement of cover material,
(e) geomembrane placement atop the concrete, and (f) installing batten strip over geomembrane/concrete connection.

20.3.3 Reservoir Lining and Upstream Blankets

A geomembrane upstream blanket can be used to minimize leakage under a dam, as shown on figure 20.3.3-1, either with partial basin coverage or full lining of the reservoir. Horsetooth Reservoir, Warren H. Brock Reservoir, Mount Elbert Forebay Reservoir, Black Lake Dam, and Pablo Dam are five examples of Reclamation and BIA projects falling into this category and are discussed further below. Other Reclamation projects involving total or partial reservoir lining include San Justo Reservoir, Black Mountain Operating Reservoir, and Ochoco Dam.

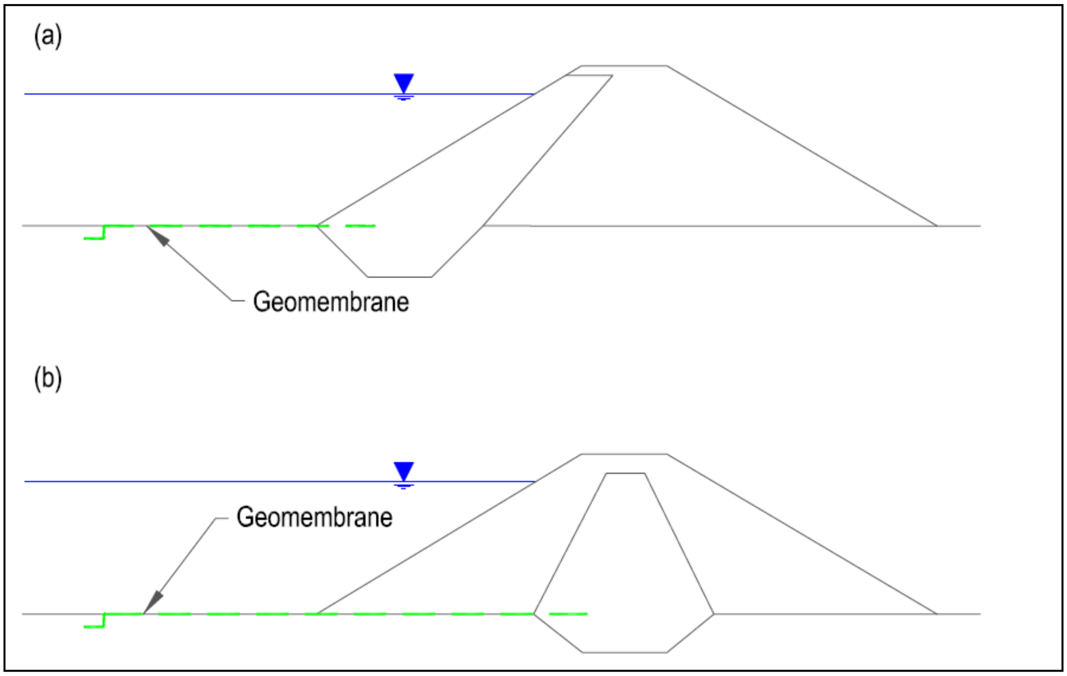


Figure 20.3.3-1. Typical reservoir lining: (a) tying into an upstream cutoff trench and (b) tying into a central core and cutoff trench through the upstream shell. Stability analysis should be conducted to prevent instability of the upstream slope.

If the partial or complete blanket geomembrane is installed on a soil containing zones that are weak or likely to collapse (for example karstic formations), consideration of differential settlement should be addressed. A layer of soil reinforced with a geosynthetic (geogrid or high-strength/high-modulus geotextile) can be used under the geomembrane for stabilization.

Uplift of geomembrane upstream blankets during rapid drawdown is a potential problem and is further discussed in section 20.4.7. Methods for estimating the effectiveness of an upstream blanket are presented in chapter 8 of Design Standards No. 13 (appendix B) [10]. Computerized numerical methods should be used to check the final design and should always be used for complex foundation and seepage conditions. In addition, soils at the seepage exit point should be evaluated to ensure that the critical exit gradients are not exceeded.

20.3.3.1 Horsetooth Reservoir

An example of a Reclamation dam in which a geomembrane was used to provide a partial upstream blanket is at Horsetooth Dam. The reservoir consists of four embankment dams at crest elevation 5444. The embankments, from north to south, are Horsetooth, Soldier Canyon, Dixon Canyon, and Spring Canyon Dams. The geomembrane seepage barrier was constructed near the upstream toe of Horsetooth Dam in response to karstic conditions underlying the embankment as evidenced by the sinkhole shown on figure 20.3.3.1-1.

Figure 20.3.3.1-1. Sinkhole near the upstream toe of the embankment of Horsetooth Dam.

Initial repair of the sinkhole and associated voids consisted of grouting the rock, after which a concrete plug was poured at the entrance to the sinkhole. A 3-foot-thick layer of sandy gravel material was placed over the sinkhole, followed by the installation of an 80-foot by 100-foot 40-mil PVC geomembrane over the sinkhole area. Subsequently, the final repair consisted of covering the sinkhole area and the trace of the soluble limestone units with 40-mil LLDPE geomembrane. The area covered with LLDPE geomembrane is approximately 300 feet by 800 feet as shown on figure 20.3.3.1-2. Five feet of sandy clay was then placed as a cap over the LLDPE geomembrane. The 40-mil PVC and sandy clay cover material are shown on figure 20.3.3.1-3.

Figure 20.3.3.1-2. LLDPE geomembrane installation.

Figure 20.3.3.1-3. Clay cap over the PVC geomembrane.

20.3.3.2 Warren H. Brock Reservoir

An example of a Reclamation reservoir in which a geomembrane was used for total reservoir lining is Warren H. Brock Reservoir. The earthfill embankment has a structural height of 26 feet at a crest elevation of 158 and impounds approximately 8,000 acre-feet of water.

The seepage barrier in the reservoir floor consists of a 60-mil HDPE geomembrane overlain by 2 feet of protective soil cover. The seepage barrier on the upstream face of the embankment consists of, from top to bottom: (1) 9-inch thick soil cement; (2) a drainage layer consisting of geotextile, geonet composite, and gravel filter; and (3) 60-mil textured HDPE geomembrane. The seepage barrier is shown on figure 20.3.3.2-1. A white geomembrane was selected to minimize wrinkling in the hot environment.

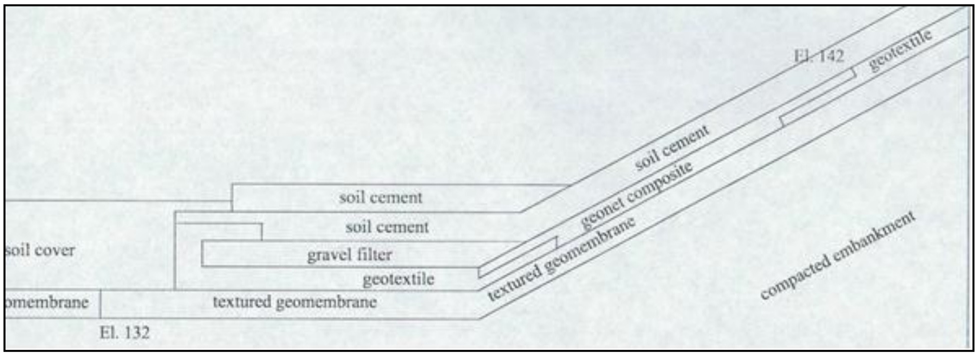


Figure 20.3.3.2-1. Designed cross section at Warren H. Brock Reservoir (not to scale).

Construction of the reservoir lining at Warren H. Brock Reservoir is shown below on figure 20.3.3.2-2.

Figure 20.3.3.2-2. Warren H. Brock Reservoir lining photos: (a) handling geomembrane rolls, (b) subgrade preparation for liner placement, (c) geotextile placement over geomembrane, (d) hot wedge welding HDPE seam, (e) soil cement placement over gravel drain, and (f) soil cement protective cover over geomembrane.

20.3.3.3 Mount Elbert Forebay Reservoir

Another example of a Reclamation reservoir in which a geomembrane was used for total reservoir lining is Mt. Elbert Forebay Reservoir. The offstream reservoir is impounded by a rolled, zoned earthfill embankment 2,600 feet long at elevation 9652, with a structural height of 92 feet, and it impounds 11,530 acre-feet of water. The reservoir is the forebay for the power generation at the Twin Lakes Powerplant. The reservoir is filled via pipeline from Turquoise Lake and/or pumping water from Twin Lakes Reservoir. Due to electrical power generation demands, the reservoir is generally full. The reservoir lining extends to elevation 9650, which is 2 feet below the crest elevation.

The reservoir is lined with 45-mil reinforced chlorinated polyethylene (CPE) geomembrane, which is sandwiched between layers of protective material. CPE is essentially a more flexible version of HDPE with good chemical and UV resistance. Its chemical structure is between that of a PVC and CSPE. Figures 20.3.3.3-1 and 20.3.3.3-2 show the installation of the membrane.

Figure 20.3.3.3-1. Installation of the Mount Elbert Forebay Reservoir geomembrane on the side slopes (note tires used as a temporary ballast during installation).

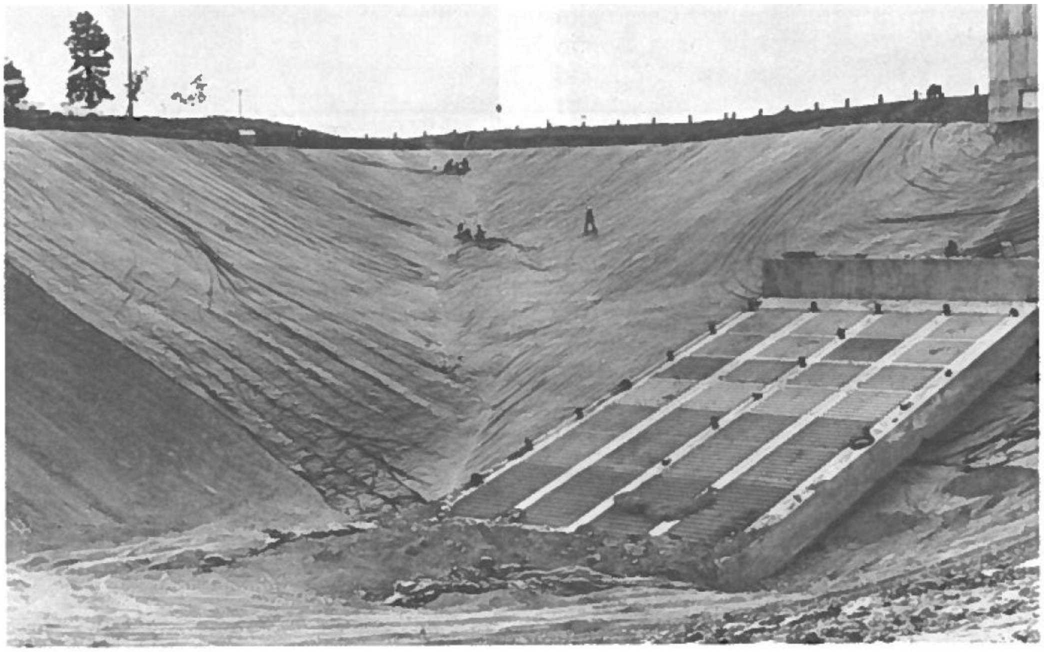


Figure 20.3.3.3-2. Six-man crew performing seaming operations near the Mt. Elbert inlet/outlet dike.

20.3.3.4 Black Lake Dam

An additional example of utilizing geomembrane for partial reservoir lining is the BIA Black Lake Dam, which was designed by Reclamation. The zoned earthfill embankment is 544 feet long at elevation 4440, with a structural height of 65 feet, and it impounds 5,200 acre-feet of water. The facility has a history of reservoir restrictions due to sinkholes and depressions. The seepage barrier was designed and constructed to prevent water from seeping into the embankment, abutments, and foundation units.

The seepage barrier consists of, from top to bottom: (1) a protective cover; (2) 60-mil textured VLDPE, which has a slightly lower density than LLDPE; (3) a 10 oz/yd^2 nonwoven geotextile; and (4) prepared subgrade. Riprap was placed over the protective material on the slopes of the facility. Seepage barrier layout designs for Black Lake Dam are shown on figures 20.3.3.4-1 and 20.3.3.4-2.

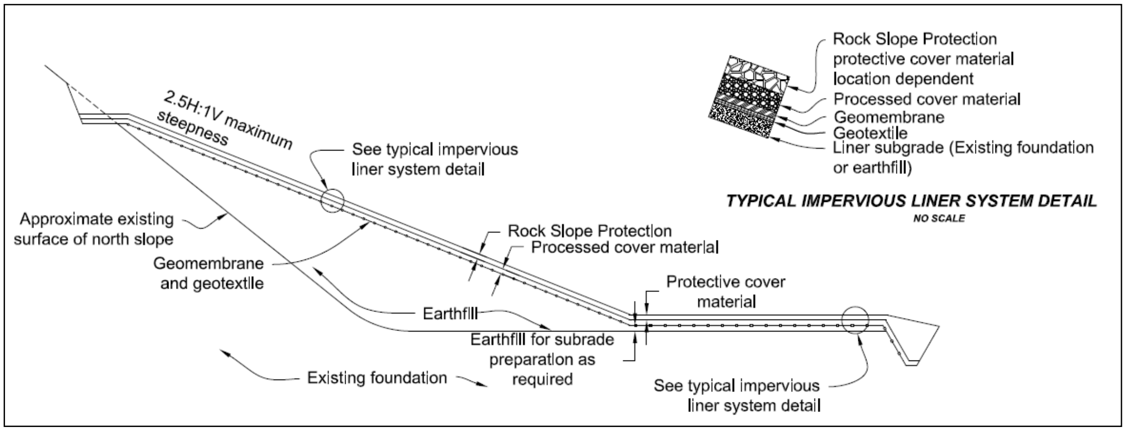


Figure 20.3.3.4-1. Black Lake Dam seepage barrier system details.

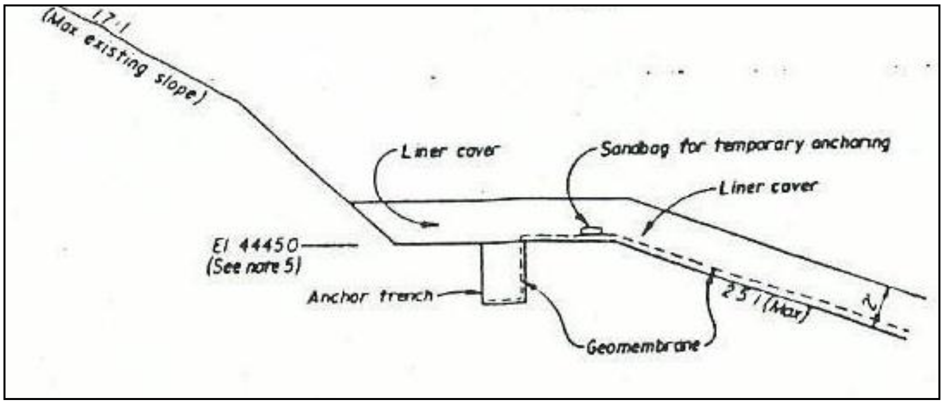


Figure 20.3.3.4-2. Proposed anchor trench detail used at Black Lake Dam.

20.3.3.5 Pablo Dam

An example of a BIA dam that utilized a geomembrane for a partial upstream blanket was designed by Reclamation for Pablo Dam, which is located near Pablo, Montana. Pablo Dam is an earthfill embankment with a structural height of 43 feet at crest elevation 3220, and it impounds 28,400 acre-feet of water. The dam was experiencing excessive seepage through the top portion of the structure and had a history of sinkhole development. The two embankment raises above the original crest of 3201 were constructed with pervious materials; therefore, a seepage barrier was installed on the upstream slope of the embankment between elevations 3198 and 3212.

The seepage barrier consists of a 60-mil HDPE geomembrane placed over a prepared subgrade. The geomembrane was overlain by a 1-foot-thick protective cover, a 1-foot-thick riprap bedding material, followed by 3 feet of riprap. The upper anchor trench had dimensions of 2 feet by 2 feet and incorporates 2 feet of runout prior to backfilling of the trench. The lower anchor trench is 3 feet deep and 2 feet wide. The upstream cutoff design and installation photos are shown on figures 20.3.3.5-1 and 20.3.3.5-2, respectively.

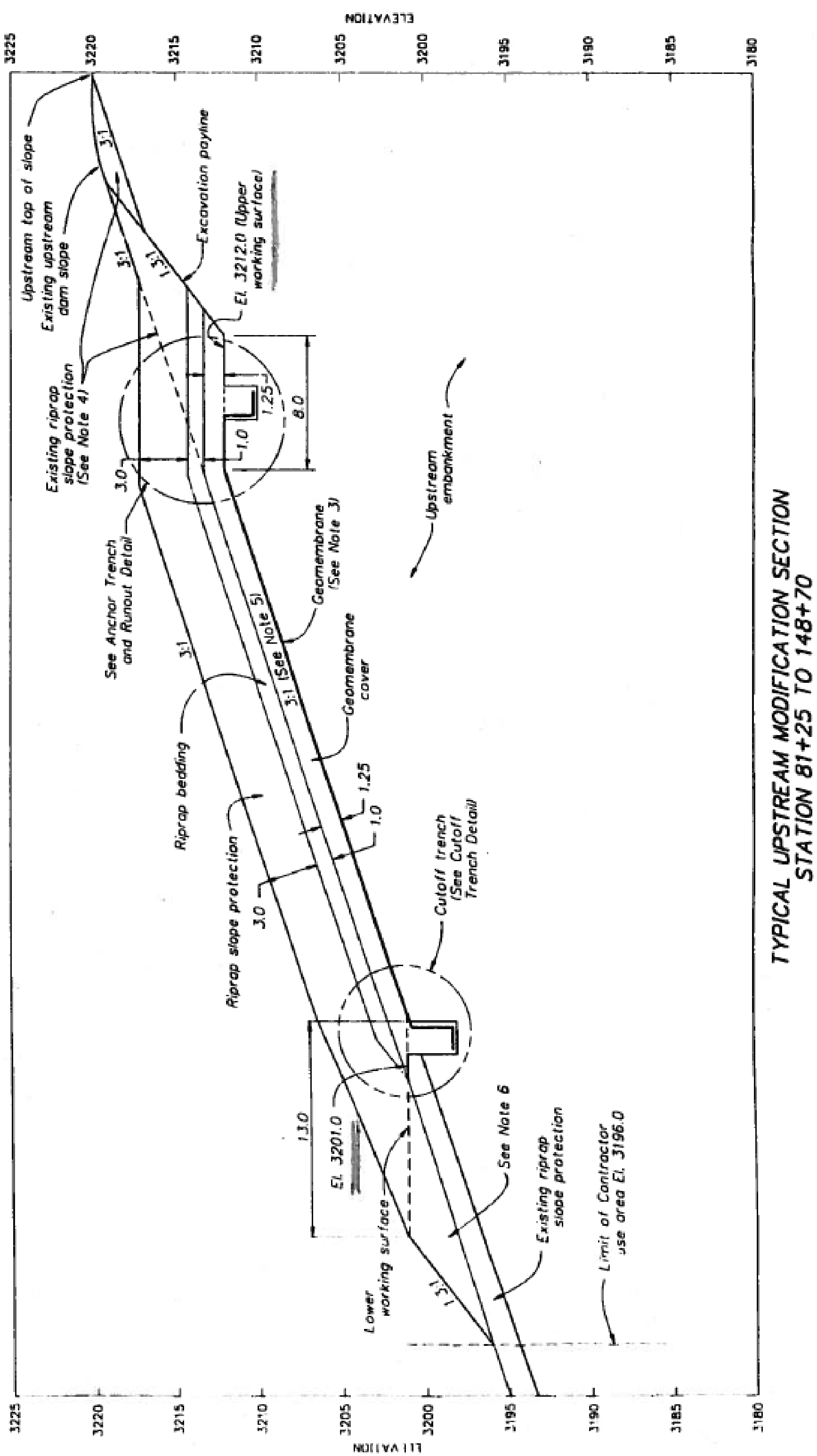


Figure 20.3.3.5-1. Pablo Dam geomembrane cutoff design.

(a)

(b)

Figure 20.3.3.5-2. (a) Anchor trench excavation and (b) installation of geomembrane.

20.3.4 Cutoff Walls

Geomembranes can be used to construct vertical seepage cutoff walls through or under embankment dams. Current information indicates that only HDPE geomembranes have been used in this type of application, with typical thicknesses of 1.5 to 3 millimeters (mm) (60 to 120 mils). The widths of the HDPE panels vary greatly depending on the installation procedure, from 3 to 30 feet.

For cutoff walls, the geomembrane panels are installed vertically. Simple overlapping between adjacent panels is not sufficient to provide watertightness. Special interlocks made of polyethylene are used, which are similar to the interlocks connecting conventional steel sheet piles. General cutoff wall configurations are shown on figure 20.3.4-1.

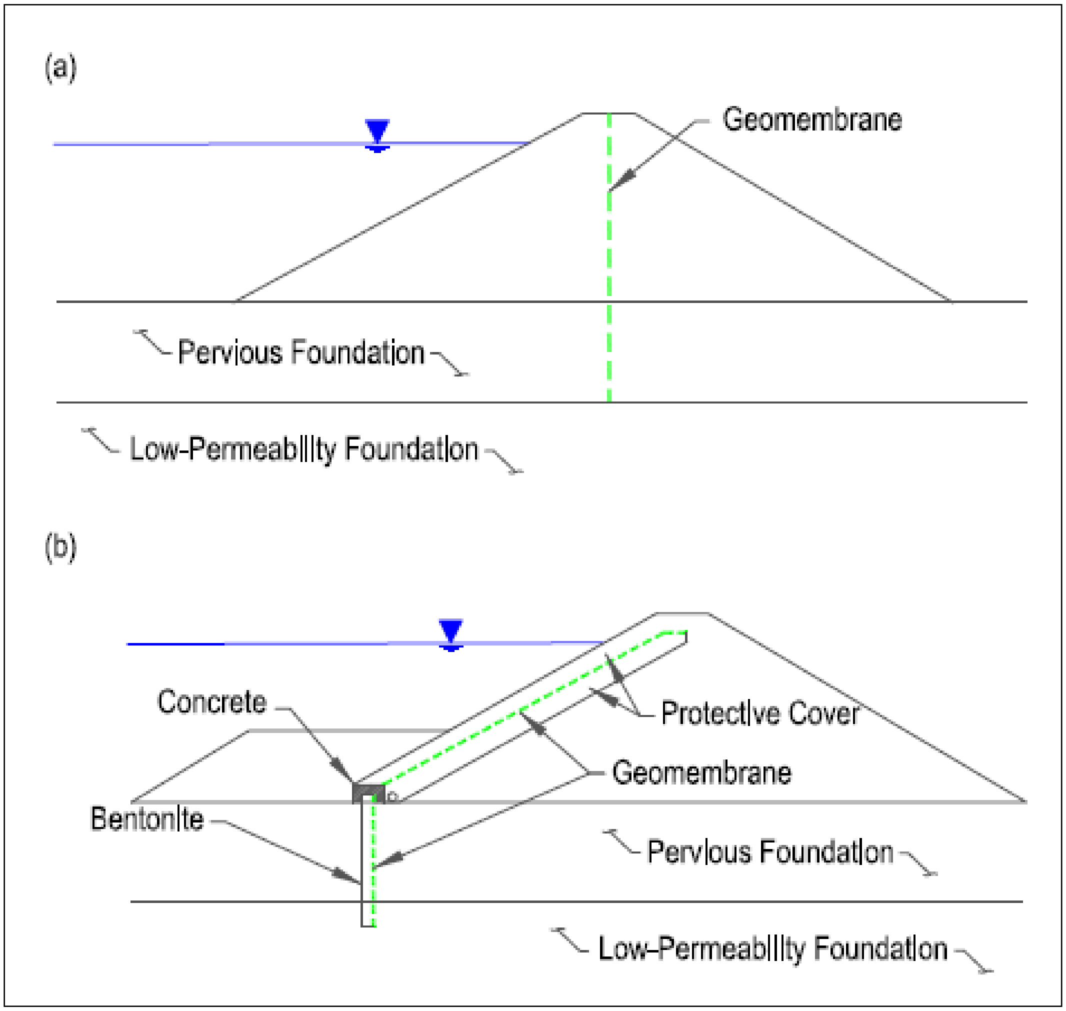


Figure 20.3.4-1. General geomembrane cutoff wall configurations.

Interlocks that are only mechanically locked cannot be completely watertight. Additional watertightness can be obtained by grouting the lock; placing a rod of expansive material, such as a polymeric compound that swells when exposed to water within the interlock; or extrusion welding using welding equipment that can go into tube-shaped interlocks. In the last case, hot air is blown in the tube prior to welding to eliminate humidity and to preheat the interlock to facilitate welding. The interlocks are welded to the geomembrane prior to insertion into the ground. The HDPE interlock is often thicker than the geomembrane to ensure that, in case of tension, the geomembrane will stretch and the interlock will not fail. An example of a geomembrane interlock is shown on figure 20.3.4-2.

Figure 20.3.4-2. Geomembrane interlock (top view).

Geomembrane cutoff walls can be installed using several techniques, which include the use of geomembrane panels attached to mandrels that are driven into the soil by vibration, geomembrane panels attached to rigid frames and driven into the soil by water jetting, and by lowering geomembrane panels that are attached to a rigid frame into a slurry trench. More details describing these techniques can be found in Scuero et al. [11]. Cutoff walls can be partial or fully penetrating. However, to be effective, cutoff walls must generally fully penetrate the pervious strata. See chapters 8 and 16 of Design Standards No. 13 for more information on cutoff walls [10, 12].

20.3.4.1   Reach 11 Dikes

An example of a Reclamation project in which a geomembrane was used for a seepage cutoff through the crest of a structure is Reach 11 Dikes. The dikes are zoned earthfill embankments, which are part of the Hayden/Rhodes aqueduct in Phoenix, Arizona. The facility was leaking excessively through the embankment and foundation, requiring a seepage cutoff that would intercept an underlying impervious foundation stratum.

A seepage barrier consisting of vertically installed 80-mil HDPE geomembrane panels were installed along the centerline of the dike, which incorporates a chimney filter immediately downstream from the geomembrane. Finger drains, connected to the trench, were constructed at 500-foot intervals along the dikes to safely carry away any seepage that may enter the trench. The trench, which was supported by revertible biopolymer slurry, was designed to be 2 feet wide and extend 10 feet into the underlying foundation. The cutoff wall design and installation photos are shown on figures 20.3.4.1-1 and -2, respectively.

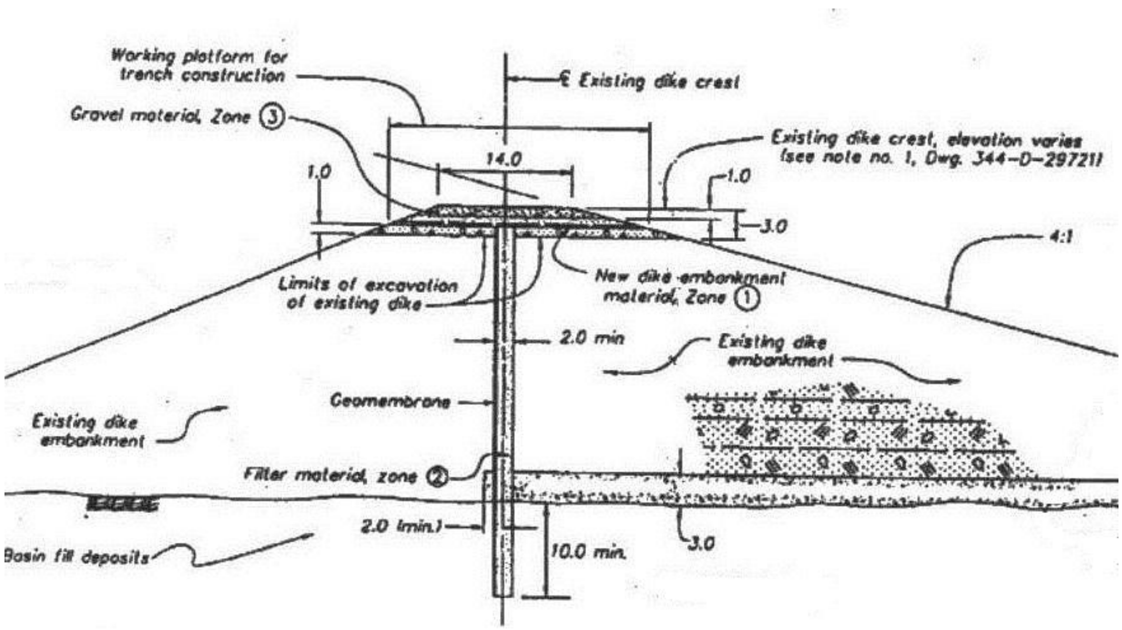


Figure 20.3.4.1-1. Reach 11 Dikes geomembrane cutoff wall design.

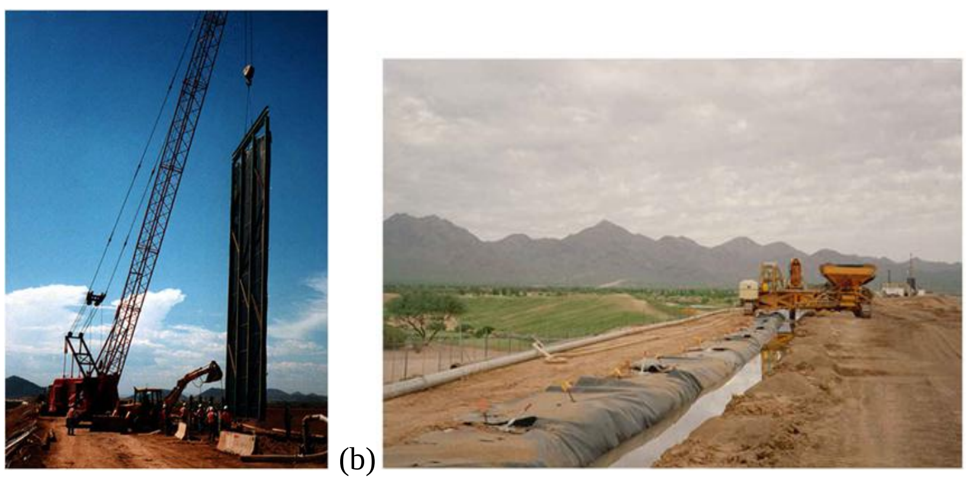
(a) (b)


Figure 20.3.4.1-2. (a) Geomembrane panel installation and (b) top view of installed panels at Reach 11 Dikes.

20.4 Design Considerations

The following sections briefly outline some of the critical design aspects of incorporating a geomembrane into an existing or new embankment dam. This section is not considered exhaustive and references several prominent textbooks for further details [1, 3, 4, 7, 9]. However, when selecting the type of geomembrane for either new construction or remediation, the following selection criteria should be considered:

- Long-term performance (loss of properties, cracking, etc.)
- Ease of installation (wrinkles, seaming, cold / hot weather requirements, quality control and assurance, etc.)
- Cost
- Interface strength (if covered)
- Ease of repair (long term)
- Puncture resistance (falling objects, impacts, particle size of adjacent soil, etc.)
- Tear strength and thickness (resistance to differential settlement)

20.4.1 Laboratory Testing

The following sections outline the typical laboratory tests that may frequently be encountered in the design or construction quality assurance (CQA) process.

20.4.1.1 Physical Properties

Physical properties of geomembranes are related to mass, dimensions, and composition. Upon receiving a geosynthetic product for installation, each individual roll or product will have a certification sheet that provides various physical properties, including mass per unit area, density, thickness, etc., which will need to be checked against the design specifications for conformance. The typical physical property tests, outlined in table 20.4.1.1-1, are not routinely completed by the designer; however, conformance sampling during the installation process commonly requires several of the laboratory tests listed below to be completed as outlined in section 20.5.2. Typical values of physical properties are provided by the geomembrane manufacturers.

Table 20.4.1.1-1. Common physical property laboratory tests (ASTM)

Physical property	PE	PVC	CSPE	fPP	EPDM
Density	D792 or D1505				
Thickness	D5199 (smooth) or D5994 (textured)				
Thermal expansion	D696				
Carbon black content	D1603 or D4218 (N/A for PVC and EPDM)				
Dimensional stability	D1204 or D1042 (N/A for LLDPE and HDPE)				

20.4.1.2 Mechanical Properties

Mechanical properties of geomembranes include (1) the behavior of the geomembrane under applied load, (2) the resistance to damage of the geomembrane during installation, and (3) the interaction of the geomembrane with adjacent materials. The mechanical behavior of geomembranes is chiefly concerned with in-plane tensile stresses. Since the function of geomembranes is primarily bidimensional, hence very thin, concentrated stresses can damage the material. Finally, the interface shear strength between a geomembrane and the adjacent material is critical in the stability of the system as well as the integrity and strength of the seams within the geomembrane. The typical mechanical property tests, outlined in table 20.4.1.2-1, are routinely executed during the design and installation (quality control) phases.

Table 20.4.1.2-1. Common mechanical and hydraulic property laboratory tests (ASTM)

Mechanical property	PE	PVC	CSPE	fPP	EPDM
Tensile properties[1] (peel/shear)	D6693	D882	D6693	D6693	D882
Wide-width tensile strength	D4885				
Multiaxial tensile strength	D5617				
Tear resistance	D1004 or D5884 (if reinforced)				
Puncture resistance[2]	D4833 or D5514				
Impact resistance[3]	D1424, D1709, D1822, or D3029				
Interface shear strength	D5321				
Stress crack resistance	D5397	N/A	N/A	N/A	N/A
Permeability (water vapor)	D5886 or E96				

[1] For reinforced membranes, use ASTM D751 and D413.
[2] For reinforced membranes, ASTM D6241 may be more appropriate.
[3] None of the outlined tests offer direct correlation with field conditions.

20.4.1.3 Endurance Properties

Any compromise in the physical property of the material over time will degrade the longevity of the membrane product. The severity of material degradation is polymer specific and typically includes increasing the brittle behavior in the stress-strain response over time, but can also include a reduction of mechanical properties, an increase in permeability, and failure of geomembrane seams. As listed in table 20.4.1.3-1, there are a number of predictive tests that indicate material suitability, although it should be mentioned that there has been extensive testing completed for the procedures listed below that can direct the designer to the proper polymer for the given climatic conditions [13, 14] without having to complete the testing for site-specific conditions.

Table 20.4.1.3-1. Common endurance property laboratory tests (ASTM)

Endurance property	PE	PVC	CSPE	fPP	EPDM
Low temperature testing	D746	D1790	D746	D1790	D746
High temperature testing	D412	D638	D412	D638	D412
Oxidative degradation	D3895 or D5885				
Ultraviolet degradation	D7238 (lab) or D4364 (field)				
Chemical resistance[1]	D5322				

[1] Chemical degradation is typically not a concern for most Reclamation reservoirs.

20.4.2 Interface Strength

Geomembranes placed on sloping surfaces are often subjected to shear stresses. If the sliding resistance between the geomembrane and the adjacent material is less than the shear stress, slippage occurs at the interface, and the lining system or the entire structure relies on the anchor trench or becomes unstable. Slope stability analyses should be performed according to chapter 4 of Design Standards No. 13 [41] and as outlined in greater detail in section 20.4.10.1.

A slip surface may occur at any interface within the system—for instance, between a geotextile and soil or between a geotextile and a synthetic drainage layer. Therefore, the shear strength of all interfaces should be evaluated.

ASTM D5321 (Interface Direct Shear) is used to determine the shear strength between soil-geosynthetic and geosynthetic-geosynthetic interfaces.

20.4.2.1 Interface Strength Scenarios

Two types of field situations are typically considered with respect to interface strength. In the case of an anchor trench, a portion of the geomembrane is embedded in the soil. If the exposed portion of the geomembrane is subjected to tensile forces, these forces tend to pull the buried geomembrane out of the anchor trench. However, the designer typically ignores any beneficial anchoring and relies on interface friction between the geomembrane and adjacent soils to provide stability. Secondarily, if an installed geomembrane on the upstream face of a dam is covered by several feet of soil to protect it against environmental degradation, the stability of the soil on the geomembrane must be considered. Local or global sloughing failures can occur due to reservoir rise and fall along the geomembrane/ soil interface.

Whereas geotextiles and geogrids have been subjected to extensive pullout testing, geomembranes have been almost exclusively subjected to shear testing. The reason is that anchor trenches for geomembranes are rarely a critical design issue, whereas stability of slopes incorporating geomembranes is always a critical issue. Consequently, only interface shear tests are discussed hereafter. Should interface shear strength testing indicate inadequate values, shear strengths can be increased by using a textured geomembrane in lieu of a smooth geomembrane or by bonding the geomembrane to a geotextile. In layered seepage barrier systems, interface strength testing should also consider other layers in addition to the geomembrane interface (e.g., a clay soil comprising a layer within a seepage barrier system may have weaker shear strength than the materials in contact with the geomembrane).

20.4.2.2 Typical Interface Strength Values

Many authors have published results of shear tests with geomembranes in contact with soils or with other geosynthetics: Saxena and Wong [15], Martin et al. [16], Akber et al. [17], Williams and Houlihan [18], Degoutte and Mathieu [19], Koerner et al. [20], and Eigenbrod and Locker [21]. A summary of typical interface strength values are summarized in tables 20.4.2.2-1 through 20.4.2.2-3 from a database collected by Koerner and Narejo [22]. The strength values are acceptable for preliminary design, but final design strength values should be determined by interface direct shear testing using site-specific materials.

Table 20.4.2.2-1. HDPE geomembranes against various materials

Interface #1	Interface #2	Peak friction (degrees)	Residual friction (degrees)	Peak adhesion (lb/ft^2) *	Residual adhesion (lb/ft^2)
HDPE-S	Granular soil	21	17	0	0
HDPE-S	Cohesive soil				
	Saturated	11	11	150	0
	Unsaturated	22	18	0	0
HDPE-S	NW-NP GT	11	9	0	0
HDPE-S	Geonet	11	9	0	0
HDPE-S	Geocomposite	15	12	0	0
HDPE-T	Granular soil	34	31	0	0
HDPE-T	Cohesive soil				
	Saturated	18	16	210	0
	Unsaturated	19	22	480	0
HDPE-T	NW-NP GT	25	17	165	0
HDPE-T	Geonet	13	10	0	0
HDPE-T	Geocomposite	26	15	0	0

* lb/ft^2 = pounds per square foot
Note: S = smooth, NW-NP GT = nonwoven needle-punched geotextile, and T = textured.

Table 20.4.2.2-2. LLDPE geomembranes against various materials

Interface #1	Interface #2	Peak friction (degrees)	Residual friction (degrees)	Peak adhesion (lb/ft^2)	Residual adhesion (lb/ft^2)
LLDPE-S	Granular soil	27	24	0	0
LLDPE-S	Cohesive soil	11	12	260	75
LLDPE-S	NW-NP GT	10	9	0	0
LLDPE-S	Geonet	11	10	0	0
LLDPE-T	Granular soil	26	25	160	110
LLDPE-T	Cohesive soil	21	13	120	145
LLDPE-T	NW-NP GT	26	17	170	200
LLDPE-T	Geonet	15	11	75	0

Note: S = smooth, NW-NP GT = nonwoven needle-punched geotextile, and T = textured

Table 20.4.2.2-3. PVC and CSPE-R geomembranes against various materials

Interface #1	Interface #2	Peak friction (degrees)	Residual friction (degrees)	Peak adhesion (lb/ft^2)	Residual adhesion (lb/ft^2)
PVC-S	Granular soil	26	19	8	0
PVC-S	Cohesive soil	22	15	19	0
PVC-S	NW-NP GT	20	16	0	0
PVC-S	NW heat bonded	18	12	0	0.1
PVC-S	Woven, slit-film	17	7	0	0
PVC-faille	NW-NP GT	27	23	5	0
PVC-faille	NW heat bonded	30	27	0	0
PVC-faille	Woven, slit-film	15	10	0	0
CSPE-R	Granular soil	36	16	0	0
CSPE-R	Cohesive soil	31	18	120	0
CSPE-R	NW-NP GT	14	10	0	0
CSPE-R	NW heat bonded	21	10	0	0
CSPE-R	Woven, slit-film	11	11	0	0

Note: S = smooth, NW = nonwoven geotextile, NW-NP GT = nonwoven needle-punched geotextile, and R = reinforced.

20.4.3 Slope Geometry

In general, geomembrane-lined slopes no steeper than 3:1 (H:V) should be considered for embankment dams. This is considered more prudent from a constructability standpoint rather than a design constraint. Slopes steeper than 3:1 can be lined successfully with geomembrane, but installation tends to be more difficult, and the installers will typically need to use safety ropes and other specialized safety equipment, which can slow down the installation process. A number of Reclamation projects have incorporated geomembrane installation on slopes steeper than 3:1, including Warren H. Brock Reservoir.

Long slopes should also be avoided to reduce the possibility of overstressing the geomembrane panels and seams during short-term loading such as placing protective cover material or long-term loads due to reservoir fluctuations. Geomembrane rolls should typically be installed vertically (from the crest down the slope) with horizontal seams limited to the bottom third of the slope, although seams on slopes are discouraged. If horizontal seams are placed on slopes, they should be staggered so that they are at different elevations across the slope. The recommended maximum slope length is typically 250 feet. If longer slopes are needed, it is recommended that a bench be included in the design and that horizontal seams are incorporated along the bench. If the design slope is longer than 250 feet and an intermediate bench cannot be accommodated, the designer should verify that the tensile strength of the geomembrane is not exceeded using the equation shown below:

$$\alpha = \gamma T \sin \beta x$$

Where:

α = The tensile force per unit width in the geomembrane (pounds per foot [lb/ft])
γ = Unit weight of geomembrane (pounds per cubic foot [lb/ft^3])
T = Thickness of geomembrane (ft)
β = Slope angle (degrees)
x = Distance parallel along slope (lb/ft)

If a protective cover is to be placed above the geomembrane, the design and stability of the system must be verified in accordance with section 20.4.10.

20.4.4 Seam Design

Geomembrane rolls are sometimes installed horizontally (i.e., across the slope of a dam) in the case of dams that have: (1) a small height (e.g., less than 30 feet),

(2) a great length (e.g., several thousand feet or more), and (3) an upstream slope that is not steep (e.g., less than 3:1). In all cases, the design must ensure that such horizontal seams will not be overstressed.

However, in the majority of cases, geomembrane rolls are installed along the slope, or vertically. In these cases, it is important that the length of each roll be slightly greater than the length of the slope at the location where this particular roll is to be installed due to anchor trench and overlap usage. This requires that, at the geomembrane selection stage, the designer verifies with several manufacturers that they have the capability of manufacturing rolls of different lengths, up to the maximum required length. To minimize waste, custom length rolls can sometimes be ordered depending on the total quantity of geomembrane required.

The success or failure of geomembrane installation depends to a great extent on both short-term and long-term integrity of all seams. Further discussions of seaming techniques in the field and in the factory are included in section 20.5.1. It should also be noted that for thermally bonded geomembranes, a minimum thickness of 60 mils is recommended to avoid poor seam construction. This thickness should be considered appropriate for most projects, unless other mitigating factors are involved such as difficult foundation conditions, high propensity for differential settlement, etc.

20.4.5 Anchor Trench and Connections

This section presents a design method for designing anchor trenches and provides practical information on ways to connect geomembranes to rigid structures.

20.4.5.1 Anchorage Design

A typical geomembrane installation within a reservoir incorporates a liner that is placed vertically along the slope and terminates into a shallow trench, which is offset from the crest of the embankment by several feet (runout). The anchor trench is typically excavated with a small backhoe or trenching machine. The depth and width of the anchor trench must be determined to provide adequate anchorage, but many manufacturers will specify a minimum runout length and anchor trench depth of 3 feet and 2 feet, respectively, although the final configuration should be based on site-specific considerations.

The recommended method for anchor trench design is outlined below [4], although other published methods may be used [23]. A typical anchor trench and associated free-body diagrams are shown on figure 20.4.5.1-1.

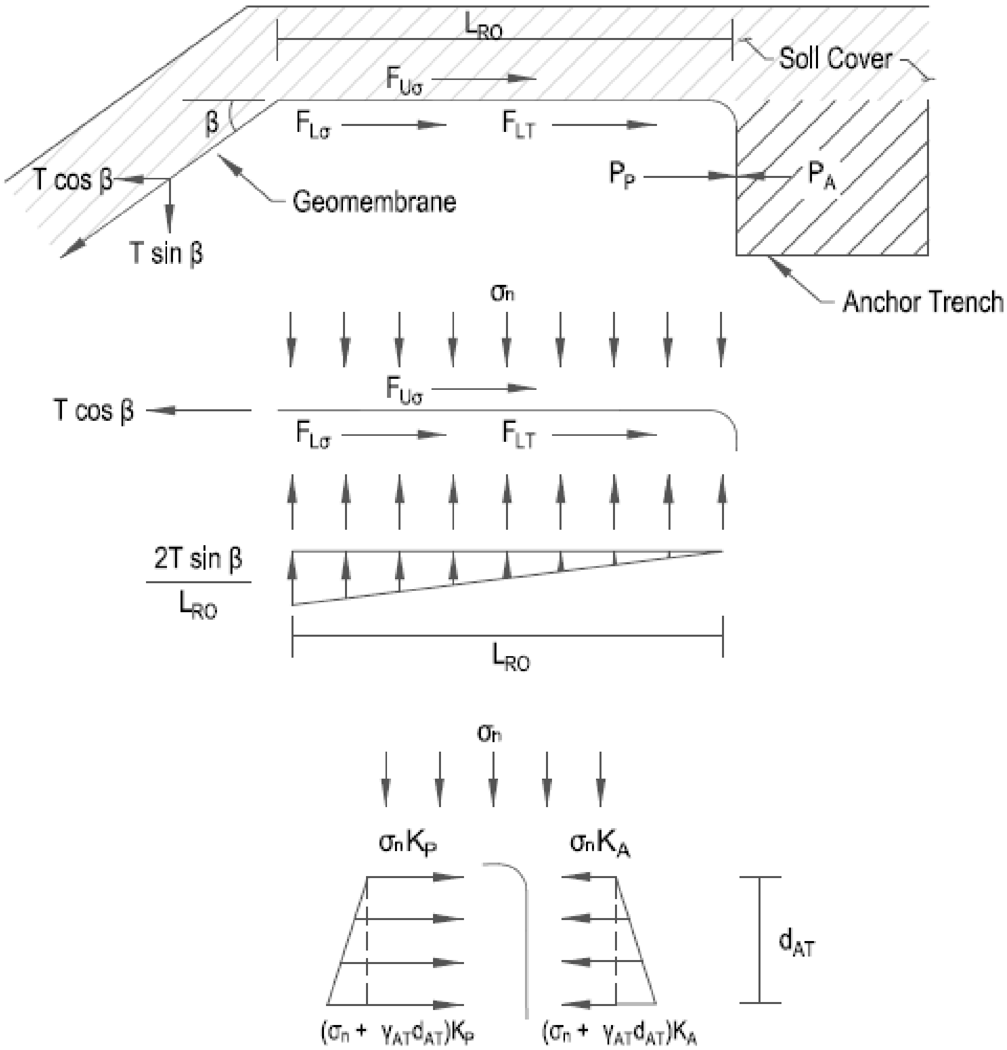


Figure 20.4.5.1-1. Geomembrane anchor trench design: cross section and free-body diagrams (adapted from [4]).

As will be shown below, the horizontal runout length between the slope break and the trench, and the passive pressures constraining the vertical portion of geomembrane within the anchor trench, are very effective at providing adequate anchorage. Using the free-body diagram above and summing forces in the horizontal direction, the following relationship is developed:

$$\Sigma F_x = 0$$

$$T_{allow} \cos \beta = F_{U\sigma} + F_{L\sigma} + F_{LT} - P_A + P_P$$

Where:

T_{allow} = Allowable force in geomembrane = $\sigma_{allow} t$ (lb)

σ_{allow} = Allowable stress in geomembrane (pounds per square foot [lb/ft^2])

t = Thickness of geomembrane (ft)

= Side slope angle (degrees)

$F_{U\sigma}$ = Shear force above geomembrane due to cover soil (lb/ft)

$F_{L\sigma}$ = Shear force below geomembrane due to cover soil (lb/ft)

F_{LT} = Shear force below geomembrane due to vertical component of T_{allow} (lb/ft)

P_A = Active earth pressure against the backfill side of the anchor trench

P_P = Passive earth pressure against the in-situ side of the anchor trench

Substitution of the above horizontal force summations with the appropriate design variables leads to the following:

$$T_{allow} \cos\beta = \sigma_n \tan\delta_u \left(L_{RO}\right) + \sigma_n \tan\delta_L \left(L_{RO}\right) + 0.5\left(\frac{2T_{allow}\sin\beta}{L_{RO}}\right)\left(L_{RO}\right)\tan\delta_L - P_A + P_P$$

Where:

σ_n = Applied normal stress from cover soil (lb/ft^2)

δ = Angle of shearing resistance between geomembrane and adjacent material either upper or lower interface (degrees)

L_{RO} = Length of geomembrane runout (ft)

The values of active and passive earth pressure (P_A and P_P, respectively) are derived from lateral earth-pressure theory, which is addressed in most undergraduate soil mechanics textbooks as shown below:

$$P_A = \left(0.5\gamma_{AT} d_{AT} + \sigma_n\right) K_A d_{AT}$$
$$P_P = \left(0.5\gamma_{AT} d_{AT} + \sigma_n\right) K_P d_{AT}$$

Where:

γ_{AT} = Unit weight of soil in anchor trench (lb/ft^3)

d_{AT} = Depth of anchor trench (ft)

σ_n = Applied normal stress from cover soil (lb/ft^2)

K_A = Coefficient of active earth pressure $= \tan^2\left(45 - \varphi/2\right)$

K_P = Coefficient of passive earth pressure $= \tan^2(45+\varphi/2)$
φ = Soil internal angle of friction (degrees)

It should be noted that the shear force above the geomembrane is often neglected due to cracks in the overlying soil.

When solving the above equations, there are two unknown variables of concern, namely the length of geomembrane runout (L_{RO}) and depth of the anchor trench (d_{AT}). Essentially, the designer must assume a runout length and then solve for the required depth of anchor trench or vice versa. The factor of safety should already be applied to the allowable force in the geomembrane (T_{allow}).

Typical stress values (σ) for various geomembranes at maximum and ultimate failure for use in preliminary design are summarized in table 20.4.5.1-1. Most manufacturers will provide maximum and ultimate stress values for T_{allow} computations. Consideration can be given to having no anchor trench and sufficient runout on a bench at the top of the slope (or dam crest); however, a v-ditch is a preferred compromise. Setting the depth of the anchor trench (d_{AT}) equal to zero and solving for the runout length (L_{ro}) will satisfy anchoring at the top of the slope and minimize the tensile stresses in the geomembrane. A small amount of movement is acceptable and expected to engage the geomembrane into the slope materials.

Table 20.4.5.1-1. Typical tensile behavior of geomembranes [4]

Test property[1.]	Units	HDPE	LLDPE	PVC	fPP-R[2.]
Maximum stress and corresponding strain	kip/ft^2 (%)	330 (15)	160 (400+)	290 (210)	650 (23)
Modulus	kip/in^2	65	10	3	44
Ultimate stress and corresponding strain	kip/ft^2 (%)	230 (400+)	160 (400+)	290 (210)	60 (79)

[1] Values were derived from wide width tensile tests.
[2] Reinforced.
Notes: Nominal thicknesses: HDPE = 1.5 mm, LLDPE = 1.0 mm, PVC = 0.75 mm, and CSPE-R = 0.91 mm.
+ indicates specimen did not fail.
Kip/ft^2 = and kip/in^2 = kip per square inch

20.4.5.2 Connections to Rigid Structures

The designer must provide connections that maintain smooth transitions and adhere to materials with minimal change in stiffness. Geomembrane connections to rigid structures must fulfill two conditions:

- They must be watertight.
- Watertightness must not be impaired in case of differential settlements.

Watertightness is encouraged by the following precautions:

- The concrete structure must be waterproof itself and, therefore, must be constructed with waterproofing provisions such as waterstops.

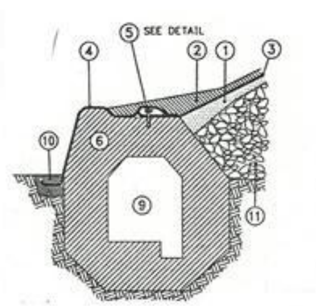
- The concrete structure should be as smooth as possible, one or more layers of soft rubber may be interposed between the concrete and the geomembrane, and a batten strip, bolted to the concrete structure, should maintain the geomembrane in close contact with the structure.

- A geomembrane cap strip can be used to cover the batten strip to prevent leakage along the bolts. Batten strips with an oval cross section are recommended to provide smooth support for the cap strip. Cap strips used from crest to toe at the periphery of the dam face are potentially dangerous. If such a cap strip leaks, it will be filled with water to a level equal to the level of water in the reservoir. In case of drawdown of the dam, the cap strip will not drain if the leak is near the top. The tube under pressure formed by the cap strip may then burst, causing tears in the geomembrane. Therefore, where a cap strip runs from the crest to the toe, the tube thus formed must be filled with a plastic sealant approximately every 10 feet.

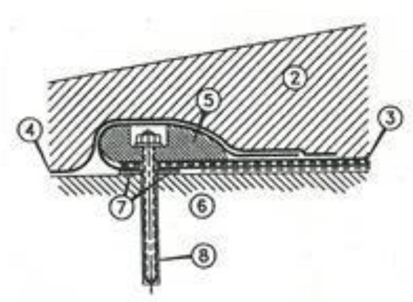
- The use of batten strips is not mandatory. Alternatively, geomembranes may be glued on concrete, or they may be inserted in a slot in the concrete structure, and backfilled with cement grout or resin.

Resistance to differential settlements can be enhanced by following the recommendations made in section 20.4.8 and incorporating some slack in the geomembrane next to the connection to provide for movement.

Two examples of connections of geomembranes with concrete structures are presented on figures 20.4.5.2-1 through -2.



(a)



(b)

Figure 20.4.5.2-1. (a) Geomembrane connection to the gallery at Codele Dam showing batter of concrete face and (b) construction detail. Legend: (1) supporting layer (bituminous concrete), (2) concrete cover, (3) geomembrane liner, (4) geomembrane cutoff, (5) HDPE batten strip, (6) concrete, (7) butyl strip, (8) bolt, (9) gallery, (10) clay-filled trench, and (11) rockfill.

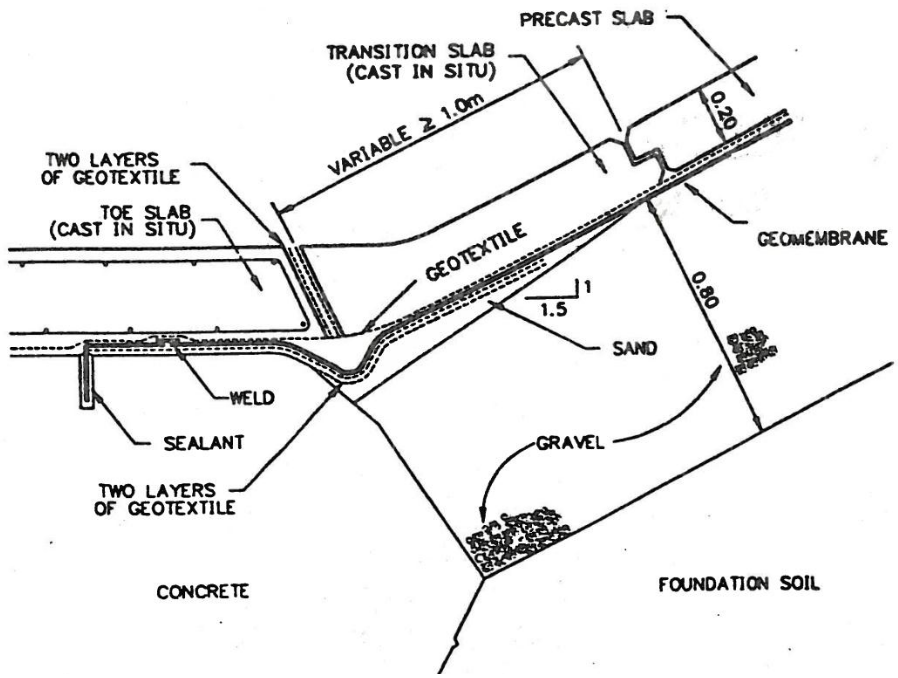


Figure 20.4.5.2-2. Geomembrane termination at Cixerri Dam, showing significant batter and convex support system [24].

20.4.6 Leakage

Because the purpose of a dam is to retain water, and because the function of a geomembrane is to act as a water barrier, leakage control is an essential part of the design of any geomembrane application in a dam. Therefore, the design of all geomembrane applications in dams should address leakage control. In all applications, it is essential that the ability of the geomembrane to act as a barrier be evaluated. Therefore, leakage analyses and calculations must be conducted as part of the design of an embankment dam constructed with a geomembrane. Leakage control design includes determining the type of liner, evaluating leakage, and designing leakage collection and detection where applicable.

It should be recognized that geomembranes are not absolutely impermeable, and none can be installed on a large area without a certain number of flaws. Therefore, although dams equipped with geomembranes are likely to leak less than other dams, leakage is not totally eliminated, and this fact should be taken into account in the design. Also, geomembranes incorporated in a dam can be breached in some extreme cases (e.g., earthquake, upstream slope instability), and the design must be such that a large breach of the geomembrane does not trigger significant damage to the dam or failure of the dam. Therefore, the following considerations should be included in leakage control design:

- Leakage of water from the reservoir should be evaluated and minimized.
- When the soil in the dam and/or in its foundation is sensitive to water (erodible, soluble, or collapsible soil, etc.), seepage of water into the soil should be evaluated and minimized.
- If possible, the design of the dam should be such that leakage through the geomembrane liner can be detected, evaluated, and located to allow the dam owner to decide if and where repair is needed.
- In all cases, the design of the dam should be such that a major breach in the geomembrane liner does not trigger deterioration of the dam (by mechanisms such as internal erosion, excess pore water pressure, etc.), which could lead to costly repair or even failure of the dam.
- In new dam construction, a geomembrane shall not be the sole engineering control for seepage (i.e., filters and drains and other impervious elements should be used).
- Water can find its way around the end of a geomembrane if the end is submerged. Be aware where the geomembrane terminates in submerged water and construct a cutoff at the edges as appropriate.

20.4.6.1 Leakage Evaluation

There are essentially two mechanisms of leakage through geomembranes [6, 25]: fluid permeation through an intact geomembrane (diffusion) and flow through geomembrane defects. Fluid permeation can be defined by applicable laboratory testing and represents near negligible loss. Geomembrane defects include pinholes and holes, which are defined by Giroud [25] as:

- Pinholes can be defined as openings having a dimension (such as diameter) significantly smaller than the geomembrane thickness. The primary sources of pinholes are manufacturing defects. Early manufacturing techniques for geomembranes often resulted in a significant number of pinholes. However, manufacturing processes, quality assurance, and polymer formulations have advanced to a degree that pinholes are now relatively rare.

- Holes can be defined as openings having a dimension (e.g., diameter) about as large as, or larger than, the geomembrane thickness. Holes are generally caused by puncture and tearing during handling, installation, covering with soil, puncturing by gravel or cobbles from above or beneath, and by defects incurred during seaming.

The rate of leakage due to permeation and pinholes is not significantly affected by the material in contact with the geomembrane and, again, is very negligible for reservoir loss and, therefore, will not be discussed further. In contrast, the rate of leakage through holes is affected by the materials in contact with the geomembrane, the contact between the soil and geomembrane (e.g., wrinkles), geomembrane thickness, and geomembrane flexibility.

20.4.6.1.1 Leakage Due to Holes

As part of the preparation to develop leakage detection rules, a survey of geomembrane liners placed with various degrees of quality assurance has been conducted [6]. This survey, along with other field data, is summarized in table 20.4.6.1.1-1 and indicates the anticipated number of installation defects given installation quality control.

Table 20.4.6.1.1-1. Typical installation defects [4]

Installation quality	Defects per acre
Excellent	Up to 1
Good	1 to 4
Fair	4 to 10
Poor	10 to 20

Accordingly, two hole sizes are recommended by the United States Environmental Protection Agency (EPA) [6] and Giroud [26, 27] for design:

- 0.16 square inch (in^2) for worst case conditions
- 0.016 in^2 for average case conditions

The larger hole should be considered for estimating anticipated seepage and sizing filters and drains downstream.

Leakage rates through a hole in a geomembrane are typically attenuated by the underlying soil. However, most equations to date developed by Bonaparte et al. [28], Giroud [26], Touze-Foltz and Giroud [29], and Weber and Zornberg [30] all incorporate restrictive head conditions. Giroud has a number of correlations for leakage through a geomembrane underlain by high, medium, and low permeable soils [32, 33, 26]; however, the head must be less than approximately 10 feet for the above-referenced relationships to be applicable. Therefore, a modified version of Bernoulli's equation for free flow through an orifice originally proposed by Bonaparte et al. [28] and Giroud [25] is recommended for use as shown below:

$$Q = C_d an\sqrt{2gh}$$

Where:

Q = Leakage rate (gallons per minute)
C_d = Coefficient of discharge typically taken as 0.6 (unitless)
a = Area of defect (ft^2)
n = Number of defects (unitless)
g = Gravitational acceleration (feet per square second)
h = Head above liner (ft)

While the above equation is certainly conservative, it is one of the few relationships that can function under high head conditions (i.e., >30 feet), which is the case for the majority of Reclamation facilities. The leakage predicted from the above relationship will be overestimated when the geomembrane is underlain by a low permeability soil; however, the relationship is still included to provide an order of magnitude estimate for design purposes.

20.4.6.2 Design Considerations to Avoid Puncturing of Geomembranes

Testing at Reclamation and other laboratories has shown that a significant amount of puncture protection to geomembranes can be accomplished when it is protected by a geotextile. On a rough subgrade, the geotextile is placed first, followed by the geomembrane (figure 20.4.6.2-1). On a slope, the geomembrane surface against the geotextile should be textured to increase the sliding resistance between the geotextile and geomembrane. The geotextile should be a nonwoven needle-punched fabric or that determined by laboratory testing. Geomembranes having subgrades with rounded particles are less likely to require a geotextile protection layer than geomembranes having subgrades with angular particles.

As stated earlier, more elastic geomembrane materials (like LLDPE, PVC or fPP) are better for rough subgrades or severe construction conditions where more brittle, less elastic materials (e.g., HDPE) will be prone to tear or puncture. Stress cracking is also more likely in the less elastic materials. A maximum height of protrusion is commonly specified above the rolled final subgrade surface. Rolling of the subgrade is usually performed by a smooth-drum roller up and down the slope so as to be parallel with the layout of the geomembrane (see figure 20.4.6.2-2).

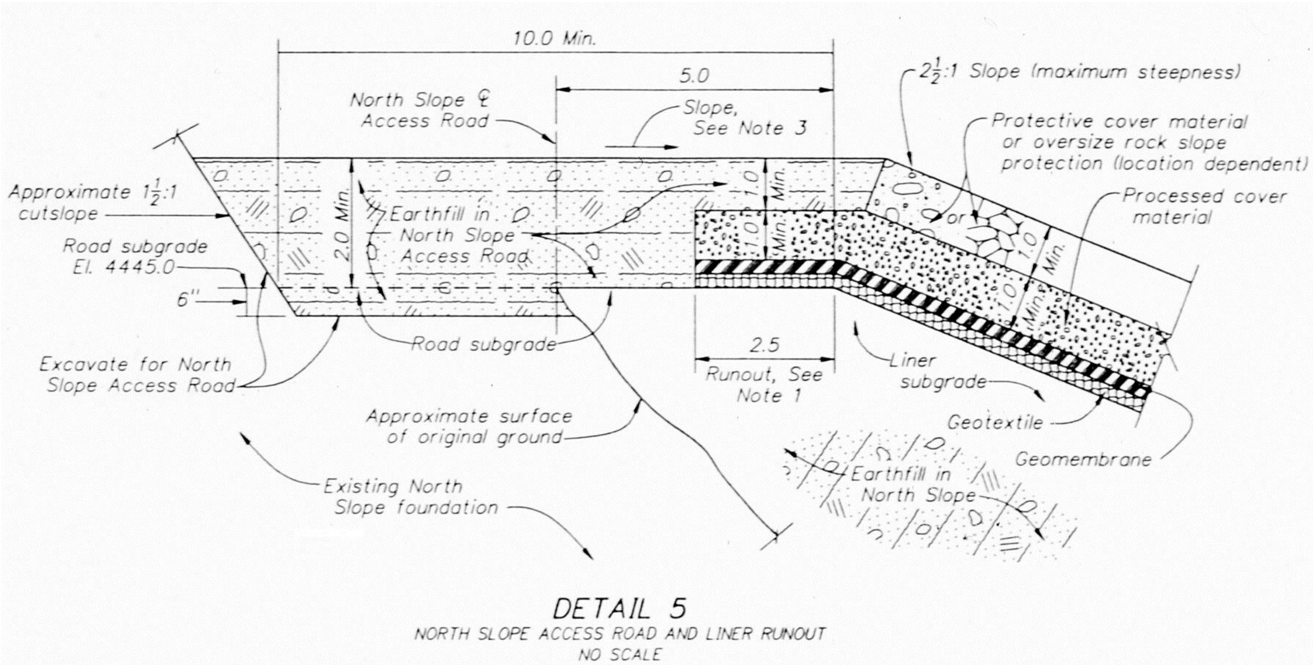


Figure 20.4.6.2-1. Detail of liner placement at the top of the reservoir slope showing runout, geotextile cushion, geomembrane, and cover materials at Black Lake Dam, Montana (BIA).

Figure 20.4.6.2-2. Final rolling of subgrade materials beneath the geomembrane liner system at Black Lake Dam, Montana (BIA).

20.4.6.3 Leakage Collection and Detection

Leakage collection and detection systems are more commonly encountered in tailing storage facilities, municipal waste repositories, and containment ponds impounding contaminated waters or materials. However, there may be situations in which a drainage system must be incorporated beneath or directly behind a geomembrane—for instance, on the upstream face of a roller-compacted or masonry dam where a synthetic drainage system such as geonet could be incorporated or in the instance of a vertical cutoff wall behind which a granular filter may be placed.

Drainage layers under geomembrane liners should be designed to handle the flow of water resulting from leakage through the geomembrane (i.e., the drainage layer should have enough flow capacity to convey the flow, and the drainage layer and underlying soils should not be damaged by the flow). A drainage layer could consist of either a granular filter material or a synthetic drainage layer such as thick, needle-punched nonwoven geotextile, a geonet, or a geocomposite. However, a geonet or geocomposite provides much better drainage than a geotextile.

The first step in drainage layer design is to estimate the anticipated leakage through the geomembrane using the methods outlined in section 20.4.6.1.1. Then, either the flow capacity or hydraulic transmissivity of the associated granular filter or synthetic drainage system must be determined to ensure adequate drainage. There are numerous references that outline the above design process for various design conditions, including water head, slope angle, granular filter and synthetic drainage system composites, and compressibility limitations of synthetic systems [31]. Chapters 5 and 8 of Design Standards No. 13 should be referenced for the design of filters and control of seepage.

20.4.7 Uplift

20.4.7.1 Wind

In all geomembrane applications (landfills, pond linings, dams, etc.), uplift of liners by wind can occur during construction. In addition, it may occur at any time during applications where the geomembrane is exposed. Typically, geomembranes in earthfill dam applications are either covered by soil on the slope face or by the impounded reservoir in the basin, which would preclude uplift due to wind. However, where the geomembrane must remain exposed, such as on the upstream face of a concrete dam or steep section of an earthfill dam, any rips or large defects in the membrane may introduce aerodynamic uplift caused by wind, which may then lead to either geomembrane damage caused by high tension or pulling of the geomembrane from its anchorage.

There are a number of practical approaches to reducing the propensity of wind uplift for both the construction phase and final configuration of a geomembrane installation. During construction, sandbag placement on the advancing geomembrane edge is common, but is only effective if the sandbags are placed continuously; otherwise, low velocity winds are capable of uplift, and the sandbags may actually damage the membrane if moved during an uplift event. Placing a thin protective soil cover, or thin soil berms, is very effective in reducing uplift, even if only a few inches thick, and is more effective than random sandbag placement. Temporary anchorage methodologies should be reviewed with the installer prior to construction activities. Figure 20.4.7.1-1 shows sandbags placed at the leading edge of a geomembrane panel to reduce the possibility of wind uplift.

Figure 20.4.7.1-1. Temporary anchorage at leading edge of geomembrane with sandbags.

The final configuration of the slope will also have a significant impact on wind (and tractive force) uplift. If the geomembrane will be either exposed or partially exposed, the designer may have to incorporate intermediate benches, intermediate anchor trenches, pavement strips, geotubes, concrete slabs, etc., to effectively constrain the geomembrane. Examples of a few of these possible design features are shown on figure 20.4.7.1-2.

The analytical analysis of geomembrane uplift is beyond the scope of this document; however, the topic is more thoroughly discussed in published literature [34, 35, 36].

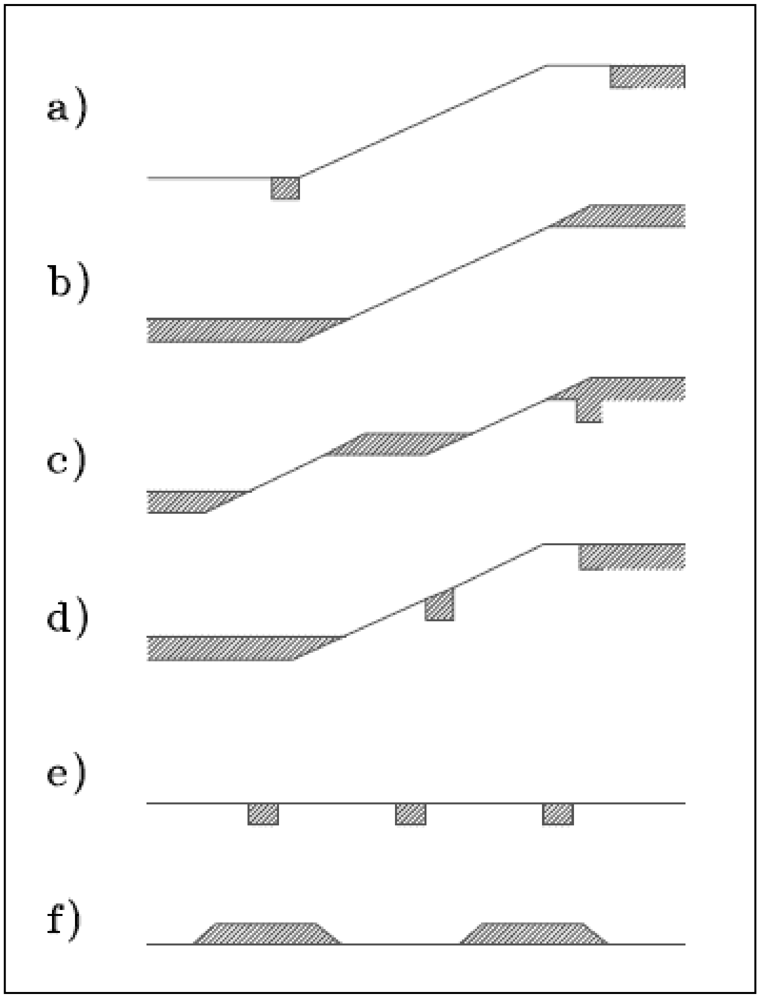


Figure 20.4.7.1-2. Design options for additional geomembrane anchorage (a) anchor trenches, (b) pavement or soil anchorage, (c) intermediate bench, (d) intermediate anchor trench, (e) basin anchor trenches, and (f) soil anchorage in basin.

20.4.7.2 Buoyancy

This problem occurs in applications associated with partial or total reservoir lining and for dam raises. The design aspects discussed in section 20.4.8 address the resistance of lining systems to differential settlements and lack of support.

There is some concern that an upstream geomembrane blanket in a reservoir basin may be uplifted by pressures due to underlying water in the case of rapid drawdown of a reservoir. Indeed, there is water pressure under a geomembrane blanket in case of rapid drawdown; however, the situation is much less critical than for a geomembrane located on the upstream slope of a dam. Because the supply of water under the blanket is limited to the water contained in the soil under the blanket, and because water is not compressible, a slight uplift of the blanket releases the pressure. From this viewpoint, a geomembrane blanket is much superior to a clay blanket, which could crack under the same circumstances. One location where uplift of a geomembrane blanket is possible is near the toe of the dam if water stored in the embankment of the dam creates an artesian situation under the blanket. This situation can be avoided by proper internal drainage of the dam, by loading the blanket near the toe of the dam with soil, or with one of the designs outlined on figure 20.4.7.1-2 that increases the anchorage.

Another critical location is the upstream end of the blanket where the geomembrane should be properly anchored in the ground to minimize the risk of seepage water bypassing the geomembrane. Constructing a cutoff wall at the upstream end of the blanket may help mitigate this issue.

Because the risk of geomembrane uplift does not seem to be critical if adequate anchorage and drainage is provided, the use of valves, as suggested by Grossmann and Sanger [37], does not appear to be justified in most cases.

20.4.8 Settlement

Geomembranes can fail due to differential settlements especially in areas where the modulus of elasticity varies significantly in the underlying geologic media (e.g., settlement between the face of the dam and abutments).

The discussions below address the issue of differential settlement, in particular:

- Connections with abutments
- Connections with concrete structures

20.4.8.1 Connections with Abutments

In order to safely use geomembranes, or any other type of facing, traditional design and construction techniques should be used to minimize differential settlements between a dam and its abutments. Traditional techniques include:

- Partial or total replacement of foundation soils
- Consolidation or dynamic compaction of foundation soils
- Shaping and smoothing of the abutments to avoid abrupt changes in slopes
- Proper selection of the materials used
- Saturation of rockfill
- Adequate compaction of embankment fill

- Increasing the thickness of geomembranes to obtain greater tear-resistant properties
- Select a different geomembrane to obtain high elongation properties

20.4.8.2 Connection with Concrete Structures

There is a major risk of differential settlement at the connection between geomembranes and concrete structures. From the standpoint of differential settlement, there are two types of concrete structures:

- The concrete structures located at the periphery of the geomembrane such as anchor beams, crests or caps of cutoff walls, etc.
- The concrete structures that penetrate the geomembrane such as intake or spillway towers passing through the upstream face

Structures of the latter category should be minimized when possible because it is extremely difficult, even impossible with some geomembranes, to place the geomembrane with slack in all directions. However, differential settlement may not be of much concern if the structures are founded on bedrock. Structures located at the periphery, or edge, of the geomembrane are much easier to handle especially if they comprise long straight stretches such as that shown on figure 20.4.8.2-1.

Figure 20.4.8.2-1. Connection between geomembrane and concrete structure. Stainless steel batten strip secured every 6 inches with stainless steel bolts.

Placing geomembranes with wrinkles is not the best way to provide the required slack to geomembranes to accommodate differential settlement for the following reasons:

- Wrinkles are difficult to control during installation because of wind action, thermal expansion and contraction, and stiffness of some geomembranes. Placement methods to avoid wrinkles are outlined in Chappel et. al [38].
- Wrinkles tend to move downslope because they creep and also because every time a geomembrane moves in relation to its support (as a result of wind, thermal expansion and contraction, maintenance operations, etc.), the resulting displacement is downslope.
- Wrinkles may be flattened by overburden or water pressure, which may induce undesirable concentrated stresses in the geomembrane, especially in seams as observed by Stone [39].
- Wrinkles often do not move (even when there is no soil on top of the geomembrane) because of friction with the underlying material, although they may be next to a zone where the geomembrane is under tension.

A better solution, as suggested by Giroud and Huot [40], consists of:

- Giving a convex shape to the embankment next to the concrete structure (which will generate slack when the embankment settles in relation to the structure)
- Placing localized low-friction geotextile between the geomembrane and the embankment, but it must be limited to a rather small fraction of the geomembrane area to minimize the risk of the geotextile-geomembrane interface acting as a slip surface
- Constructing the concrete structure with adequate batter

This solution is illustrated on figure 20.4.8.2-2. However, it should be noted that the first of the three above recommendations is possible only with straight structures. It would be practically impossible to implement this recommendation with a tower penetrating the geomembrane because it would require excessive tailoring of the geomembrane. What appears to be a good solution when a cross section is examined may prove to be impossible to implement in three dimensions.

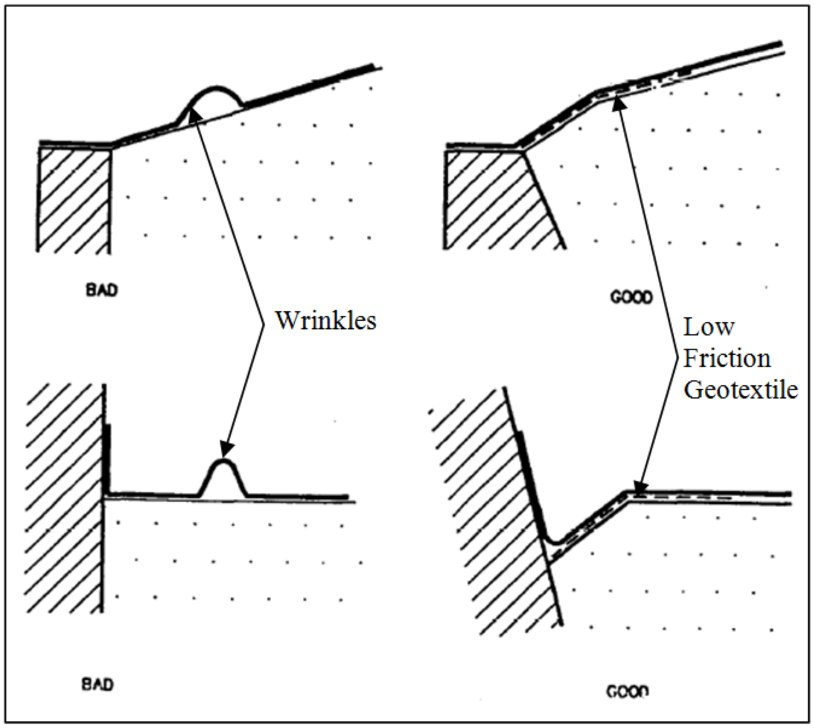


Figure 20.4.8.2-2. Correct connection between geomembrane and concrete structures [40].

20.4.8.3 Use of Soil Reinforcement to Minimize Differential Settlement

The use of soil reinforcement (with steel, geotextiles, or geogrids) may be used to minimize differential settlement between two different zones of soils, which may be the case when a dam is raised. Alternatively, the thickness of the geomembrane can be calculated as outlined by Giroud [44], based upon the anticipated differential settlement. If the membrane thickness is unreasonable, remediation may be required to mitigate the anticipated foundation issue. A detailed design of the above is beyond the scope of this design standard; however, readers should consult chapter 9 of Design Standards No. 13 [41] for more information on static deformation analysis or other numerous resources to reference geosynthetic soil reinforcement design [7, 8].

20.4.8.3.1 Geomembrane Systems Overlying Voids

If very large voids or karstic formations are unavoidable, consider design alternatives that include further foundation preparation and large-scale remediation. The first solution should include an attempt to fill the void first with soil, rock, or concrete. Two types of voids can be considered by the designer: (1) deep voids (i.e., deep cracks, karstic collapse, and bedrock fissure) and (2) shallow voids (i.e., soil dissolution, minor differential settlement, and localized subsidence).

In the case of deep voids, it is assumed that, even if the geomembrane undergoes large strains, it does not reach the bottom of the void. Therefore, in this case, there are only two possibilities: (1) either the geomembrane bridges the depression or (2) the geomembrane bursts.

In the case of shallow voids, three possibilities may occur: (1) the geomembrane bridges the void, (2) the geomembrane bursts, or (3) the geomembrane reaches the bottom of the void.

The design of a geomembrane on a void can be performed by combining the use of the tensioned membrane theory [42] and classic soil arching theory [43]. Combining these theories, Giroud [44] has developed relationships that allow the designer to select the required geosynthetic properties (including thickness), determine the maximum void size that can be bridged for a given geosynthetic system, and evaluate the load-bearing capacity of a given system.

For the sake of brevity, the design equations of the aforementioned reference are not repeated herein. If the chosen geomembrane is not strong enough or too deformable to meet the allowable deflection criterion (i.e., allowable strain), several alternatives can be considered:

- Use a thicker geomembrane or an additional geomembrane layer, (1) stronger to bridge the void, (2) with a higher modulus to minimize deflection, or (3) more deformable to reach the bottom of the void, if possible, and if compatible with the allowable deflection. This solution is acceptable if the geomembrane meets the deflection criterion, if any.
- If it is impossible to find an acceptable geomembrane, the designer can place a geotextile (typically a high-strength/high-modulus woven geotextile) directly under the geomembrane. It may be preferable to select a bonded geotextile/geomembrane composite to avoid slippage between the two geosynthetics.
- If the geomembrane is underlain by a protective soil layer, this layer may be reinforced with a high-strength/high-modulus geotextile or geogrid, which forms a “reinforced” mattress beneath the membrane to reduce the propensity for differential settlement or void development.

20.4.9 Exposed Versus Covered Geomembrane

In most geomembrane applications in dams, the geomembrane is used on, or near, the upstream face, and in most of these applications, the geomembrane is overlain by a protective cover. Some geomembranes (such as highly UV stabilized PVC or HDPE) can remain exposed for an extended length of time with little decline in their level of performance. However, most exposed geomembranes will degrade over time and are also susceptible to damage from such things as rocks, debris, equipment, wind uplift, overall environmental degradation, animal intrusion, and vandalism.

20.4.10 Protective Cover Design

The design of protective covers should include two aspects: (1) stability of the lining system (i.e., protective cover, geomembrane liner, and associated drainage layers) under the effect of gravity forces, seismic actions, and pore water pressures and (2) resistance of the protective cover to wave action. In many instances, geomembranes used for dams are protected by a soil or concrete cover. Movement of the cover can cause problems. For example, large movements resulting from instability of a soil cover on a slope can affect the integrity of the cover and damage the geomembrane. Also, small differential movements between a concrete cover and a geomembrane may induce tensile stresses in the geomembrane. In all cases, it is important to first verify that the geomembrane itself is able to withstand its own weight on a slope with no cover material.

20.4.10.1 Soil Cover

Usually a minimum of two layers of cover materials are required. The first layer closest to the geomembrane is used to protect the geomembrane. The smallest possible particles are used to best protect the geomembrane. Rounded particles are good, but must be stable on the slopes. The second and subsequent layer is used for armor protection to resist wave action. The two layers should be filter compatible with each other especially where wave action is expected.

When a soil cover is placed over a geomembrane, or any geosynthetic, the gravity stresses increase dramatically. This may cause two types of movements: (1) sliding within the soil cover and (2) sliding along the soil geosynthetic or a geosynthetic/geosynthetic interface. Two cases must be considered for soil cover stability evaluation: (1) a soil cover with a uniform thickness and (2) a soil cover with a nonuniform thickness. Additionally, stability considerations during rapid drawdown are discussed.

20.4.10.1.1 Stability for Uniform Soil Cover Thickness

In many cases, the soil cover has a uniform thickness. In this case, two types of analysis can be considered: (1) infinite slope analysis and (2) finite slope analysis.

20.4.10.1.1.1 Infinite Slope Analysis

A simple approach in the stability analysis of soil-geosynthetic systems on slopes is to consider the slope to be infinite. This is generally true if the thickness of the soil-geosynthetic system is small compared to the length of the slope. A free-body diagram is shown on figure 20.4.10.1.1.1-1 for the idealized infinite slope under consideration.

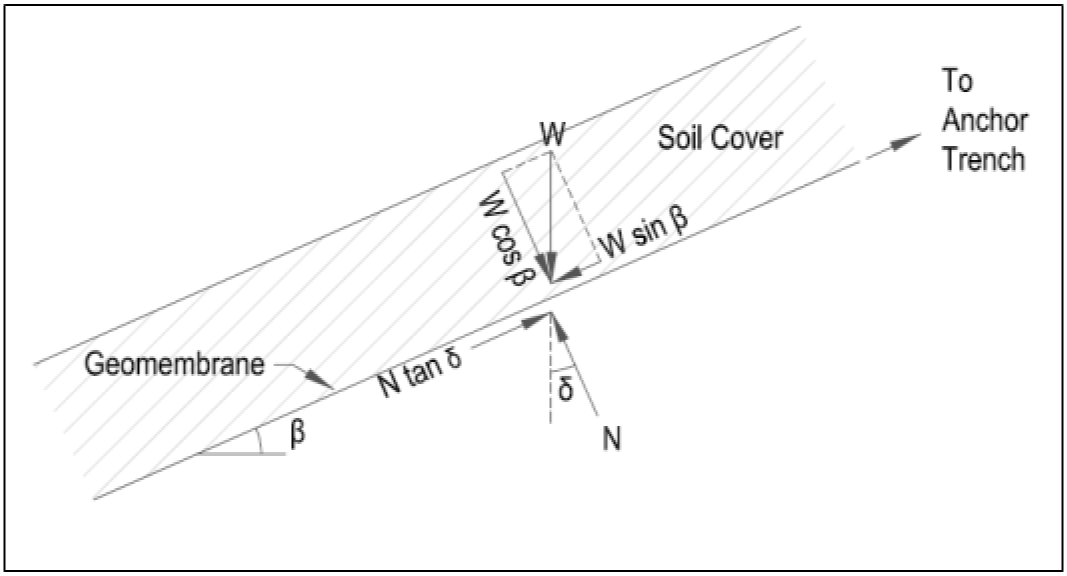


Figure 20.4.10.1.1.1-1. Infinite slope stability free-body diagram.

If the behavior of the soil and the geosynthetic interfaces is governed solely by friction (i.e., no soil cohesion or interface adhesion), the factor of safety against slippage in an infinite slope is based on limit equilibrium and is given by:

$$FS = \frac{resisting\ forces}{driving\ forces}$$

$$FS = \frac{F}{W \sin \beta} = \frac{N \tan \delta}{W \sin \beta} = \frac{W \cos \beta \tan \delta}{W \sin \beta} = \frac{\tan \delta}{\tan \beta}$$

Where:

	=	Slope angle (degrees)
δ	=	Friction angle between the soil cover and geomembrane (degrees)
W	=	Weight of overlying soil cover (lb) [2]
F	=	Resisting force (lb)
N	=	Force normal to the failure plane (lb)

The equation above indicates that the soil cover overlying a geosynthetic system on a slope is likely to be stable if the slope angle is less than the friction angle between the soil cover and geomembrane.

[2] Use buoyant weight if soil cover is submerged.

20.4.10.1.1.2 Finite Slope Analysis

In reality, slopes are not infinite, and slopes determined to be unstable from "infinite slope" analysis could be stable. Two reasons for a finite slope to be more stable than an infinite slope are:

- **Geosynthetic Anchorage at the Crest**. Geosynthetics are usually anchored at the crest of the slope. As slippage along the critical geosynthetic interface occurs, tensile forces are generated in the geosynthetics located above the critical interface. These tensile forces contribute to the stability of the potential sliding block.
- **Soil Buttress at the Toe.** The soil cover, at its toe, is assumed to rest on a firm foundation. As slippage along the critical interface occurs, downward movement of the soil cover is buttressed by the firm foundation. This "toe buttressing effect" contributes to the stability of the soil layer.

The method presented hereafter [4] is valid for either cohesionless or cohesive soils. For finite length slopes, there exists a small passive wedge at the toe of the slope, above which the active wedge is located. A free-body diagram is shown on figure 20.4.10.1.1.2-1 of a finite length slope with a uniform thickness of soil cover.

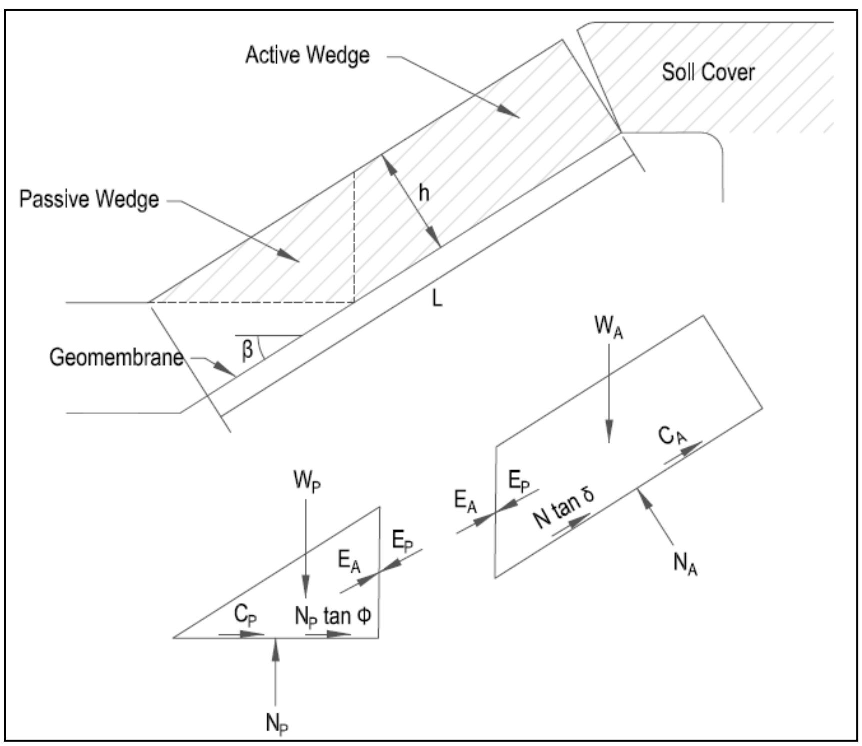


Figure 20.4.10.1.1.2-1. Finite slope stability cross section and free-body diagram.

The factor of safety for the conditions described above is given by:

$$FS = \frac{-b + \sqrt{b^2 - 4ac}}{2a}$$

Where:

$a = (W_A - N_A \cos\beta)\cos\beta$
$b = -[(W_A - N_A \cos\beta)\sin\beta\tan\varphi + (N_A \tan\delta + C_a)\sin\beta\cos\beta + \sin\beta(C_P + W_P \tan\varphi)]$
$c = (N_A \tan\delta + C_a)\sin^2\beta\tan\varphi$

W_A	=	Total weight of the active wedge (lb) $= \gamma h^2 \left(\frac{L}{h} - \frac{1}{sin\beta} - \frac{tan\beta}{2}\right)$
W_P	=	Total weight of the passive wedge (lb) $= \frac{\gamma h^2}{sin2\beta}$
N_A	=	Effective force normal to the failure plane of the active wedge (lb) $= W_A cos\beta$
	=	Unit weight of the cover soil (lb/ft^3) (use buoyant when submerged)
h	=	Thickness of soil cover (ft)
L	=	Length of slope measured along the geomembrane (ft)
	=	Soil slope angle beneath the geomembrane (degrees)
φ	=	Soil internal angle of friction (degrees)
δ	=	Interface friction angle between cover soil and geomembrane (degrees)
C_a	=	Adhesion between active wedge soil cover and geomembrane (lb/ft^2)
C_P	=	Adhesion between passive wedge soil cover and geomembrane (lb/ft^2)

If the factor of safety calculated using the equation above is below Reclamation guidelines outlined in chapter 4 of Design Standards No. 13, it can be increased by flattening the slope, using a tapered soil cover thickness that widens at the base, or by using geosynthetics that result in a higher interface friction (i.e., textured geomembrane).

20.4.10.1.2 Nonuniform Soil Cover Thickness

In some dams, the soil overlying the geomembrane has a nonuniform thickness. As previously discussed, two types of movements may cause instability of the soil cover/geosynthetic system: (1) sliding within the soil cover and (2) sliding at the soil cover/geosynthetic interface. The first case can be analyzed using the conservative infinite slope analysis. The classical wedge analysis can be also used to evaluate the stability of a soil cover/geosynthetic interface. The designer is encouraged to use two-dimensional, limit equilibrium software for the evaluation of a tapered or nonuniform soil cover while adhering to the guidelines outlined in chapter 4 of Design Standards No. 13 [41].

20.4.10.1.3 Stability During Rapid Drawdown

The methods presented above assume that the reservoir is either empty or full. If the water level in the reservoir is lowered, the water level in the soil cover moves down. If the drawdown of the reservoir is fast, excess pore water pressures develop in the soil cover, which may render the cover unstable. This phenomenon, known as "rapid drawdown," exists when the soil cover permeability is less than the value given by the following expression [45]:

$$k = {}^{v}\!\big/_{\sin^2 \beta}$$

Where:

k	=	Required hydraulic conductivity (length/time)
v	=	Velocity of drawdown (length/time)
	=	Slope angle (degrees)

For typical drawdown rates, this equation indicates that only clean coarse sand or gravel can be assumed to drain. If a cover consist of silty materials, this expression may not work. It is essential during design of soil covers to consider the rapid drawdown situation.

In the case of sliding along the geomembrane interface or in the soil, the worst case for rapid drawdown occurs when the water level is drawn down from the maximum level to the upstream toe. The stability of the soil cover can be evaluated using the method presented above by considering pore pressures or seepage forces within the soil cover. Alternatively, commercially available slope stability computer programs can be used.

20.4.10.2 Concrete and Cement-Based Cover

Concrete or cement-based (e.g., soil cement) protective covers may also be used to protect the upstream slope of dams constructed with a geomembrane liner. Cement-based covers may be composed of prefabricated panels, slabs, pavers, cast-in-place, or in the case of soil cement, placed with conventional earthmoving equipment. Cement-based covers are usually stable under the effect of gravity forces because of the high compressive strength and because they are typically resting on a concrete foundation, such as a plinth, at the toe of the dam. The only potential instability with these types of covers results from:

- Underpressures in case of rapid drawdown
- Shocks and underpressures caused by wave action
- Freeze/thaw action

Drainage between the cement-based cover and the geomembrane may be necessary to minimize pressure buildup. A possible option for addressing the required drainage is to place a thick, needle-punched nonwoven geotextile between the concrete cover and the geomembrane. This geotextile could protect the geomembrane from damage induced by the concrete cover during construction and operation (especially under wave action). However, the designer must thoroughly evaluate the stability of the above system. For the geotextile to provide sufficient protection and to have adequate hydraulic transmissivity, a minimum mass per unit area of 10 oz/yd^2 is sometimes recommended, and 12–18 oz/yd^2 is preferable.

The required hydraulic conductivity of the drainage layer to prevent the development of excess water pressure in case of rapid drawdown can be evaluated using the equation presented in section 20.4.10.1.3.

Therefore, a needle-punched nonwoven geotextile, with a hydraulic conductivity greater than 3.28×10^{-3} feet per second (ft/s) under the compressive stress due to the weight of the concrete cover, would provide adequate drainage for a drawdown slower than 3.28×10^{-4} ft/s (i.e., less than 28 ft/day). In practically all cases, drawdown will not be this rapid.

Conditions imposed by wave action are more severe because the water level then fluctuates much faster than in the case of rapid drawdown. As a result, the condition expressed by the equation in section 20.4.10.1.3 cannot be met by a typical nonwoven geotextile. The drainage capacity can be increased by grooves under prefabricated slabs, holes through the slabs, or drainage pipes inserted in the concrete protection. Furthermore, there are some geocomposites that would be advantageous for protecting the underlying geomembrane and increasing transmissivity.

20.5 Specifications and Construction Considerations

20.5.1 Seaming Techniques

Applicable seaming methods depend on the type of geomembrane; however, hot-wedge welding is the preferred method of installation under most circumstances. Some geomembranes can be seamed by several different methods, which are presented in some detail below, as Reclamation has used numerous techniques in the past to construct geomembrane systems. The most common seaming methods for polymeric geomembranes are listed below:

- Methods involving heat only
- Methods involving supply of hot base products (extrusion products)
- Methods involving solvents and/or cements
- Methods involving vulcanizing tapes or adhesives

Methods using heat are applicable only to geomembranes made with base products sensitive to heat (i.e., thermoplastics or thermoplastic rubbers). All seaming methods can be used in a plant or in the field, except the dielectric method, which is not used in the field because it is sensitive to dust and humidity and the equipment is cumbersome.

20.5.1.1 Types of Seams and Seaming Methods

Seaming techniques that are currently used in the factory to fabricate panels of thermoplastic geomembranes, or in the field to assemble the panels or rolls of geomembranes into a final liner, or both, include:

Chemical methods:

- Solvent welding with neat solvents
- Bodied solvents
- Special adhesives

Thermal methods:

- Heat gun
- Heat sealing
- Dielectric seaming
- Extrusion welding
- Hot wedge
- Ultrasonic

Table 20.5.1.1-1 presents a list of the possible alternative methods for seaming polymeric materials depending on the polymer, type of compound, and location of seaming (i.e., factory or field).

Table 20.5.1.1-1. Seaming methods for geomembranes

Geomembrane type	Extrusion methods	Thermal methods	Chemical methods	Adhesive methods
HDPE	X[1]	X		–
LLDPE	X	X	–	–
PVC	–	X	X	X
CSPE	–	X	X	X
fPP	X	X	–	–
EPDM	–	–	–	X

[1] X indicates available method.

Figure 20.5.1.1-1 illustrates the configuration of the various seams and the methods of seaming that are used. Seam overlap requirements vary with geomembrane manufacturers, geomembrane type, and seaming procedure. Recommended overlaps range from 4 to 12 inches.

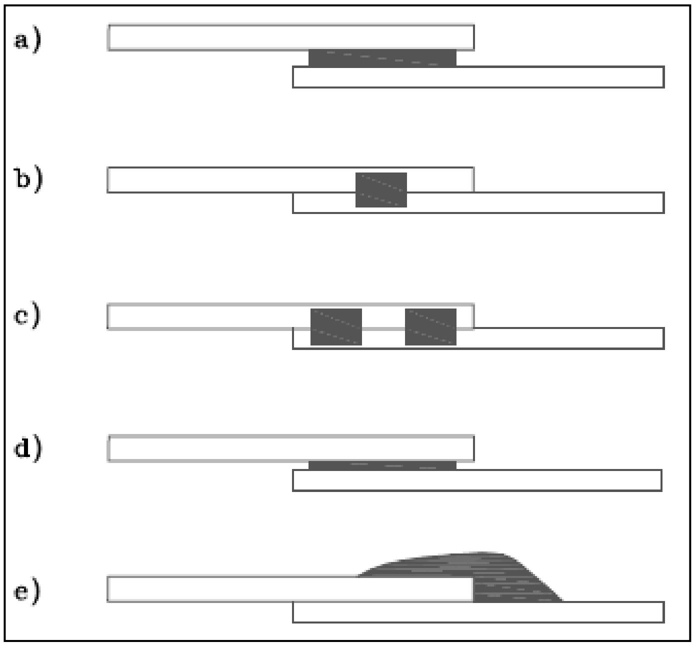


Figure 20.5.1.1-1. Various seam configurations: (a) chemical adhesive or fusion, (b) single hot wedge, (c) dual hot wedge, (d) thermal or dielectric, and (e) fillet extrusion weld.

20.5.1.1.1 Chemical Methods

Because of the solubility of noncrystalline thermoplastic polymer compositions in appropriate solvents and the lack of crosslinks, a geomembrane based on a noncrystalline thermoplastic polymer (e.g., PVC and CSPE) can be seamed with chemical solvent mixtures or with solvents in which the geomembrane compound has been dissolved to form a bodied solvent. Sometimes, solvents are not allowed to be used in a water supply reservoir because of concerns regarding the effect of the chemical solvents on water quality. Seaming by these techniques is described in the next two sections.

20.5.1.1.1.1 Solvent Welding

Solvent welding of noncrystalline thermoplastic geomembranes with neat solvents can be achieved by coating the mating surfaces of the geomembranes with a solvent or a mixture of solvents suitable for the compound. The two surfaces are then pressed together firmly (e.g., by “stitching” with rollers) on a firm base. The time for such a seam to “cure” or set up ranges from 5 minutes to an hour depending on the type of geomembrane and environmental conditions. Up to 28 days may be needed for the solvent to evaporate completely from within the seam and for it to achieve full strength. Though this method can be used both in the field and in the factory, it is sensitive to weather conditions (e.g., temperature, humidity, and wind). Volatile solvents that may be desirable at lower temperatures will evaporate too quickly at higher temperatures or may fail under humid conditions to yield an adequate bond because of moisture condensation. In making repairs, it is also necessary to change or refresh the exposed surface to remove dirt, exudation from the geomembrane (e.g., waxes, and moisture).

20.5.1.1.1.2 Bodied Solvents

The use of a bodied solvent to seam thermoplastic geomembranes is an adaptation of the solvent "welding" methods described previously. A bodied solvent is a solution of the geomembrane compound to be seamed in a mixture of solvents. The "adhesive" is applied to both surfaces, and the two surfaces are pressed together after becoming "tacky." There should be no surface "skinning" or drying of the adhesive when the two surfaces are joined.

The major advantage of a bodied solvent over a straight solvent is the increased viscosity of the solution, which allows more control of the evaporation of the adhesive and aids in making seams on a slope. Another advantage of bodied solvents is that the dissolved polymer fills voids or imperfections in the surface of the geomembrane and thus improves the consistency and strength of the seams. As with solvent "welding," bodied solvents can only be used with thermoplastic materials that can be dissolved in a suitable mixture of solvents.

The bodied solvent technique can be used to seam geomembranes in the factory and is particularly useful in the field. It has been used primarily in the seaming of CSPE and PVC geomembranes and in making field repairs during the installation of geomembranes. Testing of seams must wait until the solvent in the seam has evaporated through the geomembrane or has been driven out by heat.

20.5.1.1.2 Thermal Methods

A variety of thermal seaming methods are applicable to thermoplastic geomembranes that soften, melt, and flow at higher temperatures to fuse the sheets being joined. Thermal seaming methods include:

- Heat gun
- Heat sealing
- Dielectric seaming
- Hot-wedge welding
- Ultrasonic welding

20.5.1.1.2.1 Heat Gun

Seaming with a heat gun has been used for all types of thermoplastic geomembranes under both factory and field conditions, including repair of unexposed liners. In this method, high temperature air or an inert gas, such as nitrogen, is directed between two sheets to melt the surfaces to be joined. The two pieces are then forced together with pressure and allowed to cool to form a lap seam.

The major advantage of the heat gun method is its broad range of application to many thermoplastic materials. The two disadvantages are the great care required to obtain uniform, reproducible seams and the tendency of the hot air to oxidize and degrade the surface of the geomembrane during the seaming process and thus produce a poor bond. This method also requires that the surfaces to be joined be clean and free of moisture, dust, oil, and all solvents. These requirements pose problems when seaming in the field, particularly when seaming geomembranes that have been exposed to the weather.

20.5.1.1.2.2 Heat Sealing

In this thermal seaming method, the heat required to melt and bond the two layers of thermoplastic geomembrane is applied through the sheets by clamping them between a pair of jaws that are quickly and reproducibly heated, normally by passage of an electrical current through a resistance wire. The sheets remain clamped for a preset period of time following cessation of the current, and the molten polymer solidifies to form a lap bond.

The advantage of heat sealing is that the complete bonding cycle is readily controlled by a timer, and thus, seams can be made rapidly and reproducibly. Since exposure of the heated plastic to air is minimal, the problem of oxidation and embrittlement is reduced.

Another form of heat sealing, which is not considered advantageous over clamping, is a heated roller that can be used manually to simultaneously press and melt together both sides of the seam. Both roller and clamp heat sealers share a serious disadvantage in that heat must pass through the seam and, thus, are generally limited in application to relatively thin geomembranes. With thicker membranes, the bonding process is very slow, and the heated surfaces tend to become fluid, flow, and thin down before the bonding surfaces are sufficiently molten for fusion to occur.

20.5.1.1.2.3 Dielectric Seaming

In dielectric seaming, heat is generated internally within the pieces of geomembrane to be joined by directing electromagnetic energy in the radiofrequency region to the seam. The energy field oscillates and causes the permanent or induced dipoles in the polymer to oscillate with the same frequency, creating internal friction and heat. Advantages of dielectric heating are that the entire cross section of the geomembrane is heated quickly and uniformly, the heating process can be instantly started and stopped, the method is very efficient as it does not generate waste heat, and the process is readily controlled and highly reproducible. Pressure is applied until the area being seamed has cooled and a strong bond is formed.

Dielectric seaming can only be used with geomembranes based on thermoplastic polymers synthesized from easily polarizable monomers. The presence of water in an exposed geomembrane can result in internal blowing and sponging of the geomembrane. This technique is suitable only for factory operations in which the environmental requirements of the equipment can be met. Geomembranes that can be seamed by this technique are based on such polymers as PVC, CPE, and CSPE; polyethylenes (PEs) cannot be seamed by this technique. Within these limitations, dielectric seaming provides very rapid and reliable seaming, but it is not suitable for field seaming of geomembranes.

20.5.1.1.2.4 Hot-Wedge Welding

The hot-wedge method consists of a hot electrically heated element in the shape of a blade or V-shaped wedge that is passed between the two sheets to be sealed. Contacting the two sheets to be seamed together, the heated element melts and smears the two surfaces, causing fresh material to come to the surface. Immediately following the melting, roller pressure brings the molten surfaces together to form a homogeneous fused bond.

The hot-wedge method is particularly suited for LLDPE, HDPE, and PVC geomembranes thicker than 0.75 mm (30 mil), but it is also used with reinforced thermoplastics. Single-hot-wedge and dual-hot-wedge systems (figure 20.5.1.1.2.5-1) are both available. The dual-hot-wedge weld forms a continuous air channel between two welds. The air channel can be used as a means of testing the bond continuity when air pressure is injected into it. Welding rate (movement of the machine) as well as temperature and roller pressure are adjustable and continuously monitored. Adjustments are made according to environmental conditions such as ambient temperatures and moisture. The dual-hot-edge technique is preferred by Reclamation because of its reliability and verifiability.

The hot-wedge method has been used in both the factory fabrication of panels and in field installation. It is particularly suited to long, continuous, straight seams. However, without special modification, it is not suitable for making repairs because of the irregularity of the shapes required to patch liners. A closed loop cannot be welded using this equipment.

Dual-hot-wedge welding is considered to be a superior seaming method as compared to ultrasonic welding. Reclamation practice is to specify only dual-hot-wedge welding for seaming and only allow extrusion welding for patches and penetrations unless unusual circumstances are present.

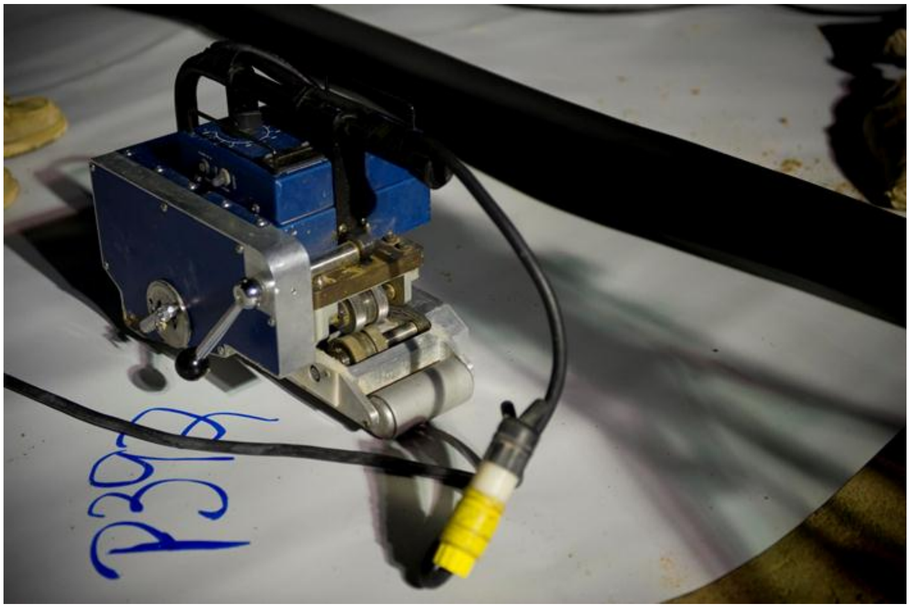


Figure 20.5.1.1.2.5-1. Dual-hot-wedge welder.

20.5.1.1.2.5 Ultrasonic Welding

A newly introduced welder for seaming geomembranes involves the use of ultrasonic energy that is designed to concentrate the vibrational energy at the point of contact of the two geomembranes to be seamed, causing the geomembranes to become molten as a result of the heat generated by frictional activity. Immediately upon melting, the membrane surfaces pass through two rollers that squeeze the two sheets together to create a bond from 1 to 2 inches in width. The welder is mounted on a three-wheel frame. The rollers, which are motor driven, serve to propel the unit at a controlled rate along the seam line. This seaming method has been applied to thermoplastic films from 0.010 to 0.125 inch thick and may not be suitable for thicker geomembranes.

20.5.1.1.2.6 Extrusion Method

Extrusion welding is more commonly used for geomembrane repairs or small seaming jobs, such as around corners or near structures, rather than large seaming tasks. Seaming of HDPE geomembranes is being performed in the field with a variety of proprietary and specially designed seaming equipment based on the extrusion of molten HDPE of the same composition as the liner either between the geomembranes being seamed to form a lap weld or at the edge of the top sheet to form a bead or fillet. Also, seaming equipment based on heat guns has been devised in which coiled plastic welding rods or strips can be melted and placed. The rod is fed to the seam area to form a fillet-weld seam.

In the first extrusion welding procedure, a jet of hot air is injected into the overlap area to blow away debris and heat the area to be welded. Directly following the hot air, a ribbon of molten polymeric compound of the same composition to that of the geomembrane being seamed is injected into the overlap through an extruder nozzle. A roller moving behind the extruder nozzle presses the overlap together so the sheets will be fused by the extruded ribbon. Welding speed, pressure roller movement, and temperature are adjustable with the extrusion equipment. The result can be a homogeneous weld that is immediately load bearing.

In the second extrusion welding procedure, a hand-held extruder, in which pellets or strips are fed and melted, places a bead or fillet of the molten PE at the edge of the overlap of the two geomembranes that are being seamed. The surfaces of the geomembranes are always buffed and cleaned prior to seaming; also, the edges of thicker geomembranes are beveled to give greater surface and to ensure that air pockets are not left at the edge of the top geomembrane. In performing this seam, the top geomembrane is positioned and tacked to the lower geomembrane through the use of heat guns or gum tape between the two geomembranes. This type of seaming is used both in assembling the geomembranes and in the repair and patching of geomembranes.

With extrusion and fusion seaming methods, continuous seams of extended length can be made in the field at a broad range of ambient temperatures. The critical temperature is that of the geomembrane and the extrudate. Welding can be carried out at geomembrane temperatures greater than 35 degrees Fahrenheit (°F). With extra measures such as (1) slowing down welding rate, (2) preheating the sheet, and (3) setting up windshields for the welder, welding is possible down to sheet temperatures of 5 °F. Success at these low temperatures should be verified by test welds.

Extrusion seaming methods, as with all other seaming methods, require careful preparation of the surfaces to be bonded (e.g., drying and buffing, removal of any oxidized layer, as well as proper adjustment of temperatures at the surfaces of the layers to be joined) to ensure blending and molecular mixing of the polymeric compound at the interface.

20.5.1.1.3 Other Bonding Methods for Seaming Geomembranes

In addition to the seaming methods, described previously for thermoplastic and thermoplastic rubber geomembranes, other methods are used in the seaming of crosslinked geomembranes (i.e., butyl rubber [IIR], EPDM, polychloropene [CR], and some thermoplastics). Discussions of these seaming methods are included for information because geomembranes currently in service were seamed by these methods and because Reclamation has conducted research of these methods.

Other bonding techniques, including hot vulcanization and vulcanizing adhesives have been used, but are no longer common.

20.5.1.1.3.1 Solvent Cements and Contact Adhesives

“Solvent cements” is an expression used by the adhesive industry to refer to any of a large variety of chemical adhesives that are applied dissolved in a nonaqueous solution. The strength of the bond is achieved either contemporaneously with or after the volatilization of the solvent. Thus, a solvent cement can be anything from a solution of a thermoplastic resin to a contact cement. Two types of solvent cements are of interest to the lining industry:

- Contact cements
- Chemical adhesives that volatilize their solvent while forming the adhesive bond

Surfaces to be bonded by the second type of adhesive are usually pressed together while the solvent cement is still "wet." Because polymeric geomembrane materials can have low permeability to a number of solvents, it is important to choose a chemical adhesive that can volatilize out of the seam assembly. This can happen when the adhesive either dissolves or partially dissolves the surface of the geomembrane and forms what might be called an "interpenetrating" bond with the lining material.

Contact cements are adhesives that are applied wet to surfaces of geomembranes that are to be bonded and allowed to dry to a "nontacky" and solvent-free state before the two surfaces are joined. The use of this type of adhesive requires careful alignment of the geomembrane before bonding because the joined surfaces should not be realigned after assembly. After joining, the seam should be rolled with a steel or plastic roller in a direction perpendicular to the edge of the seam.

Based on meeting safety requirements, solvent cements could be used either in the field or in the factory to seam geomembranes; however, they are more likely to be used only in the field.

20.5.1.1.3.2 Tapes

Tapes have been used in the past to seam geomembranes in the field. They are made with pressure-sensitive adhesive applied either to both sides of a flexible substrate or to a flexible backing. The latter is removed once the tape has been placed on one of the surfaces to be joined. Tapes can be used to hold the geomembranes in place while another seaming technique is used, or they can be used to provide the permanent bond.

Tapes can be used to seam HDPE and LLDPE geomembranes in the field; however, the use of tapes alone for making permanent seams in geomembranes is not recommended.

20.5.2 Construction Quality Assurance and Quality Control Measures

Construction quality assurance is a planned and systematic pattern of all means and actions designed to provide adequate confidence that items or services meet specification requirements and will perform satisfactorily in service. In the context of geomembrane-lined facilities, CQA refers to means and actions employed by Reclamation through the quality assurance team to ensure conformity of the design, production (i.e., manufacture and fabrication) and installation with the quality assurance plan as well as with drawings and specifications.

The sections below present the elements of CQA pertinent to the installation of geomembranes in embankment dam applications. A quality assurance plan is a document, prepared as part of the CQA, that describes the actions required in order to ensure the highest quality during all phases of the design, construction, and operation of the geomembrane-lined facility.

The CQA plan for a specific project should delineate in great detail the responsibilities and interactions of the various parties. Several of the parties should possess specific credentials and/or qualifications in order to demonstrate an acceptable level of competence to perform the assigned role. The following is a listing of qualifications required of the various parties involved with the manufacture, fabrication, installation, and transportation of geomembranes and other geosynthetic components of embankment dams:

- **Manufacturer** – The geomembrane manufacturer is responsible for production of geomembranes from raw polymer. The manufacturer should be required to demonstrate adequate production capability to produce quality materials with consistent properties. The manufacturer should demonstrate experience in producing significant quantities of similar materials and be able to show adequate quality control facilities and procedures for the past as well as the present products. The geomembrane manufacturer should be pre-qualified and approved by Reclamation.

- **Polymer or Resin Supplier** – The polymer or resin supplier produces and delivers raw polymer (typically in the form of flakes or pellets) to the manufacturer. Qualifications of the polymer supplier are specific to the manufacturer's requirements. The polymer supplier should have a demonstrated history of providing raw polymer with consistent properties.

- **Fabricator** – The geomembrane fabricator is responsible for the fabrication of factory panels of geomembranes constructed from rolls received from the manufacturer. The fabricator may also be responsible for delivery of the factory panels to the project site. The fabricator should show documentation from the manufacturer certifying experience in fabricating and handling of the manufacturer's products and special equipment.

- **Transporter** – The transporter is responsible for transporting geomembrane rolls from the manufacturer to the fabricator on the site and/or factory panels from the fabricator to the site. All personnel responsible for loading, transporting, and unloading the geomembranes must be fully aware of the consequences of damage to the geomembranes and be familiar with the handling and transporting constraints required by the manufacturer and/or fabricator.

- **Installer** – The geomembrane installer is responsible for the field handling, storing, placing, seaming, loading (against wind), and other aspects of the geomembrane installation. Adjusting and seaming the geomembrane panels to site-specific conditions is the responsibility of the installer. The experience of the installer is critical to fitting long rectangular sheets to a variable ground surface without wrinkles, folds, excessive waste, or seaming. Each job is different, so expertise with geomembrane installation is vitally important. The installer may also be responsible for transportation of the geomembrane to the site and may also be responsible for anchor trenches and all temporary anchoring or loading required to support the geomembrane during installation. The installer should show documentation from the manufacturer certifying experience in the installation of the manufacturer's products and special equipment. The installer should have significant experience on similar projects and be able to provide resumes of experienced personnel who will be involved in the project.

- **Contracting Officer's Representative (COR)** – The COR and inspectors should have adequate training prior to installation of geomembrane. The COR should implement an inspection program to verify that the geomembrane is installed and constructed as intended. An effective inspection program depends largely on recognition of all construction activities that should be monitored and on assigning responsibilities for the monitoring of each activity. This is most effectively accomplished by and verified by the documentation of quality assurance activities. The inspector should document that all quality assurance requirements have been addressed and satisfied. The designer should consider post-construction leak detection to verify that the geomembrane is functioning as intended. See section 20.5.10.2 for a discussion of possible leak detection techniques.

20.5.3 Geomembrane Factory

In many cases, rolls are transported directly to the site, and the fabrication of large panels by seaming individual sheets at an offsite location is not necessary. Geomembrane rolls are sometimes installed horizontally (i.e., across the slope of a dam, but this should be avoided if at all possible). In the majority of cases, geomembrane rolls are installed down the slope. In these cases, it is important that the length of each roll be slightly greater than the length of the slope at the location where a particular roll is to be installed. Therefore, the manufacturer should have the capability to manufacture rolls of different lengths, up to the maximum required length, and that rolls are properly labeled because lengths of the various rolls may vary.

The following should be requested from the manufacturer at the time, or shortly before, the geomembrane rolls are delivered to site:

1. A copy of each of the Quality Control Certificates on each lot of resin issued by the resin supplier for the specific material for this project, including certification of the resin for extrusion welding.

2. The results of quality control testing conducted by the manufacturer on the resin used in manufacturing the specific material for this project.

3. A listing that correlates the resin to the individual geomembrane rolls and welding rods.

4. A copy of the geomembrane roll Quality Control Certificates. It is suggested that the certificates be supplied at a minimum frequency of one per every 50,000 square feet of geomembrane material produced. The certificates should contain test results of properties listed in the section below.

20.5.3.1 Conformance Testing

During manufacturing of the geomembrane, conformance testing conducted by Reclamation should be completed on samples to verify that the material meets the specification requirements. It is suggested that the geomembrane be tested every 150,000 ft^2 and that samples be taken across the entire width of the sheet. The samples should not be taken within the first 3 feet of the roll. The tests listed in table 20.5.3.1-1should be conducted on each conformance sample.

Table 20.5.3.1-1. Suggested minimum geomembrane tests (ASTM)

Description	Test procedure
Thickness	D5199 (smooth) or D5994 (textured)
Compound density	D1505 or D792
Carbon black dispersion	D5596
Carbon black content	D1603 or D4218
Ultimate tensile strength	D6693 Type IV
Ultimate elongation	D6693 Type IV
Puncture resistance	D4833 or D5514
Shear strength	D6392 or D751
Peel strength	D6392 or D751

20.5.4 Large Panel Fabrication

Large panels can be fabricated by seaming rolls together in a fabrication plant. This is typically done with flexible geomembranes, such as PVC and CSPE geomembranes, that are available in narrow rolls. Because HDPE and LLDPE geomembranes are stiff and are usually available in large rolls, large panel fabrication is typically not performed.

Fabrication of geomembranes that combines the rolls into large panels is accomplished to meet the actual field conditions at the site. The rolls are factory-seamed whenever possible into the largest sections that are manageable, which generally weigh 2 tons or contain 20,000 ft^2. In general, the geomembrane is rolled onto handling tubes, except for some thin geomembranes that may be accordion-pleated, folded, and shipped to the site in boxes [4].

20.5.5 Transportation

Transportation is the process of shipping or transporting geomembrane rolls or factory panels from the manufacturing plant to the site, from the manufacturing plant to the fabrication plant, or from the fabrication plant to the site. Three important considerations relevant to transportation are packaging, labeling, and delivery.

20.5.5.1 Packaging

Care should be taken to ensure that the geomembrane rolls or panels are not damaged during transportation. Fabricated geomembrane panels are usually shipped accordion-folded in cardboard boxes. The use of wooden boxes with nails are not recommended because they can cause severe damage to geomembrane panels if the nails come in contact with the geomembrane during transportation.

Rolls shipped directly from a manufacturing plant to the site are often unprotected. As a result, damage can occur during handling, and the first 10 feet (approximately 1 roll wrap) of geomembrane may have to be discarded. In some cases, the entire roll could be damaged and must be discarded.

20.5.5.2 Labeling

The package containing each roll or panel should bear a label indicating:

- Manufacturer’s name
- Geomembrane type
- Thickness
- Roll number
- Batch or lot number
- Panel installation number (if applicable)

- Roll dimensions and weight
- Special handling instructions (if required)

20.5.5.3 Delivery

Upon delivery of the geomembrane rolls or panels, it is important to review all the labels on the packages to verify that the proper material and that all required rolls or panels have been delivered. The condition of the products should be inspected before and after removing the tiedown restraints. Unloading and transport to temporary storage should be monitored. Wide, cloth straps or steel pipes threaded through the rolls should be used for lifting. Do not transport rolls with the forks of a fork lift or other method that could potentially damage the geomembrane.

20.5.6 Storage

Care should be exercised to prevent damage to the membrane before it is installed. All geomembranes should be stored out of sunlight if possible to prevent degradation. The geomembrane should be stored on a prepared surface to prevent punctures. The manufacturer’s recommended limits for stacking rolls on top of each other should be obtained and followed, as overstacking of rolls can cause damage. The geomembrane should also be protected from excessive heat, cold, cutting, puncture, or other harmful conditions. An additional, important consideration in storing geomembranes at a site is prevention of vandalism and theft.

Once deployment of the geomembrane begins, it can be moved from the storage site to the construction site by means of a front-end loader or other suitable piece of equipment with proper slings as shown on figure 20.5.6-1 or other lifting devices. Care should be exercised to avoid damage to the geomembrane.

Figure 20.5.6-1. Storage of geomembrane rolls on top of geotextile to prevent damage from underlying material (note the use of nylon slings for lifting).

20.5.7 Deployment

20.5.7.1 Subgrade Acceptance

The subgrade should be inspected to make sure that it is firm and free of sharp rocks, debris, or standing water. If inspection of the soil surface indicates the need for further fine finishing, this work should be performed as required. The subgrade should be inspected on a daily basis to verify that it is acceptable for deployment. If necessary, the subgrade should be returned to the condition that was originally accepted prior to geomembrane deployment. In some instances of rough conditions, additional material such as clay or sand may need to be spread and recompacted to achieve a uniform, smooth surface. An example of an acceptable subgrade surface is shown on figure 20.5.7.1-1.

Figure 20.5.7.1-1. Subgrade preparation prior to geomembrane installation.

20.5.7.2 Installation Planning

A panel layout drawing, typically supplied by the installer, showing the proposed installation layout that identifies field seams, including locations of pipe penetrations and connections to appurtenant structures, should be reviewed and approved prior to placement of geomembrane. The layout should be sufficiently detailed so that it can be used as a construction plan and should include items such as panel dimensions, panel numbers, seam numbers, and connections to appurtenant structures.

20.5.7.3 Visual Observation

Visual observations that should be documented during field operations include:

- Observations to ensure that the geomembrane is free from dirt, dust, and moisture

- Observations to ensure that the seaming materials and equipment are as specified
- Observations to ensure that a proper foundation is available for deployment and seaming
- Observations of weather conditions (e.g., temperature, humidity, and wind) to ensure that they are acceptable for seaming
- Measurements of temperatures, pressures, and speed of seaming, when applicable, to ensure that they are as specified (e.g., gages and dials should be checked and recorded)
- Observations to ensure that the geomembrane is not damaged by equipment or personnel during the seaming process

Figure 20.5.7.3-1 shows a typical example of seaming operations being documented.

Figure 20.5.7.3-1. Visual observation of dual-hot-wedge welder seaming operations.

20.5.7.4 Placement

In general, panels should be placed so that field seams are directed up and down the slope. This minimizes short-term stresses on field seams during placement of a protective cover and minimizes long-term stresses on seams due to fluctuating reservoir loads. In order to prevent wind damage, a sufficient ballast, such as sand bags, to prevent uplift of the geomembrane panels should be supplied. Deployment of geomembrane during adverse weather conditions should be avoided if it will preclude material seaming on the same day as deployment.

The geomembrane should be pulled relatively smooth over the subgrade. If the subgrade is smooth and compacted, then the geomembrane should be relatively flat on the subgrade. However, sufficient slack must be left in the geomembrane to accommodate possible shrinkage due to temperature changes, which may result in tension in the geomembrane. It is very difficult to readjust a geomembrane sheet that has already been deployed, particularly textured sheet, due not only to self-weight and friction with the subgrade, but oversized soil particles may be rolled out of the subgrade and cause subsequent damage to the membrane when covered with soil and the reservoir. Care must be taken to avoid shifting a deployed geomembrane sheet.

It is important to make sure that no "bridging" occurs in the geomembrane in which angles are formed by the subgrade directly under a geomembrane (i.e., meeting of two berms at a 90-degree angle). Bridging is a condition that exists when the geomembrane extends from one side of an angle to the other, leaving a void beneath the geomembrane at the apex of the angle. Bridging occurs most often at penetrations and where steep sidewalls meet the subgrade. Particular attention has to be directed to keeping the geomembrane in contact with the subgrade at these locations and keeping it in a relaxed condition.

On embankment dam slopes, bridging may occur if there is a horizontal bench across the upstream slope. In this case, it may be preferable to install the geomembrane in two stages with a horizontal seam on the bench. Also, care should be taken not to install geomembranes on areas that may eventually become depressed as a result of water pressure. Geomembrane failures have been reportedly caused by the settlement of poorly backfilled trenches for underdrains.

A geomembrane should be installed during dry weather, between ambient temperatures of 35° F and 100° F, unless special measures are taken. To the extent practicable, all panels should be installed in similar temperature conditions to avoid length differences between adjacent panels, resulting in "fish mouths" during seaming. Installation during extremely cold, extremely hot, and/or wet weather can be performed, but it should be demonstrated that adverse weather conditions do not affect the integrity of the installed liner. Particular care should be taken when installing HDPE geomembranes because they have a high coefficient of thermal expansion, and undesirable wrinkles could result during installation in hot weather conditions. Considerations to avoid this situation are to place the geomembrane at night, or if hot weather cannot be avoided, select an alternative geomembrane type or color that will not expand excessively in hot weather.

20.5.8 Seams

An important aspect of the quality assurance of geomembrane installation is the complete documentation of seaming operations, which includes a record indicating, for each section of seam, the name of the operator, identification of the equipment used, the date, the weather conditions, etc. Prior to seaming geomembrane rolls or panels, an inspector should observe the trial seams (discussed in section 20.5.8.3) performed at the beginning of every shift on extraneous pieces of geomembrane to test the operators and their equipment. A successful trial seam only indicates that the operator and equipment perform adequately at the time and under the conditions of the trial and can be used in that shift for making the seams.

All seam and nonseam areas should be subjected to 100-percent visual examination for identification of defects, holes, blisters, undispersed raw materials, and any sign of contamination by foreign matter. Because light reflected by the geomembrane helps to detect defects, the surface of the geomembrane should be clean at the time of examination. The geomembrane surface should be cleaned by the installer if dust or mud inhibits inspection.

20.5.8.1 Seam Layout

In general, seams should be oriented parallel to the line of maximum slope (i.e., oriented down, not across the slope). In corners and odd-shaped geometric locations, the number of field seams should be minimized. If horizontal seams cannot be avoided, they should not be closer than 5 feet from the toe of the slope. The seams should also be aligned to prevent wrinkles and “fish mouths.” If a “fish mouth” or wrinkle cannot be avoided during installation, it should be removed and capped. Panels of geomembrane should have sufficient overlap to allow peel tests to be performed on the seam.

20.5.8.2 General Seaming Procedures

The following is a list of general procedures to follow when seaming adjacent panels together:

- Areas to be seamed should be cleaned and free of moisture, debris, or any marking on the geomembrane.
- Use a flat board, slip sheets, or similar hard surface directly under the seam overlap to achieve proper support if required.

- Cut "fish mouths" or wrinkles at the seam overlap along the ridge of the wrinkle in order to achieve a flat overlap. The "fish mouths" or wrinkles should be seamed, and if the overlap is inadequate, it should be patched with an oval or round patch of the same geomembrane material extending a minimum of 6 inches beyond the cut in all directions.
- Extend seams to the outside edge of the panels placed in the anchor trench.

T-seams are defined as a location where three panels intersect each other and a dual wedge weld typically crosses another seam at approximately 90 degrees. T-seams should be capped with a geomembrane sheet that extends a minimum of 1-foot beyond the T-seam intersection in all directions and either extrusion welded or chemically welded, depending on the geomembrane material.

20.5.8.3 Trial Seams

It is recommended that trial seams be conducted for all types of welds to be used at the beginning of each seaming period and within 30 minutes of commencement of seaming and immediately following any work stoppage (i.e., lunch, weather conditions, etc.) that are greater than 30 minutes or more for each seaming apparatus used that day. If ambient temperatures changes more than 20 degrees, new trial seams are required. The trial seams should be at least 10 feet long and be tested for peel and shear strength using an onsite tensiometer. Seaming of the geomembrane panels should not commence until all trial seams have passed peel and shear tests. As part of the trial seam procedure, the installer should mark the test weld with the date, ambient temperature, welding machine number, welding technician identification, machine temperature, and machine settings. An example of a trial seam is shown on figure 20.5.8.3-1.

Figure 20.5.8.3-1. Trial seam performed on suitable, clean surface.

20.5.9 Patching and Repairs

It is important that specifications include procedures to follow in the event of failing destructive tests. This is especially true if the test results from the laboratory lag significantly behind the placement of cover material. Similarly, the specifications must clearly establish procedures for repairing holes caused by test sampling. Currently used tests to evaluate seam and patching repairs are outlined in section 20.5.10.1.

20.5.10 Field Testing

20.5.10.1 Seams

Geomembrane seams should be subjected to nondestructive testing to evaluate seam continuity. Continuity is the term used to describe the existence, but not the strength, of the seam (i.e., a seam may be continuous over its entire length [100-percent continuity], but be so weak that it may be broken by light pressures or thermal gradients). It is therefore necessary to also evaluate seam strength and seam continuity. Currently, there are no known nondestructive methods of testing for seam strength. As a consequence, both destructive and nondestructive testing methods are required. An air pressure test in a wedge-welded seam is shown on figure 20.5.10.1-1, and a vacuum test of a geomembrane repair is shown on figure 20.5.10.1-2. For an air pressure test, a needle is inserted into the channel created by the dual-hot-wedge welder while the other end is plugged. Air pressure is applied, and the seam is required to hold pressure without dropping for a specific time duration. This type of test is preferred by Reclamation. Air pressure and time duration vary between geomembrane type and thickness (ASTM D5820). Once the defect in the seam is located, it should capped with a geomembrane strip that extends a minimum of 1 foot beyond in all directions beyond the defect. In some cases, the entire seam being tested may need to be capped if the defect cannot be found. The cap should be either extrusion welded or chemically welded, depending on the material, to ensure that minimal leakage will occur at the defect.

To the greatest extent possible, seams should be 100-percent nondestructively tested for continuity. The nondestructive tests that are currently in use are described in table 20.5.10.1-1.

The degree of destructive testing should be limited because the geomembrane liner is damaged in the process of taking the test samples. The frequency of sampling should be stated in the specifications, but the actual sampling locations should be selected only after seaming is completed. The selection of sample locations should be made by the inspector based on his/her experience and judgment. However, a suggested frequency for destructive testing is one per 500 lineal feet of seam or minimum of one sample per day, whichever is greater. While selecting destructive samples at the end of panels may avoid creating holes in an otherwise good installation, it is recommended that samples be obtained at specific intervals along seams to ensure quality [51, 52], as operators may preferentially seam with greater care at areas where destructive samples are known to be taken. A typical patch is shown on figure 20.5.10.1-3 in which the destructive sample was obtained along the seam.

Figure 20.5.10.1-1. Air pressure testing of a dual-wedge-welded seam.

Figure 20.5.10.1-2. Vacuum testing of an extrusion welded patch.

Table 20.5.10.1-1. Nondestructive tests used to evaluate seam continuity

Test	Description	Applicability	Comments
Vacuum box	A soapy solution is applied to the geomembrane. A box with a transparent window is sealed against the geomembrane, and a vacuum is established in the box. Soap bubbles will form if there is a leak.	Mostly for stiff geomembranes	• Most commonly used test with stiff geomembranes, such as HDPE, whose thickness exceeds 30 mil. • Cannot be used in corners or around small radii without special apparatus. • Relatively slow process since testing area is limited by size of vacuum box.
Air pressure (ASTM D5820)	A double seam with an intermediate open channel is made. Pressurized air is blown into the channel. Leakage is detected if the specified air pressure cannot be kept constant for the required amount of time. Pressure and time requirements vary between polymer type and thickness.	Can be used on all geomembranes that have a thermal fusion double seam	• Used only with double seams with intermediate open channel (i.e., seams made with hot wedge or hot air). • More severe loading than vacuum test, but tests only a small fraction of seam strength. • Causes minor damage to geomembrane because “leading hole” must be cut. • Quite efficient method since long sections of seam (up to 100 meters) may be tested at one time. • When defects are found, a vacuum box is often used to locate the defect. • Underseam may fail, in which case seam may require capping.
Ultrasonic (ASTM D7006-03)	Several types of ultrasonic techniques are used to assess the continuity of a seam: (1) the measured thickness of the seam can be compared to the thickness it should have and/or (2) voids in the seam can be detected directly.	Geomembranes that are chemically fused	• Reliable test when conducted by very experienced operator over small areas. • Difficult to interpret readout over long periods of time due to operator fatigue.
Spark testing	A conducting wire is placed in the seam during seaming. A spark can be established between the wire and an electric device if the wire is exposed (i.e., if a portion of the seam is missing).	All geomembranes, but requires a wire inserted into the seams	• Difficult to set up accurately over large areas. • Applicable in areas where vacuum cannot be used (corners, etc.). • Results not always reliable.
Air lance	A pipe with a nozzle is used to blow pressurized air at the edge of the seam. If there is a lack of continuity in the seam, air flows under the geomembrane and inflates it or causes it to vibrate, often audibly.	Mostly for pliable geomembranes	• Qualitative test only. • Results not very reproducible.
Probe	A stiff probe, such as a blunt screwdriver, is used to verify mechanically if the seam is continuous.	All geomembranes and seams with well-defined edges	• Qualitative test only. • Results not very reproducible.

Source: Based on Giroud and Fluet [46].

Figure 20.5.10.1-3. Destructive sample patch (Warren H. Brock Reservoir) seamed by extrusion methods (note initials and date of vacuum test on patch).

Destructive laboratory testing should include shear tests as well as peel tests. Results of these tests should be available as soon as possible (typically 48 hours after sampling) to permit prompt action in case of failure of a test. Geomembrane cover material should not be placed before the test results are known. The destructive test samples should be: (1) tested in the field using a tensiometer, (2) tested by the quality assurance laboratory, and (3) tested by the installers' laboratory if possible. A portion of the sample should also be retained at the site.

20.5.10.2 Leakage Detection Techniques

The techniques available for leak detection fall into two main categories: (1) drainage layer techniques based on observations of the leak detection and drainage system between the upper and lower liners of a double-liner system and (2) technologies involving the use of remote sensing techniques.

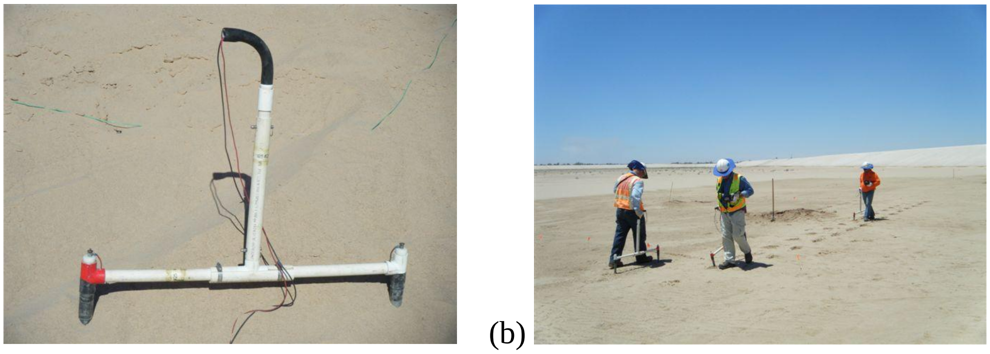
The concept of using the drainage layer between the upper and lower liners of a double-liner system for leak detection is that, by monitoring the liquids that accumulate in the drainage layer sump, the presence of leaks can be detected. This method of leak detection has several attractive features. In addition, to providing leak detection, the method provides information on the volume of leakage collected. Thus, the drainage layer monitors the performance of the upper liner. This is a direct method of leak detection that does not require sophisticated data interpretation. This leak detection technique is discussed in detail by the EPA [6].

Remote sensing techniques are those that can determine the existence of a leak and its location so it can be repaired even when covered with a protective soil. The currently available methods are electrical resistivity, time-domain reflectometry, and acoustical emission monitoring. Other less developed technologies include lysimeters, seismic measurements, electromagnetic techniques, and seismic blocks; these different types of remote sensing techniques are discussed in detail by the EPA [6]. These techniques are highly recommended for critical projects. Electrical resistivity remote sensing techniques were used at Warren H. Brock Reservoir and identified numerous geomembrane defects due to soil cover placement damage as evidenced by figures 20.5.10.2-1 and 20.5.10.2-2.

Figure 20.5.10.2-1. Small damage to geomembrane identified under a protective soil cover at Warren H. Brock Reservoir with electrical resistivity sensing.

Electrical resistivity surveys can be very expensive; however, if project economics allow, it is highly recommended to improve the confidence of the geomembrane integrity. A typical probe and equipment layout used at Warren H. Brock Reservoir is shown in figure 20.5.10.2-3.

Figure 20.5.10.2-2. Large damage to geomembrane identified under a protective soil cover at Warren H. Brock Reservoir with electrical resistivity sensing.



(a) (b)

Figure 20.5.10.2-3. (a) Typical electrical resistivity probe and (b) equipment layout.

20.5.11 Corrective Measures

If a monitored geomembrane-lined dam is known to have some flaws (e.g., leaks), several measures can be implemented depending on the size of leaks, type of facility, and type of lining system. If possible, the reservoir should be drained and repairs made as soon as possible. However, care should be taken to ensure that rapid drawdown of the reservoir does not cause stability problems. It is also essential that care be taken so as not to damage the geomembrane liner. Crews working on repairs should be supervised by someone familiar with the geomembrane to ensure that additional punctures or tears are prevented or patched if they do occur.

Underwater techniques for repairing leaking dams without emptying the reservoir can be used. For more information regarding this repair technique, the reader is referred to published literature by McDonald et al. [47] and Christensen et al. [48].

20.5.12 Final Acceptance

Typically, the contractor shall retain all ownership and responsibility for the geomembrane until final acceptance. The geomembrane shall be accepted by Reclamation when all of the following conditions are met:

1. Installation is finished.

2. Verification of the adequacy of all seams and repairs, including associated testing, and all quality control documentation is complete.

3. Certification, including quality control documentation, is provided by the installer to Reclamation.

4. The entire protective cover placement is completed.

20.5.13 Protective Cover Observation

The procedure for placing materials on top of an installed geomembrane depends on the type of geomembrane, the type of cover material, and the geomembrane application. Placement of two types of cover materials are discussed here: (1) cement based and (2) granular materials.

20.5.13.1 Placement of Cement-based Covers

Several types of cement-based cover materials are used and include prefabricated pavers or slabs, cast-in-place concrete, or compacted soil cement.

20.5.13.1.1 Placement of Prefabricated Pavers or Slabs

Prefabricated pavers or slabs are relatively small elements. They are too light to withstand wave action individually. They work only because they are interlocked. Therefore, it is essential that placement be such that interlocking is ensured.

There should be a needle-punched nonwoven geotextile between the geomembrane and the prefabricated concrete pavers or slabs to protect the geomembrane during and after placement.

20.5.13.1.2 Concrete and Soil Cement Cover

A needle-punched nonwoven geotextile should be placed on a geomembrane prior to placing cement-based materials to protect the geomembrane and to enhance cover stability during construction.

20.5.13.2 Placement of Granular Materials

Granular materials placed on geomembranes should be limited to a maximum particle size of 0.5 inch order to prevent damage or puncturing of the geomembrane. Consideration can be given to the placement of a geotextile protective layer placed between the geomembrane and the granular material, but slope stability must be assured. During construction of the cover, particular care should be taken to prevent damage to the geomembrane. The cover material should never be pushed down the slope because the gravitational stresses may cause the geomembrane to come out of the anchor trench or cause the liner to tear. Also, attention should be given to verify the thickness of the cover materials being placed.

Equipment placing the cover material should not be driven directly on top of the geomembrane. Care should be taken to prevent operator error from damaging the geomembrane (or underlying geosynthetics). Damage to the underlying geomembrane can still occur from construction equipment (tracked or rubber tire) when turning too sharply or rapidly applying the brakes for sudden stops on the cover material. In addition, blades or buckets of heavy construction equipment can also cause damage if they are allowed to work too close to the geomembrane. Bulldozers, as shown on figure 20.5.13.2-1, should be specified as low-ground pressure-type configuration. A minimum of 18 to 24 inches of cover should be placed prior to allowing equipment to travel over the geomembrane. When large trucks or scrapers are used to deliver cover soils, specific haul routes should be planned with temporarily increased soil cover (i.e., 3 to 6 feet depending on equipment size) to protect the underlying geomembrane.

As placement of a soil cover progresses, care should be taken to prevent wrinkles from developing at the leading edge of the soil as shown in figure 20.5.13.2-2.

Figure 20.5.13.2-1. Placement of protective cover over a geomembrane.

Figure 20.5.13.2-2. Development of wrinkles at the leading edge of the protective material placement.

The geomembrane should be in intimate contact with the underlying subgrade and, if not, the wrinkles could fold over and be stressed at the apex, which could produce stress cracks over time, leading to excessive leakage. Avoiding wrinkles, field techniques, and quantification of anticipated wrinkles can be reviewed in published literature [38, 49, 50]. Solutions for preventing and correcting wrinkles, as adapted from Koerner and Koerner [53], are summarized in table 20.5.13.2-1.

Table 20.5.13.2-1. Suggested remedial and preventative measures for wrinkles

Method	Advantages	Disadvantages
Push/accumulate/cut/seam	Quick and cheap	Extrusion welds, chances for leaks
Fixing berms or piles	Helps keep panel taunt	Slow and expensive
White panels	Quick and easy	Small waves still present
Temporary tent	Helps moderately	High cost, low productivity
Night or early morning backfill	Panels are cool	Limits productivity and raises safety concerns

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