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Numerical Analysis of Leakage through Defective Geomembrane Liners in Embankment Dams

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by

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A thesis submitted in partial fulfillment
of the requirements for the degree of
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DEDICATION

To My Father

And

To Karl Terzaghi and Ralph B. Peck

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“Every dam should be designed on the assumption that the core may crack and that the dam should be safe even if it does.” Ralph B. Peck

“We need engineers who think, not engineers who cut and paste and we need engineers who learn and understand new materials.” J.P. Giroud

“Engineers designing dams should not be afraid of using geosynthetics nor should have unrealistic expectations about their capabilities.” J.P. Giroud

“Gencler, bu millet sizleri yetistiriyor. Bu millete layik olmaya bakin!” M.K. Ataturk

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ABSTRACT

Placing a geomembrane liner in the core of a dam is an alternative construction technique to traditional clay core types. This study aims to assess the performance of such internal geomembrane sealing systems in an earthen dam. Two-dimensional (2D) numerical analysis was performed to evaluate leakage through defective seams within an earthen dam. Five possible applications of internal geomembrane systems were initially modeled to locate the zero-pressure lines in an earthen dam. Then, another application where the geomembrane is placed on the upstream face was modeled to compare the upstream and internal geomembrane systems. The results of this study show that use of a geomembrane system, either upstream or internal, significantly decreases the pore pressure at the downstream face of the earthen dam.

In addition, limit equilibrium analysis was performed to evaluate the effects of leakage through defects in geomembranes on the dam stability. The stability analyses for the upstream and downstream slopes were performed for three loading conditions: (1) end of construction, (2) long-term, and (3) rapid drawdown. The frequencies and locations of defective seams had a significant impact on the factors of safety of the downstream slope. It is shown that, in the case of upstream geomembrane systems, the factor of safety for the downstream slope has the highest value when the geomembrane hole occurs at a relatively lower location. On the other hand, in the case of internal geomembrane systems, the highest factor of safety occurs when the geomembrane hole is at a higher location. Additionally, rapid drawdown simulations show that the upstream slope of an embankment dam must be flat enough to overcome the upstream stability issues when

geomembranes are placed within embankment dams. This study not only showed the advantages of using a geomembrane in the core of a dam as an impervious lining system but also provided comparative information on the performance of internal and upstream geomembrane systems with respect to the stability in earthen dams.

CHAPTER 1: INTRODUCTION

Dams are engineered structures that impound water and form reservoirs. These structures built across a river or a stream are generally constructed for the purposes of irrigation, power generation, flood prevention, water supply, industrial usage, navigation, and recreational use. According to the International Commission on Large Dams (ICOLD), almost 50% of the dams in the world are used for irrigation.

Dams can be defined by their size. The majority of dams in the U.S. are less than 50 ft. in height as reported by the National Inventory of Dams (USACE 2016) (Figure 1.1).

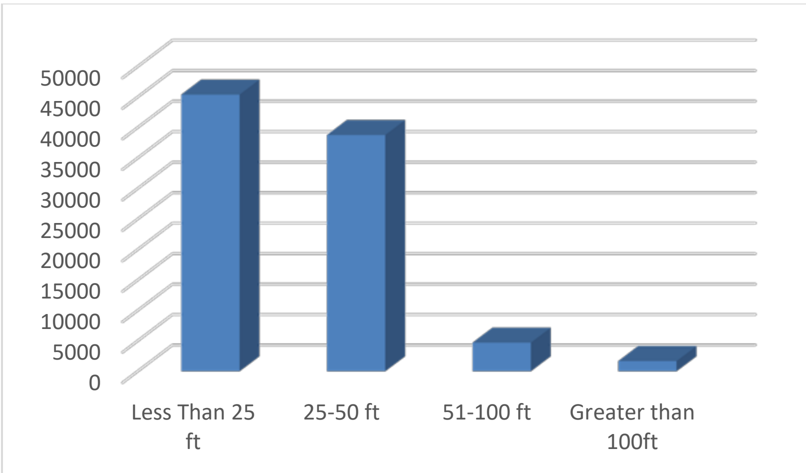


Figure 1.1 The Number of Dams by Height in U.S. (USACE 2016)

Dams can also be classified in a variety of ways. The classification is generally based on their intended use, construction materials, and structure type. For instance, dams are categorized as arch dams, masonry dams, embankment dams, gravity dams, and buttress dams as to their structure and construction materials.

Embankment dams are by far the most common types of dams in the U.S. as shown in Figure 1.2 (USACE 2016). Embankment dams can be divided into two parts - earth and rock-fill. In the design of embankment dams, material deterioration and instability issues are the main concerns that need to be addressed. Therefore, prevention of the deterioration of the dam fill and leakage reduction through the dam body are essential goals in leakage control. In rockfill dams, leakage reduction is the primary aim compared with the prevention of deterioration of the dam materials because the risk of the deterioration of fill by water is low. On the other hand, both deterioration of the dam body and leakage should be carefully considered in earthfill dams due to the possibility of internal erosion and instability issues (Giroud 2016).

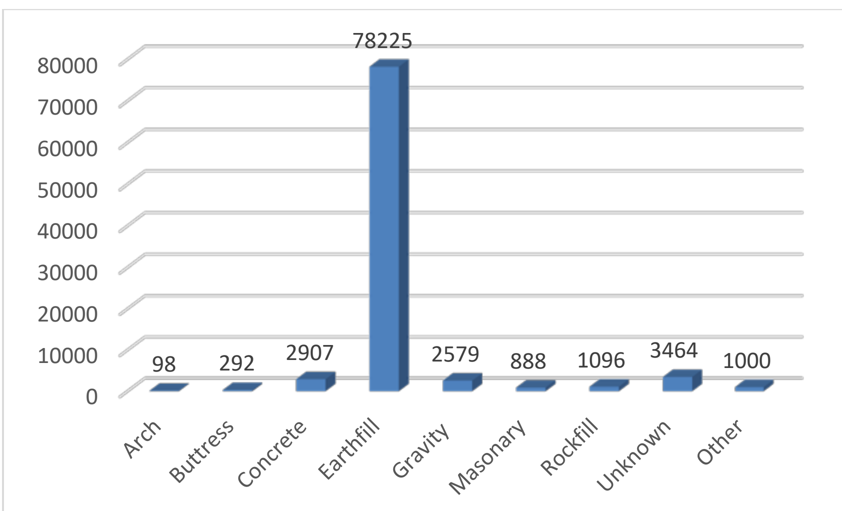


Figure 1.2 The Number of Dams by Type in U.S. (USACE 2016)

In earthen dams, liners and drainage systems are two necessary elements that have functions of minimizing the adverse effects of internal erosion and instability issues. Low-permeability liners are generally used to reduce the leakage through the dam. A geomembrane, for instance, is one of the effective sealing materials in embankment dams.

Geomembrane liners are alternatives to traditional materials such as silts and clays in embankment dams due to their low-permeability (Koerner 2012). There are many application types of geomembranes in embankment dams: impervious facing, impervious embankment elements, dam raises, reservoir lining and cutoff walls (Reclamation 2014).

According to the International Committee on Large Dams, ICOLD, 270 dams have incorporated geomembranes all over the world (0.47 % of total dams). A total of 188 fill dams out of 270 are reported in Bulletin 135 (ICOLD 2010). Geomembranes are most frequently placed on the upstream face of the embankment dams either covered or exposed. On the other hand, geomembranes have been installed as internal systems in approximately 10% of dams with geomembrane sealing systems (ICOLD 2010).

Geomembranes could be installed inside the embankment dams as impervious sealing layers with the advent of new construction techniques with internal geomembrane systems used in 20 dams (ICOLD 2010). There are four possible application types of internal geomembranes: a) inclined, b) vertical, c) zig-zag with small lifts and d) zig-zag with large lifts (Giroud 1990; ICOLD 2010; Reclamation 2014). In addition, there is another application of possible future evolution demonstrated by ICOLD, which is the double geomembrane placed in the core of a dam with a drainage monitoring layer (ICOLD 2010). Nowadays, internal geomembranes systems are preferred to traditional clay core or asphalt concrete core in some cases where there is a lack of availability of conventional low-permeability materials, or when the construction time is limited (Pietrangeli et al. 2009).

Geomembrane liners in embankment dams could be damaged during the installation, placement of cover soil or post-construction. Leakage through geomembrane liners essentially occurs through holes that are made typically in the field (Rowe 2017). As a result, the characterization of the frequency and size of holes is vital in the design of embankment dams with geomembrane liners (Giroud 2016). Previous studies have mainly focused on the determination of leakage through geomembrane liners in landfills while several studies have been conducted to evaluate the leakage through defects on geomembrane liners in embankment dams. However, such studies related to embankment dams are limited to the application of geomembranes that were placed on upstream faces (Foose et al. 2001; Weber & Zornberg 2008). Although the internal geomembrane liners have been used in 20 dams out of 188 fill dams, the study of leakage through defects, actually holes, in internal geomembrane systems has not been conducted.

In this thesis, two-dimensional (2D) numerical analysis was conducted to evaluate the leakage through geomembrane liners within an earthen dam. Using SEEP/W, another application with geomembranes on the upstream face of the dam was modeled to compare the performance of the upstream and internal geomembrane systems. Moreover, the effects of leakage through internal geomembrane liners on slope stability of an earthen dam were analyzed by using limit equilibrium analysis. In this study, it is aimed to assess the effect of frequency and location of geomembrane holes on the pore pressure distribution in earth dams associated with internal geomembrane systems and evaluate the impacts of leakage through geomembrane holes on dam stability. This study is expected not only to provide the advantages of using a geomembrane in the core of a dam as an impervious lining system but also comparative information on the performance of internal and upstream geomembrane systems with respect to the stability in earth dams.

CHAPTER 2: GEOSYNTHETIC LINER SYSTEMS

2.1 Introduction

Geosynthetics are natural or man-made polymers that are used with geotechnical materials in civil engineering applications (ASTM D4439). Geosynthetic materials include eight main products: geotextiles, geomembranes, geogrids, geonets, geosynthetic clay liners (GCL), geofoams, geocells, and geocomposites. These materials have been commonly used in a variety of civil engineering applications such as roads, dams, canals, landfills, embankments, retaining structures, etc. There are six primary functions of geosynthetics: reinforcement, filtration, separation, drainage, containment, and erosion control (Koerner 2012).

Geomembranes are relatively thin and very low permeability materials. Their primary function is to control fluid flow in geotechnical, hydraulic and transportation applications. The physical, mechanical, and endurance properties of geomembranes change depending on the aspects of the formulation, manufacture, and fabrication (Koerner 2012).

To control leakage through dam bodies, geomembrane sealing systems have been placed either on the upstream face or within the core in different types of dams such as rockfill and earthfill dams, roller compacted dams, concrete dams, and masonry dams.

Geomembranes can be damaged in the stages of manufacturing, transportation, installation or post-construction due to their thinness and vulnerability. Defects on geomembrane liners generally occur during construction or in service by sharp objects. Therefore, leakage through geomembrane liners should be carefully considered. According to Giroud (2016), a hole in a geomembrane liner should always be assumed at the design phase since visual inspection is not enough to find all holes in geomembranes, and electrical leak location methods which also rarely used cannot find all the holes in liners.

In landfills and reservoirs, water is entirely contained by the geomembrane liners. However, significant leakage can occur around the liners in dams because they are in contact with the natural ground. As a result, the main purpose of using these liners should be leakage reduction instead of zero-leakage in dams (Giroud 2016).

2.2 Geomembranes as Dam Liners

Geomembrane lining systems are now considered as long-term sealing techniques in dams if they are properly designed and installed. They have been increasingly used in dams as hydraulic barriers since 1959. There are over 400 geomembrane (mainly PVC) lined large dams in today's world. The performance of geomembranes after 59 years shows that synthetic liners are still performing very well (Scuero & Vaschetti 2017).

2.2.1 Geomembranes

A geomembrane is defined as "A very low permeability synthetic membrane liner or barrier used with any geotechnical engineering related material so as to control fluid (or gas) migration in a human-made project, structure, or system." according to ASTM D4439. Geomembranes are relatively thin with thicknesses ranging from 1-5 mm (Giroud 2016). Different type of geomembrane products can be seen in Figure 2.1.

Geomembranes are considered as relatively impermeable materials although it is commonly known that all liners leak and geomembranes are so not impervious materials (Giroud & Bonaparte 1989a; Giroud 2016). Their permeability ranges from 10^{-12} to 10^{-15} m/s (when intact).

In Table 2.1, typical values of coefficients of permeability of different lining materials including geomembranes are shown.

Table 2.1 Coefficients of Permeability for Different Type of Liner Materials (Giroud 2016)

Liner Type	**Hydraulic Conductivity (m/s)**
Compacted Clay Layer (ordinary):	10^{-8}
Compacted Clay Layer (excellent):	10^{-9}
Cement Concrete (in field):	10^{-10} to 10^{-8}
Cement Concrete (in lab):	10^{-12}
Roller Compacted Concrete:	10^{-8} to 10^{-6}
GCL (when hydrated)	1 to $5x10^{-11}$
Geomembranes	10^{-15} to 10^{-12}

Geomembranes are typically made from bitumen or polymers. Compared with the bituminous types, polymeric geomembranes are by far the most common types installed in civil engineering applications (Koerner 2012). High-density polyethylene (HDPE), linear low-density polyethylene (LLDPE), polyvinyl chloride (PVC) and flexible polypropylene (fPP) are widely used types of geomembranes in hydraulic applications. Their mechanical and physical properties depend highly on the types of polymer resin. HDPE geomembranes are non-flexible while PVC geomembranes are flexible and relatively soft (Bhatia & Kasturi 1996). In addition, HDPE geomembranes have a high apparent strength. Also, they are more durable under UV radiation because of their chemical structure.

2.2.2 Geomembrane Applications in Embankment Dams

Low-permeability materials are always required to reduce migration of water through a dam body. At that point, geomembranes have been used as an alternative method to traditional materials (e.g., silts and clays) in seepage control (Koerner 2012). There are many application types of geomembranes in embankment dams, which are: impervious facing, impervious embankment elements, dam raises, reservoir lining, cutoff walls and so on (Reclamation, 2014). In this study, only the applications of the embankment facing, and embankment core will be discussed.

Figure 2.1 Geomembrane Products with Different Colors

According to the International Committee on Large Dams (ICOLD), 270 dams have incorporated with geomembranes (188 of fill and 82 of concrete + RCC + unknown) (Figure 2.2). In 1959, the first application of geomembranes in dams was at the Contrada Sabetta Dam in Italy. 2 mm polyisobutylene geomembranes were installed on the upstream face in this 32.5 m high rockfill and rubble masonry dam (Sambenelli & Rodriguez 1996).

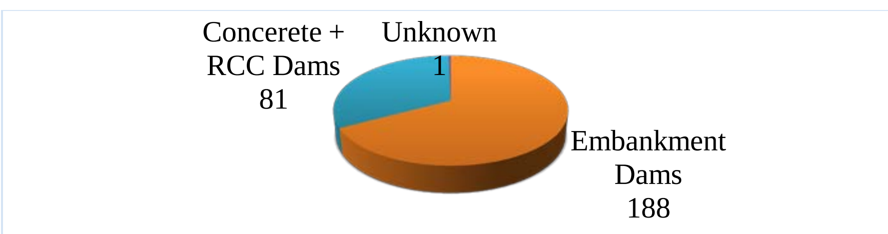


Figure 2.2 Number of Dams Associated with Geomembrane Liners (From ICOLD-International Commission on Large Dams, Bulletin 135, www.icold-cigb.org)

Polyethylene is the most commonly used polymer type of geomembranes especially in landfills (Koerner 2012). On the other hand, PVC is the most widely preferred polymeric geomembranes in dam applications. Table 2.2 shows the different types of geomembranes that have been installed in dams.

Table 2.2 Geomembranes Installations in terms of Their Types in Dams (From ICOLD-International Commission on Large Dams, Bulletin 135, www.icold-cigb.org)

GMB Type*	**Basic Material**	**Abbreviation**	**Total dams**				**Percentage of Dams by GMB Types (%)**
			Exposed	**Covered**	**Unknown**	**Total**	
Polymeric	Polyvinylchloride - Plasticized	PVC-P	80	73	3	156	59.32
Polymeric	Low-density polyethylene	LLDPE	0	29	1	30	11.41
Polymeric	High-density polyethylene	HDPE	3	12	1	16	6.08
Polymeric	Butyl rubber, polyisobutylene, ethylene-propylene-diene monomer	IIR, PIB, EPDM	5	4	2	11	4.18
Polymeric	Other types					27	10.26
Bituminous	Various					23	8.75
Total known						263	100

** "GMB" is the abbreviation standing for the geomembrane.*

ICOLD's Bulletin 135 presents that the geomembrane sealing systems have a widespread application area all over the world (Figure 2.3). Out of 270 dams with geomembranes, 48 are in the USA, 47 in China, 42 France, 35 in Italy, 10 in Germany and in Spain each, 9 in Austria, 6 in the Czech Republic, 5 in Portugal, 4 in Bulgaria and in the UK, 2 each in Belgium, Romania, Cyprus, Switzerland and Slovakia, and 5 scattered in other European countries.

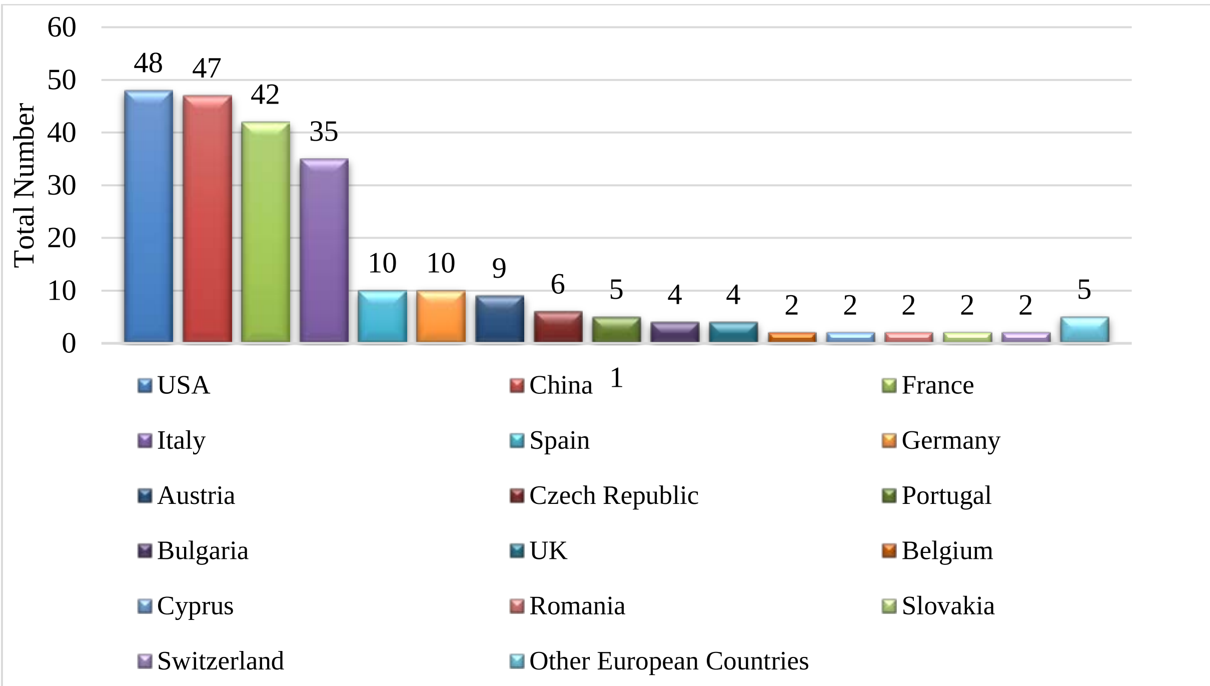


Figure 2.3 Total Number of Dams with Geomembrane Liners in Different Countries (From ICOLD-International Commission on Large Dams, Bulletin 135, www.icold-cigb.org)

As shown in Table 2.3, geomembranes are most frequently placed on the upstream face of the embankment dams either covered or exposed. On the other hand, geomembranes have been installed as an internal system in approximately 10% of dams with geomembrane liners. Although the geomembrane installation within a dam core is relatively a new and rare application, they provide reliable solutions when there is lack of availability of low permeability materials (ICOLD 2010).

Table 2.3 Reported Uses of Geomembranes in Embankment Dams (From ICOLD-International Commission on Large Dams, Bulletin 135, www.icold-cigb.org)

	Total	Upstream		Internal
		Exposed	Covered	
Total number of fill dams	174	47	106	20
Total number of new constructions	103	22	66	15
Total number of rehabilitations	56	21	31	5
Unknown if new construction or rehabilitation	14	5	9	0

The selection of proper geomembrane systems for embankment dams is essential at design stages. There are many advantages and disadvantages of installing the upstream and internal systems in embankment dams. For example, the construction costs of the internal geomembrane systems are generally lower than the upstream geomembrane systems because less material is needed to construct a water tight surfaces. Also, the durability of the geomembrane is quite high in the case of internal geomembrane systems since they are protected against external effects. Moreover, the risk of vandalism is the highest in exposed systems compared with others whereas visual inspection is not possible in covered upstream and internal geomembrane systems. It is important to note that upstream and internal geomembrane systems are all very efficient in seepage reduction through the embankment dam body. Table 2.4 compares such geomembrane systems in terms of the cost, durability, risk of uplift, etc. (ICOLD 2010).

Table 2.4 Comparison of Geomembrane Liners in Embankment Dams (Modified from ICOLD-International Commission on Large Dams, Bulletin 135, www.icold-cigb.org)

	Embankment Facing*		Embankment Core
	Covered	Exposed	
Cost of Installation	High	Medium	Low
Durability	High	Medium	Extremely High

Table 2.4 (Continued)

	Embankment Facing*		Embankment Core
	Covered	**Exposed**	
Cost of repair	Medium to High	Low	Extremely High
Visual Inspection	Not possible	Possible	Not Possible
Risk of vandalism	Minimum	High	Not Possible
Risk of damage during construction	High	Low	Medium to High
Construction challenges	Medium	Low	High
Reducing seepage	High	High	High
Risk of uplift	Medium to High	High	Not possible

** The part of the embankment facing was taken from ICOLD-Bulletin 135. On the other hand, the embankment core was created as a result of the comprehensive literature review.*

2.2.2.1 Geomembranes in the Embankment Facing

Geomembranes are generally placed on the upstream face of the embankment dams to restrict water migration through the dam body (Reclamation 2014). Upstream geomembrane sealing systems are typically divided into two parts: exposed and covered. Exposed and covered geomembrane systems have different application areas in embankment dams depending on the project budget, external exposure conditions (e.g., UV rays, vandalism, and variable temperature), and intended lifetime. In the following chapters, typical configurations of exposed and covered geomembrane systems and their advantages and disadvantages in embankment dam designs are described in detail.

2.2.2.1.1 Exposed Geomembrane Systems

Exposed geomembranes systems are not covered by any protection layers such as concrete slabs or heavy soils and they have a direct interaction with environmental factors. As a result, they are potentially under the risk of detrimental effects such as mechanical damage, degradation, and displacement (Cazzuffi et al. 2010). According to the Bureau of Reclamation (2014), the service life of exposed geomembranes is considered as 30 years, but some exposed geomembrane applications are still performing well after 30 years. A typical configuration of exposed geomembrane systems is illustrated in Figure 2.4.

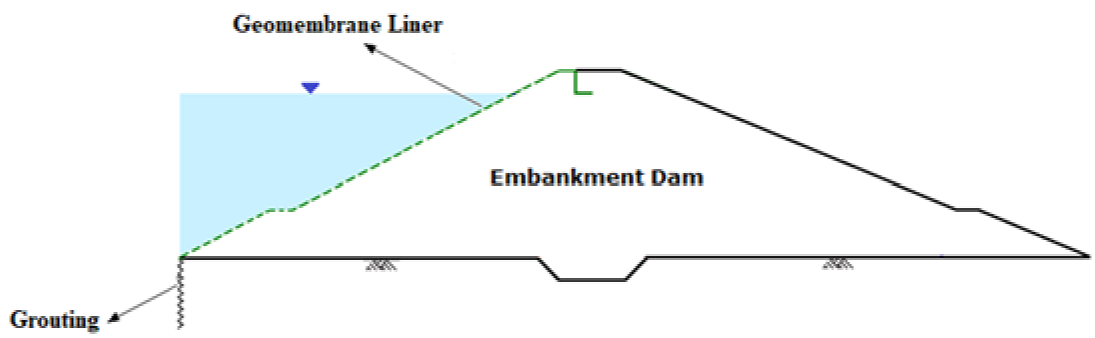


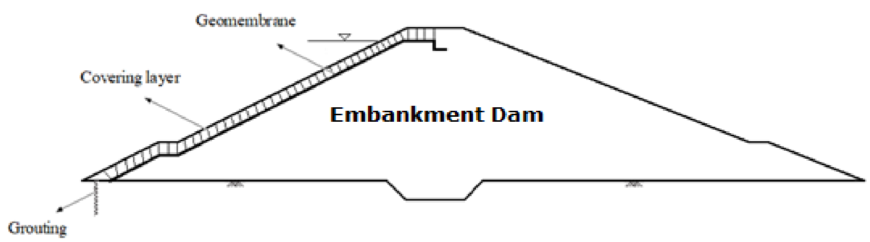
Figure 2.4 Typical Configuration of Exposed Geomembrane Liners (ICOLD 2010)

In exposed geomembrane systems, it is easy to construct the liners on the upstream face of dams due to the lack of protection covers (Cazzuffi et al. 2010). Also, the availability of visual inspection and easy accessibility of the geomembrane liners are two of the main advantages of exposed geomembrane systems. Additionally, they provide cost-effective solutions for controlling seepage through dams because there is no need to cover the liners (ICOLD 2010).

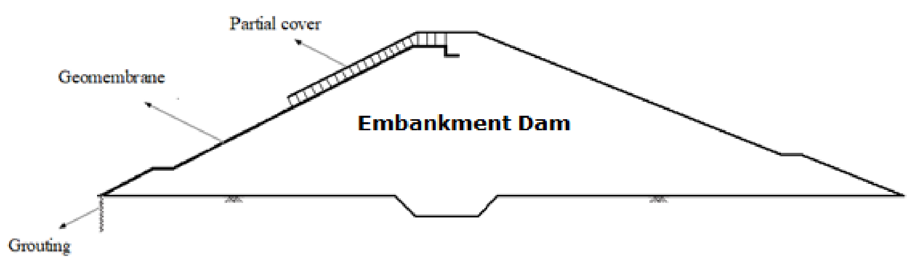
On the other hand, there are obviously some disadvantages of using the exposed geomembrane systems in embankment dams. First, the durability of the geomembrane in exposed conditions substantially decreases in time because of the environmental effects, especially UV rays are the principal cause of degradation to the geomembranes (Koerner et al. 2017). Second, the exposed geomembranes can also be damaged by sharp objects dropped from the crest or vandals. Finally, there is a possibility of geomembrane uplift by wind and wave forces if the liners are not installed properly (ICOLD 2010).

2.2.2.1.2 Covered Geomembrane Systems

Geomembrane liners on the upstream face of dams can be covered by concrete or soil layers. There are many essential reasons why protective layer can be employed to the geomembranes in the embankment dams. First, geomembrane liners should be protected against mechanical damages caused by rock falls, animals, and vandals. Second, the risk of environmental damage (UV rays, heat) can be minimized with the aid of a protective layer. Last, the possibility of uplift due to wind and wave forces could be reduced when concrete or soil layers are placed on geomembrane liners (Cazzuffi et al. 2010). Typical configurations of entirely or partially covered geomembrane systems are shown in Figure 2.5.



(a)



(b)

Figure 2.5 Typical Configurations of: a) Completely, b) Partially Covered Geomembrane Systems in Embankment Dams (ICOLD 2010)

A covered geomembrane system is generally preferred in dams when the durability of the liner is a significant concern. Covering the geomembrane with a protective layer significantly increases the performance and lifetime of geomembrane liners. It is commonly known that dams are the most critical civil engineering structures and safety concerns about ones with geomembrane liners must address the of how long those geomembrane liners last. Previous studies predict that covered PVC or PE geomembranes have a life of 950 years (Reclamation 2014). According to ICOLD (2010), a geomembrane placed under concrete layer should last a minimum of 200 years.

On the other hand, there are some drawbacks of using a covered geomembrane liner in embankment dams. First, it is not possible to access the geomembrane for inspection and maintenance. Also, the construction cost is obviously higher than the exposed geomembrane systems due to the covering layers (Cazzuffi et al. 2010).

2.2.2.1.3 Case History of a Dam with Upstream Geomembranes

Mission dam, now known as Terzaghi Dam, is a rockfill dam in British Columbia, Canada (Figure 2.6). In this dam, a 0.75 mm thick PVC geomembrane was installed over a 1.5 m-thick clay layer to distribute the overburden pressure on the clay layer. As a result, the cracks that could occur in the clay layer would be prevented with the aid of the flexibility of the geomembrane liner. If the geomembrane liner had not been placed on the clay liner, leakage through cracks in clay could cause differential settlement (Terzaghi & Lacroix 1964; Weber 2008; Cazzuffi et al. 2010).

2.2.2.2 Geomembranes in the Embankment Core

A geomembrane liner can also be installed inside an embankment dam as an alternative or supporting layer to traditional impervious cores. Internal geomembrane systems have been used in 20 dams all over the world. The first geomembrane application within the dam was in Odiel Dam in Spain. A chlorinated polyethylene (CPE) geomembrane was placed inside this rockfill dam in 1970 (Cazzuffi et al. 2010).

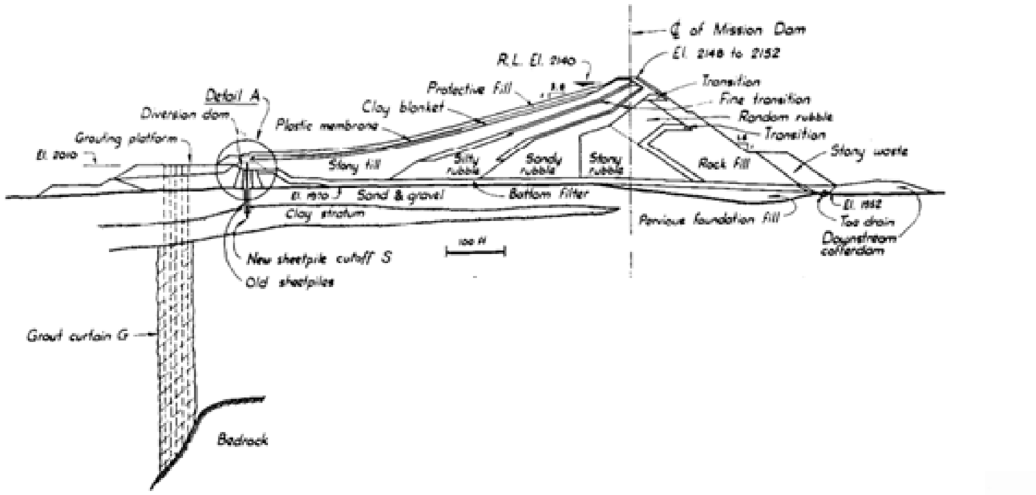


Figure 2.6 Cross-Section of the Mission Dam (Terzaghi & Lacroix 1964)

There are a variety of geomembrane types that have been installed in embankment dams, but polyvinyl chloride (PVC) geomembranes have been commonly preferred in internal systems as shown in Figure 2.7 with 12 cases over a total of 20 dams with internal geomembrane systems.

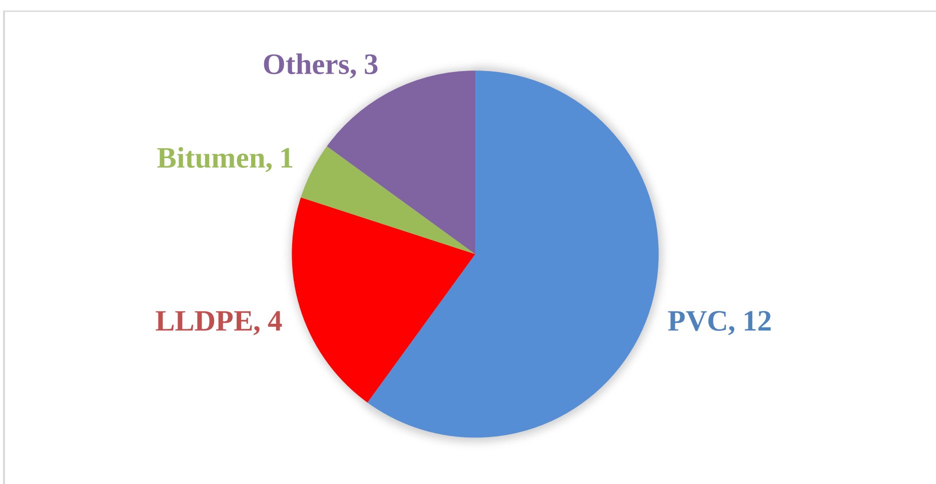
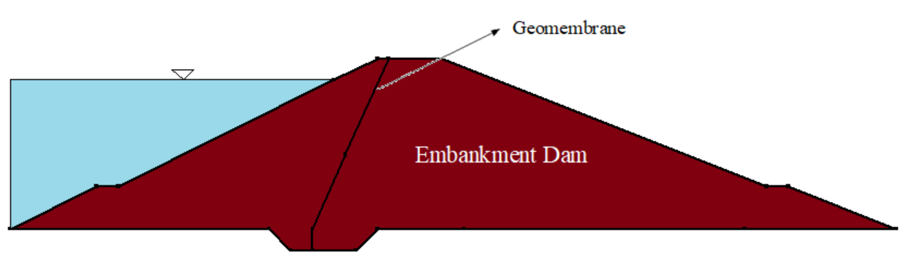


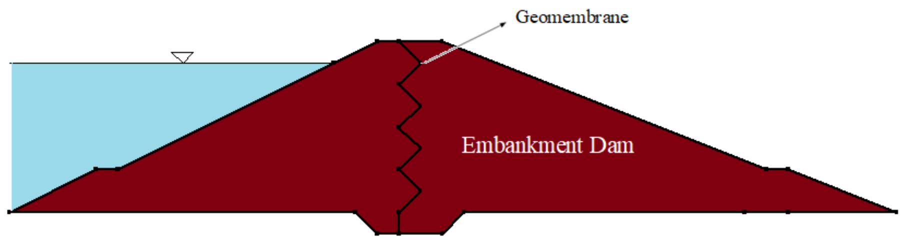
Figure 2.7 The Distribution of Geomembrane Types Used as Internal Geomembrane Systems Over a Total of 20 Dams (From ICOLD-International Commission on Large Dams, Bulletin 135, www.icold-cigb.org)

There are four possible application types for geomembranes within the embankment dams (Zornberg 2005; ICOLD 2010; Reclamation 2014) (Figures 2.8). As shown in Figure 2.8a, the geomembrane liner can be placed in the upstream shell as a seepage barrier. Also, the placement in Figure 2.8b is called the "zig-zag" and this configuration has an advantage limiting the stress development to the liner, but the application of this internal system is sometimes not recommended due to construction difficulties (Reclamation 2014). In the third application shown in Figure 2.8c, the geomembrane is installed in several stages over a completed dam section. It is highly dependent on the progression of construction in this case. However, there is a potential for the creation of a slip surface in the slopes of the dam. Therefore, the risk of slip surfaces created by geomembranes can be eliminated by using geotextiles with geomembranes or textured geomembranes. In order to construct a vertical geomembrane core shown in Figure 2.8d, bentonite slurry method is used to first excavate a trench for the insertion of geomembrane panels. Additionally, there is a possible future evolution type of internal systems illustrated in ICOLD Bulletin 135 (2010). This is the double geomembrane placed in the core of a dam with a drainage monitoring layer and groutable intermediate layer (Figure 2.8e).



(a)

Figure 2.8 The Configurations of Internal Geomembrane Systems: a) Inclined, b) Zig-Zag with Small Lifts, c) Zig-Zag with Large Lifts, d) Vertical, e) Double (ICOLD 2010)



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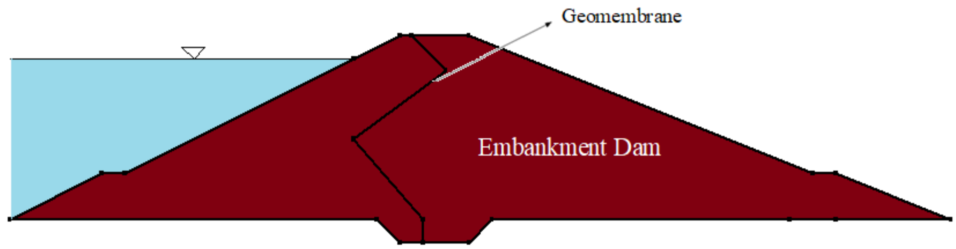
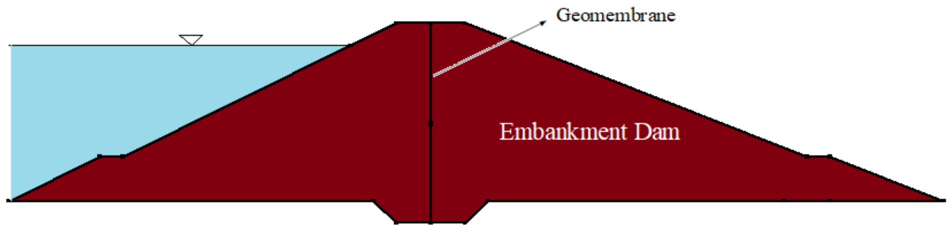


(c)



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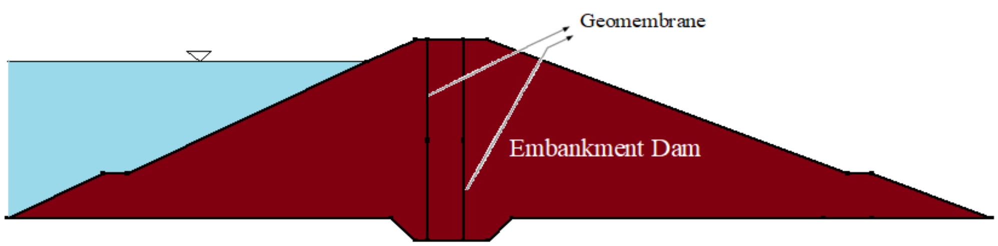


(e)

Figure 2.8 (Continued)

Although there are 20 fill dams associated with internal geomembrane liners, there is, unfortunately, no detailed information about these systems regarding construction techniques, stress-strain analysis, settlement behavior during the time, difficulties at the installation stage and effects on dam stability. Table 2.5 was created to show the details of internal geomembrane applications all over the world (Weber 2008; Pietrangeli et al. 2009; Cazzuffi et al. 2010; ICOLD 2010; Reclamation 2014; Scuero & Vaschetti 2017).

Table 2.5 Internal Geomembrane Applications in Dams from All Over the World (Weber 2008; Pietrangeli et al. 2009; Cazzuffi et al. 2010; ICOLD 2010; Reclamation 2014; Scuero & Vaschetti 2017)

Dams with an internal Geomembrane liner	**Dam Type**	**GM type**	**Thickness**	**Application Type**	**Country**	**Year**
Odiel Dam	Rockfill	CPE	N/A	N/A	Spain	1970
Valence d' Albi	N/A	Bitumen	4 mm	Inclined	France	1988
Gibe III	Rockfill	PVC	3.5 mm	Zig-zag (small lifts)	Ethiopia	2009
Heihe Dam	Cofferdam	PVC	0.3 mm	N/A	China	1999
Wangfuzhu Dam	Cofferdam	PVC	0.5 mm	Zig-zag (small lifts)	China	1999
Shirensigou Dam	Cofferdam	PVC	0.8 mm	N/A	China	2002
Atbashinsk Dam	Rockfill	N/A	N/A	Vertical	Kirgizstan	1970
Fencheng Dam	N/A	N/A	N/A	Zig-zag (large lifts)	China	2000
Signal Buttes Dam	Earth Dike	HDPE	2.5 mm	Zig-zag	USA	N/A
Hongya Dam	Rockfill	N/A	N/A	Inclined	China	2007
Zushou Dam	N/A	N/A	N/A	Inclined	China	N/A
Goose Lake Dam	N/A	N/A	N/A	Inclined	USA	N/A
Reach 11 Dikes	N/A	N/A	N/A	N/A	USA	2016

2.2.2.2.1 Pros and Cons of Installing Geomembranes inside the Embankment Dams

Placing a geomembrane within an embankment dam is relatively a new construction method to minimize the seepage through the dam body. There are some positive and negative outcomes of using geomembrane liners within embankment dams. First, internal geomembrane systems are one of the most practical ways to reduce seepage through the dam body when the required impervious materials are not available at the dam site or are costly to transport. Second, the risk of uplift of the geomembrane liner can be prevented with the placement of geomembrane in the dam core. Third, the geomembranes, which are vulnerable materials, are protected against external factors that could reduce the service life of the geomembrane. Fourth, internal systems allow the construction to be finished in a very short time (Pietrangeli et al. 2009). Finally, sealing the embankment dam with the internal systems require fewer materials compared with the upstream installations. Therefore, the construction cost of the internal systems is relatively lower than upstream systems (Cazzuffi et al. 2010).

On the other hand, the placement of geomembranes within embankment dams has some associated installation difficulties due to its complex application geometry. Similarly, visual inspection is not possible in the internal system, and it is challenging to repair the geomembrane liners if they are damaged in service (either in the short or the long term). As a result, the application of internal systems in critical embankment dams should be carefully considered both in the design and construction stages due to safety concerns (ICOLD 2010).

2.2.2.2.2 Case Histories of Dams with Internal Geomembrane Systems

(1) GIBE III Cofferdam, Ethiopia

Gibe III is one of the biggest hydropower projects in Africa according to Pietrangeli et al. (2009). This vast hydroelectric project included a 50 m rockfill cofferdam that was constructed by river gravel, basalt and trachyte. In this project, the construction time was very limited (six-month dry season) due to the high average flow during the rainy season. Therefore, water tightness surface was completed in a very short time for this cofferdam.

3.5 mm thick PVC geomembrane was selected as an impervious element within the GIBE III cofferdam. Needle-punched geotextile was used on both faces of the geomembrane as protection layers against puncture or tear. The zig-zag pattern was selected for the impervious liner because it provides reasonable protection against settlements of the cofferdam. As construction proceeded step by step, the zig-zag shape geomembrane liner was installed from the bottom cut-off to the crest. Synthetic liners were placed on each section that has a slope of 1H:1V.

There are several reasons why the designers used geomembrane in the core of the GIBE III Cofferdam. First, the construction had to be finished in a very short time. More importantly, there was no proper impervious material at the site for the dam core (Pietrangeli et al. 2009).

(2) Examples of Geomembrane Cores in China

There are many central geomembrane applications in China. According to Cazzuffi et al. (2010), the geomembranes were generally used in cofferdams as elements of internal systems (essentially rockfill dams). In addition, very thin geomembranes were permanently placed in embankment dams. Heihe Dam, Wangfuzhu Dam and Shirensigou Dam are three of the examples of dams with inclined internal geomembranes in China.

2.2.2.3 Other Type of Applications

Apart from the application in the embankment facing and embankment core, there are a number of other application types of geomembranes in embankment dams such as reservoir lining, cutoff walls, rehabilitation of leaking dams, cofferdams, etc. Horsetooth Reservoir, Warren H. Brock Reservoir, Mount Elbert Forebay Reservoir, and Black Lake Dam are some of the examples of reservoirs associated with geomembrane liners (Reclamation 2014). Reservoir liners have reduced the leakage under these dams by acting as upstream blankets. Also, geomembrane cutoff walls are a relatively new type of vertical barriers. They have been installed through or under the dams as vertical seepage barriers.

2.3 Liquid Migration through Defective Geomembrane Liners

As mentioned before, leakage through embankment dams can not only degrade the dam materials but also may cause stability issues. Three reasonable precautions need to be taken to minimize the adverse effects of these problems. First, leakage through liners should be reduced. Second, water leaks through and around the liner should be prevented. Third, excess pore pressure should be removed from the dam body. All in all, a good liner, especially a geomembrane, is required for the first activity while a proper drainage system is needed for the second and third actions (Giroud 2016).

Giroud & Bonaparte (1989a) stated that all liners leak. Therefore, leakage through the geomembrane liners can be carefully considered in dams and particularly in embankment dams. Leakage through the liners can be due to two main mechanisms: diffusion and advective flow. Diffusion through the geomembrane liners is negligible because of their very-low permeability. On the other hand, the advective flow includes laminar flow and non-laminar flow as stated by Giroud (2016). Laminar flow occurs through a porous medium and tiny small holes whereas non-laminar flow occurs when the geomembranes have huge holes and cracks that are resting on coarse-grain materials.

2.3.1 Geomembrane Holes

“Defect” is generally used to define a hole on geomembrane liners. However, this is not the proper term to refer to the passage of liquid through the liners since defects cannot create a corridor for liquid. According to Giroud (2016), “All holes associated with a liner are defects, but not all defects are holes.”

Holes in geomembrane liners could occur during the construction stage or in operation by the adjacent fill materials. Therefore, the frequency and size of the holes are very critical for the evaluation of leakage through geomembrane liners. Giroud (2016) has reviewed data on electric liner integrity surveys (Beck & Darilek 2016) performed on HDPE geomembranes for more than 150 cases. He concluded that 5-6 holes per hectare for HDPE with typical quality assurance at the end of the installation. It should be noted that electrical leak location surveys were used in only 2% of the geomembrane liner area installed in the U.S in 2016.

Defect size is also an important factor affecting leakage through the geomembrane liners. Depending on damage types (stress cracking, puncture or tear), the size of the holes can range from 1mm^2 to 100,000 mm^2 (Giroud 2016).

2.3.2 Previous Numerical Studies

Foose et al. (2001) conducted a study to predict leakage through composite landfill liners by using analytical and numerical models. Two-dimensional (2D) numerical models were used to evaluate leakage through defective seams. Also, three-dimensional (3D) numerical models were used to analyze leakage caused by circular defects. The numerical results of leakage rates were compared with the leakage rates obtained from the analytical models in that study. It was concluded that present equations and models for predicting leakage rates in geomembrane liners cannot be used in every landfill conditions. The limitation of this study is that the numerical analysis was performed for only landfill conditions rather than dams that have high hydraulic heads (Weber 2008).

Weber & Zornberg (2008) performed a numerical analysis for leakage through geomembrane liners under high hydraulic heads. SVFlux, a software using finite element methods, was used to study the leakage thorough geomembrane defects on the upstream face of a dam. The defects in liners were modeled by applying a constant head or flux boundary conditions. Weber & Zornberg (2008) called the two-dimensional numerical analysis as a “worst-case scenario” because the defects placed in 2D simulations were infinitely long and would not occur in the field conditions. The more realistic defects were modeled in three-dimensional (3D) simulations. The results from the numerical analysis conducted by Weber & Zornberg (2008) shows that the installation of a geomembrane on the upstream face of a dam lowers the phreatic surface in the dam body. In addition, the defect location affects the position of the zero-pressure line. Additionally, stability analysis was performed by using the limit equilibrium method in UTEXAS4 to understand the effect of leakage through liners on the downstream slope of the embankment dam. Due to highly conservative defect modeling, the factor of safety on the downstream face increased slightly when the geomembrane liner placed on the upstream face.

On the other hand, toe drains significantly increased the factor of safety of the downstream slope. It is important to note that the length of the drain is an essential consideration in earthfill dams in both unlined or geomembrane lined dams as stated by Weber & Zornberg (2008). In the above study, the simulations were limited to the upstream face of the dam. Consequently, finite element analysis has not been conducted to investigate the geomembranes within the dams.

CHAPTER 3: NUMERICAL ANALYSIS OF LEAKAGE THROUGH INTERNAL AND UPSTREAM GEOMEMBRANE SYSTEMS IN EMBANKMENT DAMS

3.1 Introduction

In this study, two-dimensional (2D) finite element analysis was conducted to evaluate the effect of leakage through geomembrane liners within the embankment dams. Also, a geomembrane liner was modeled on the upstream face of the embankment dam to compare the performance of upstream and internal geomembrane systems. These analyses were performed in SEEP/W which is a finite element software that is used to analyze groundwater flow within porous media. In SEEP/W, the pore pressure distributions of dams in unsaturated and saturated soils can be simulated by using numerical models (Geo-Slope 2012). In this study, steady-state seepage analysis was performed for the end of construction and long-term conditions while rapid drawdown condition was simulated in transient seepage analysis.

The limit-equilibrium analysis was also performed to evaluate the effect of leakage through geomembrane liners on the stability of the upstream and downstream slopes of embankment dams. Three different conditions were considered for the slope stability of an earthen dam with an internal geomembrane: end of construction for both upstream and downstream slope, long-term for downstream slope, and rapid drawdown for upstream slope. Not only will these analyses show the beneficial effect of geomembrane application on the performance of the embankment dam but also they will provide the comparative results of the upstream and internal geomembrane systems in seepage and stability.

3.2 Cross-Section, Properties of Materials, Boundary Conditions and Mesh Properties for Finite Element Analysis of an Embankment Dam

3.2.1 Schematic Cross-Section of an Earth Dam

To perform finite element analysis in an embankment dam with a geomembrane within the core, typical embankment dam configuration was used (Figure 3.1). The dam has a height of 16 m. It has an upstream slope of 1V:2H and a downstream slope of 1V:2.5H. It should be noted that the upstream slopes of 1V:2.5H and 1V:3H were used only for the rapid drawdown case to understand the effect of geometry on pore pressure distribution and the factor of safety for the upstream slope. Also, the reservoir level of 14 m and the crest width of 6 m were selected for the finite element simulations.

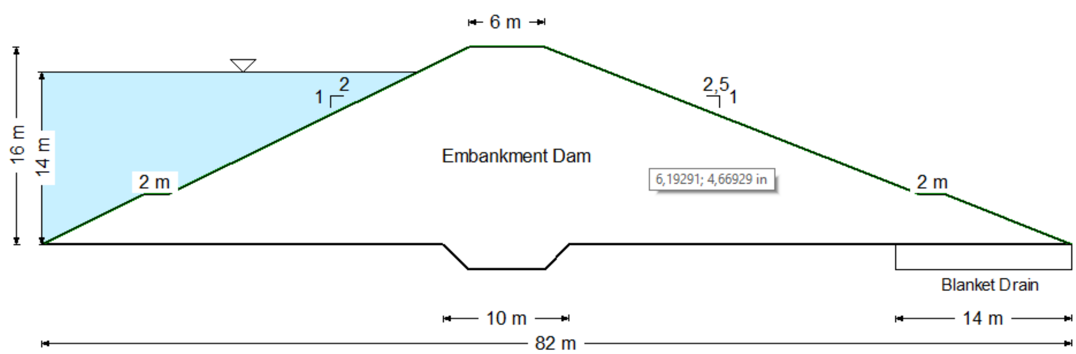


Figure 3.1 Geometry of the Embankment Dam Used in Simulations (GeoStudio 2018)

3.2.2 Soil and Drainage

Homogenous soils in embankment dams should be sufficiently impervious. According to Terzaghi and Peck (1967), “practically impermeable” soils, which have a permeability less than 10^{-9} m/s, are suitable for embankment dams. Cohesive soils (silts and clays) are typically used for that purpose.

The soil type selected for the earth dam used in finite element analysis was silty clay. The unified Soil Classification System (USCS) classified this soil as CL. The saturated hydraulic conductivity of the soil was assumed as $5x10^{-8}$ m/s (Geotechdata.info 2013). Since unsaturated zones were expected to occur above the phreatic surface in the dam body, the soil model was employed as saturated/unsaturated in SEEP/W. Water content and hydraulic conductivity functions are required to perform the saturated/unsaturated model in finite element analysis. Typical water content functions are provided for different types of soils in SEEP/W. These sample functions are very effective when the models are needed to be set up quickly (Figure 3.2). Sample material was selected as silty clay with the saturated water content of 0.45 and residual water content of 0.045 to create the volumetric water content versus matric suction curve (Figure 3.3). A pre-defined volumetric water content function was used for the estimation of hydraulic conductivity function (Figure 3.4). All parameters used in seepage analysis regarding these functions are shown in Table 3.1.

Table 3.1 Soil Parameters Used in Finite Element Analysis

Parameters	**Silty Clay (Dam)**
Permeability (m/s)	$5x10^{-8}$
Saturated WC	0.45
Residual WC	0.045
Sample Material	Silty Clay
Compressibility (1/kPa)	0.0001

Drainage systems are mainly placed in embankment dams for two essential purposes. First, they reduce the pore pressure on the downstream side and increase the stability. Second, they prevent the zero-pressure line from exiting the downstream face. It should be noted that most engineers prefer a blanket drain to toe drain when the reservoir depth is greater than 15 m (Sherard 1963). In this simulation, a 14 m blanket drain was modeled in the earthen dam.

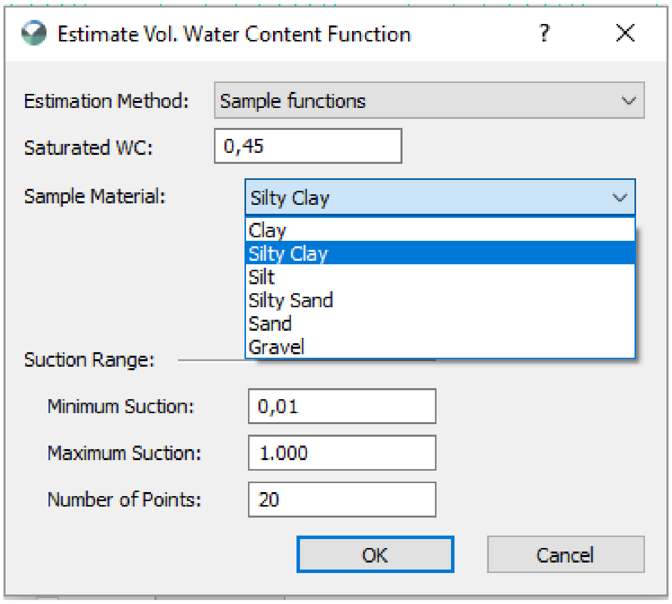


Figure 3.2 Sample Materials for the Estimation of Volumetric Water Content in SEEP/W (GeoStudio 2018)

3.2.3 Geomembrane Properties

To assess the leakage through geomembrane defects within the dam, a 3.5 mm thick geomembrane was selected for the models since there are some current applications of 3.5 mm geomembrane in cores of dams. For example, a 3.5 mm zigzag geomembrane (PVC) was used within the 50m high rockfill cofferdam in Ethiopia-GIBE III (Pietrangeli et al. 2009). It should be noted that even if the geomembrane of 3.5 mm thickness was selected, the stability analysis was performed with thicknesses ranging from 1 to 10 mm. Also, a hydraulic conductivity of 10^{-14} m/s was used for geomembrane liners in the finite element analysis. It should also be noted that different thicknesses and hydraulic conductivities of geomembranes were considered in the stability analysis to understand their effect on factors of safety of the downstream slope.

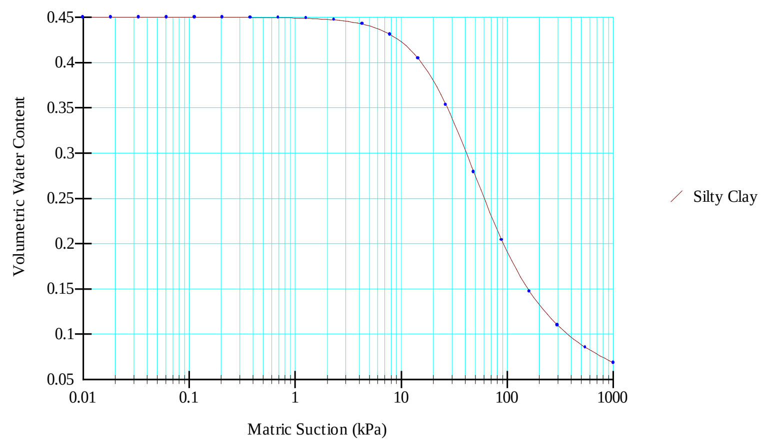


Figure 3.3 Volumetric Water Content versus Matric Suction Curve for Silty Clayey Soil (GeoStudio 2018)

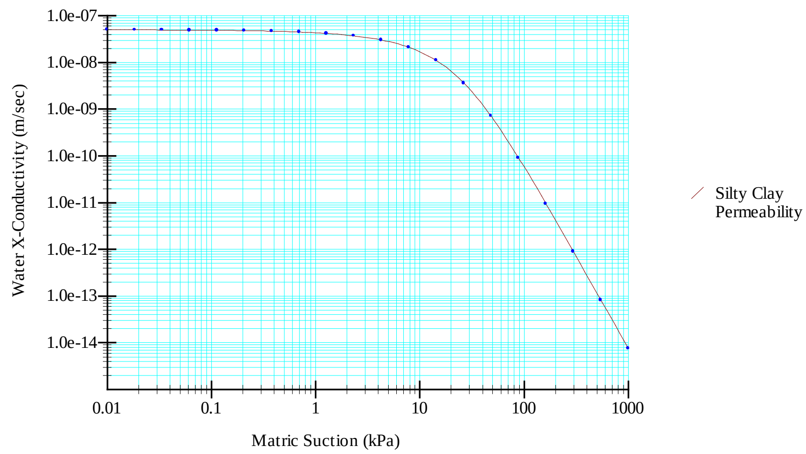


Figure 3.4 Hydraulic Conductivity versus Matric Suction Curve for Silty Clayey Soil (GeoStudio 2018)

3.2.4 Defects in Geomembranes

As previously mentioned, geomembrane defects on the upstream face of an embankment dam were simulated by Weber and Zornberg (2008). The upstream face was assumed as an impervious layer. A geomembrane defect with a diameter of 1 m was simulated on that impermeable layer by using either flux or a constant head boundary condition.

In the current study, the width of a defect was selected as 10 cm in all the models. It should be mentioned that even though the defect widths of 1 cm, 10 cm, and 100 cm were performed in stability analysis, only slight changes are observed for the factors of safety of the downstream slope due to two-dimensional worst-case modeling (Appendix G). Therefore, 10 cm width was used in all finite element analysis. Both flux and constant head boundary conditions were not known in this case of geomembrane modeling within the embankment dam. As such, there are two options to model the geomembrane with a defect or defects in the dam core: (1) defining a thin region and assigning a material property or (2) setting the geomembrane as an impervious element, which is equivalent to leaving the geomembrane completely out of the analysis. As can be seen in Table 3.2, the pore pressure distribution of these two modeling in the downstream side of the dam gave similar results. Therefore, either can be used to model geomembrane defects within the embankment dams.

Table 3.2 Pore Pressure Comparison of Two Different Geomembrane Modeling in SEEP/W

Geomembrane Modeling Type			
Impervious		**Region**	
Distance (m)	**Water Pressure (kPa)***	**Distance (m)**	**Water Pressure (kPa)***
0	69.56	0	69.61
1	67.05	1	67.11
2	64.83	2	64.88
3	62.59	3	62.64
4	60.30	4	60.34
5	57.93	5	57.97
6	55.48	6	55.52
7	52.93	7	52.97
8	50.27	8	50.31
9	47.47	9	47.51
10	44.52	10	44.56

** The pore pressures were collected from the bottom point of the liner through the downstream side*

In SEEP/W, a geomembrane with a defect or defects within the embankment dam was simulated by defining a thin region and assigning the properties accordingly. A gap, demonstrated in Figure 3.5, was placed on this thin region to represent the geomembrane defect. This simulation assumes that there is a perfect contact condition between the geomembrane and the soil, which means that the interface transmissivity is neglected.

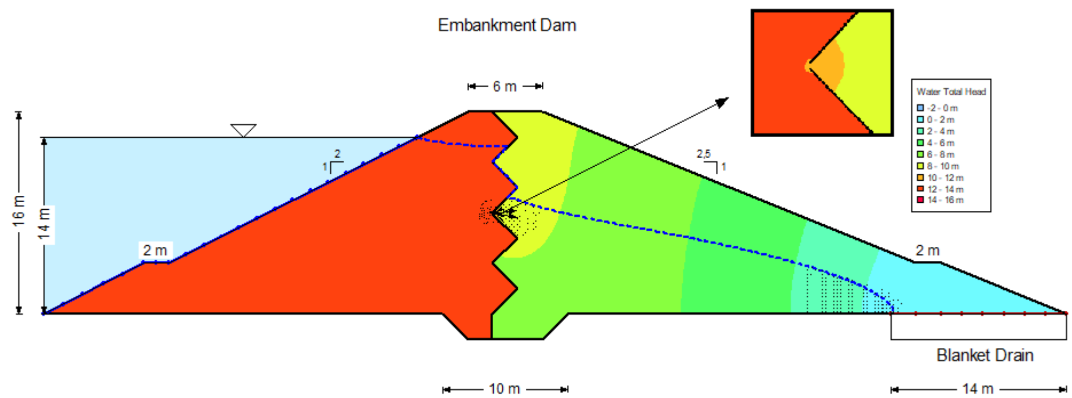


Figure 3.5 Geomembrane Modeling with a Hole in SEEP/W (GeoStudio 2018)

In two-dimensional (2D) finite element analysis, the dam is assumed to be infinitely long. Therefore, the defect modeled in this analysis represents the horizontal defective seams and tears rather than circular defects (Foose et al. 2001). Weber & Zornberg (2008) called this situation as ‘’worst-case scenario’’ that is not likely seen in the field. Even if a defect modeled in two-dimensional finite element analysis represents the worst case, field seams are one of the most problematic locations for leakage through liners (Darilek et al. 1989; Rollin et al. 1999).

3.2.5 Boundary Conditions and Mesh Properties

In SEEP/W, two boundary conditions can be specified; either Q (total flux) or H (total head). Also, drainage and zero pressure boundary conditions are given as a default option in this program as shown in Figure 3.6. The drainage boundary condition is generally used for a dam face where both the total flux and the total head are unknown. It is usually applied on a seepage face of a dam. On the other hand, the zero pressure boundary condition dissipates pore pressures instantaneously, and it is commonly used to model drainage systems (Broaddus 2015).

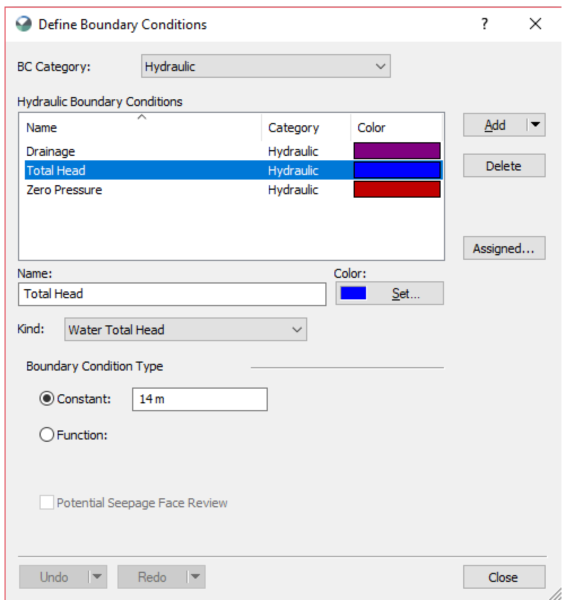


Figure 3.6 Defined Boundary Conditions in SEEP/W (GeoStudio 2018)

In steady-state seepage analysis, the total head boundary condition was applied as 14 m on the upstream face of the embankment dam. Also, a horizontal blanket drain along the downstream side was modeled by using zero pressure boundary conditions instead of creating a region and assigning drainage material properties to it. The reason behind this assumption is that blanket drains are generally so pervious materials.

A transient analysis was conducted to simulate the instant and slow drawdown cases in SEEP/W. Upstream boundary conditions used in the steady-state analysis were modified for the rapid drawdown cases. Details of the upstream boundary conditions for the rapid drawdown are explained in Section 3.3.2.

Finally, the mesh properties were defined by approximate global element size as shown in Figure 3.7. The mesh was generated automatically for each model. The number of elements and trial surfaces were increased until there was no change in the results after any refinement.

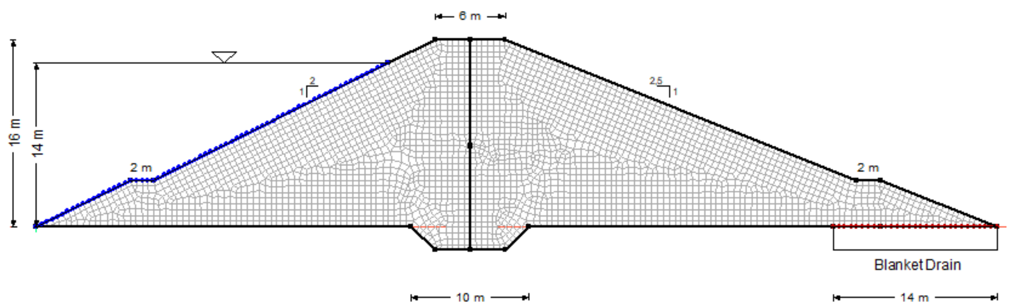
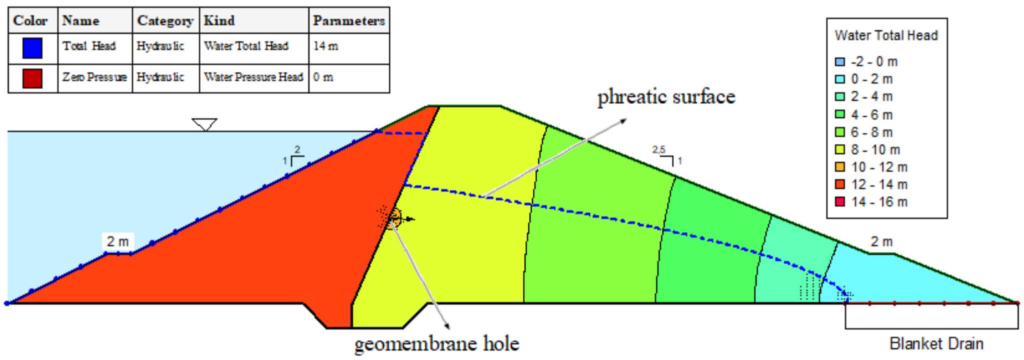


Figure 3.7 Specified Meshes as Approximate Global Size of 0.3 m in Numerical Analysis (GeoStudio 2018)

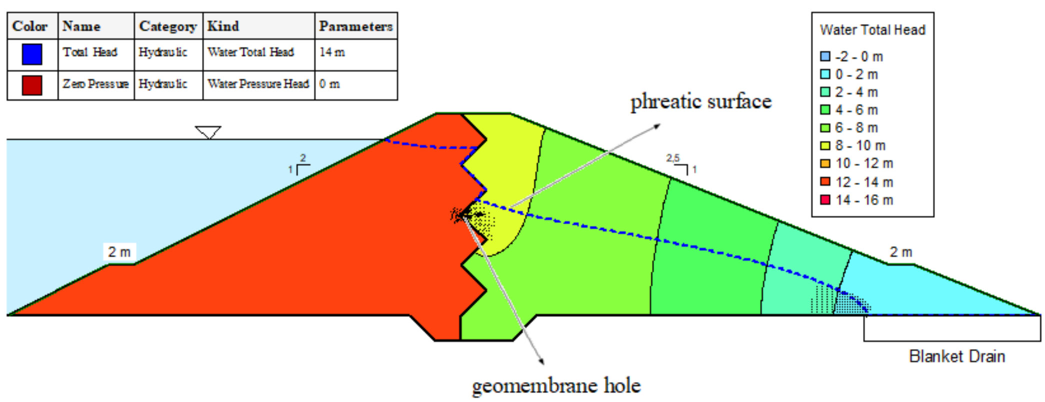
3.3 Seepage Analysis of Leakage through Defective Geomembranes in Embankment Dams

3.3.1 Steady-State Analysis

According to ICOLD's Geomembrane Sealing Systems for Dams: Bulletin 135 (2010) and Bureau of Reclamation's Design Standards No. 13 Embankment Dams Chapter 20: Geomembranes (2014), there are four possible applications of geomembranes within the embankment dam, which are: inclined geomembranes, vertical geomembranes, zig-zag geomembrane with small lifts and zig-zag geomembrane with large lifts. Additionally, there is a possible future evolution of geomembrane application in the dam core as mentioned previously in Section 2.2.2.2 (ICOLD 2010). All these application types were simulated in SEEP/W to evaluate the effect of leakage through geomembrane liners in dam cores. Also, an unlined (homogenous) dam and a geomembrane liner on the upstream face of the dam were simulated for comparison of the performances of all these systems. The total water head distributions and phreatic lines for internal geomembrane systems are shown in Figure 3.8. Additionally, the total water head distribution and phreatic surface demonstrations for unlined and upstream geomembrane systems can be found in Appendix A.

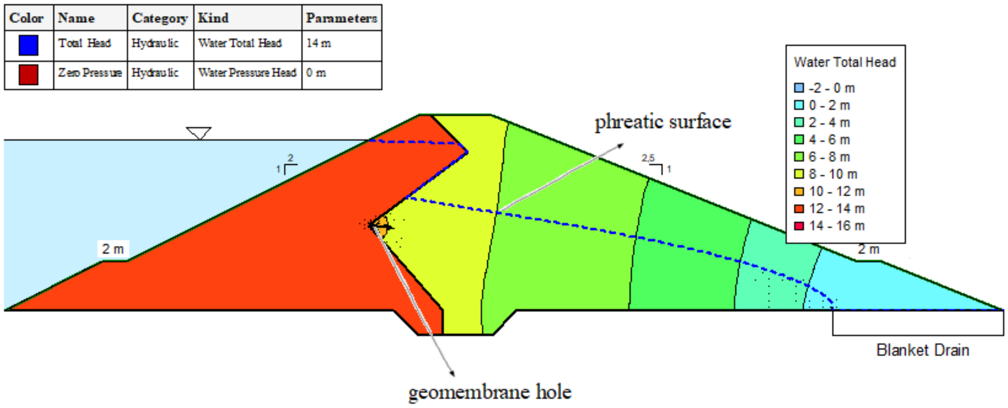


(a)



(b)

Figure 3.8 Water Total Head Distributions and Zero-Pressure Lines for All Application Types of Geomembranes within the Embankment Dams: a) Inclined, b) Zig-Zag with Small Lifts c) Zig-Zag with Large Lifts d) Vertical, e) Double (GeoStudio 2018)



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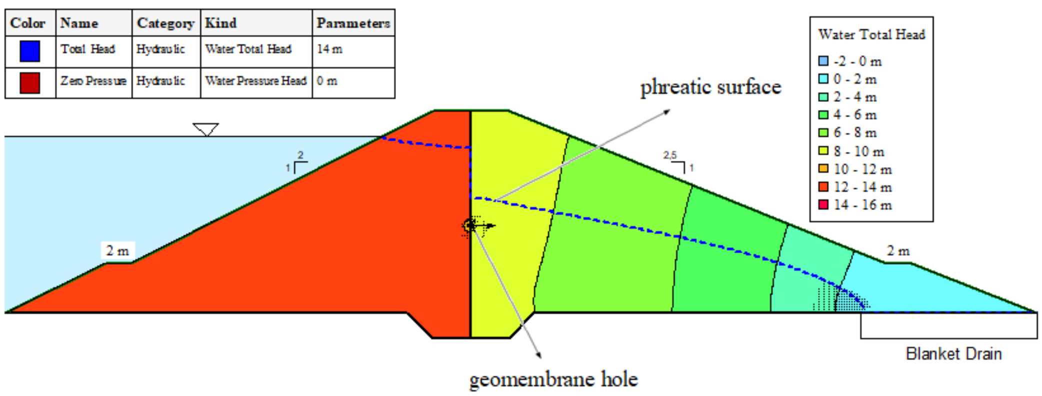

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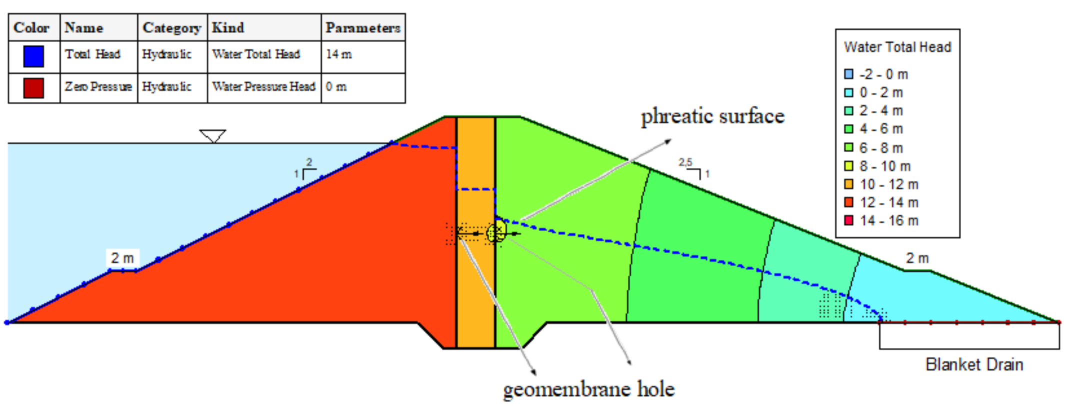


(e)

Figure 3.8 (Continued)

Determination of the size and frequency of defects is the most important design criterion in geomembrane liners since the leakage essentially occurs through geomembrane defects (Giroud 2016) (Appendix B). In the current study, two-dimensional (2D) finite element simulations that incorporated different frequencies and locations of geomembrane defects was performed for the typical configurations of geomembrane applications in dams. The numerical simulations were performed for seven different cases, which were: a) an unlined dam, b) a geomembrane on the upstream face with a defect or defects located at low, middle and high locations of the slope, c) an inclined geomembrane within the dam with a defect or defects located at low, middle and high elevations, d) a vertical geomembrane within the dam with a defect or defects located at low, middle and high elevations, e) a zig-zag geomembrane with large lifts within the dam with a defect or defects located at low, middle and high elevations f) a zig-zag geomembrane with small lifts within the dam with a defect or defects located at low, middle and high elevations, g) double geomembrane within the dam with defects located at low, middle and high elevations.

Material properties that were used in finite element analysis are described in Section 3.2. In SEEP/W, the total head boundary condition was selected as 14 m for the upstream face. Also, the zero pressure boundary condition was applied on the downstream toe to represent the blanket drain, which is 14 m as well. Volumetric water content and hydraulic conductivity functions were created by using data point function in the software. Also, sample material type was selected as a silty clay with 0.45 saturated water content. A saturated hydraulic conductivity of $5x10^{-8}$ m/s and residual water content of 0.045 was used to develop the hydraulic conductivity curve.

Based on the analysis, the unlined dam had the highest elevation of the phreatic surface in the earth dam among all models. Therefore, it had the highest pore pressures on the downstream side. When a geomembrane is used on the upstream or within the dam, the elevation of the zero-pressure line lowered substantially. The least pore pressures were observed in the model where the double geomembranes were placed within the dam. Pore pressure distributions of all models along the bottom line of the embankment dam are demonstrated in Figure 3.9.

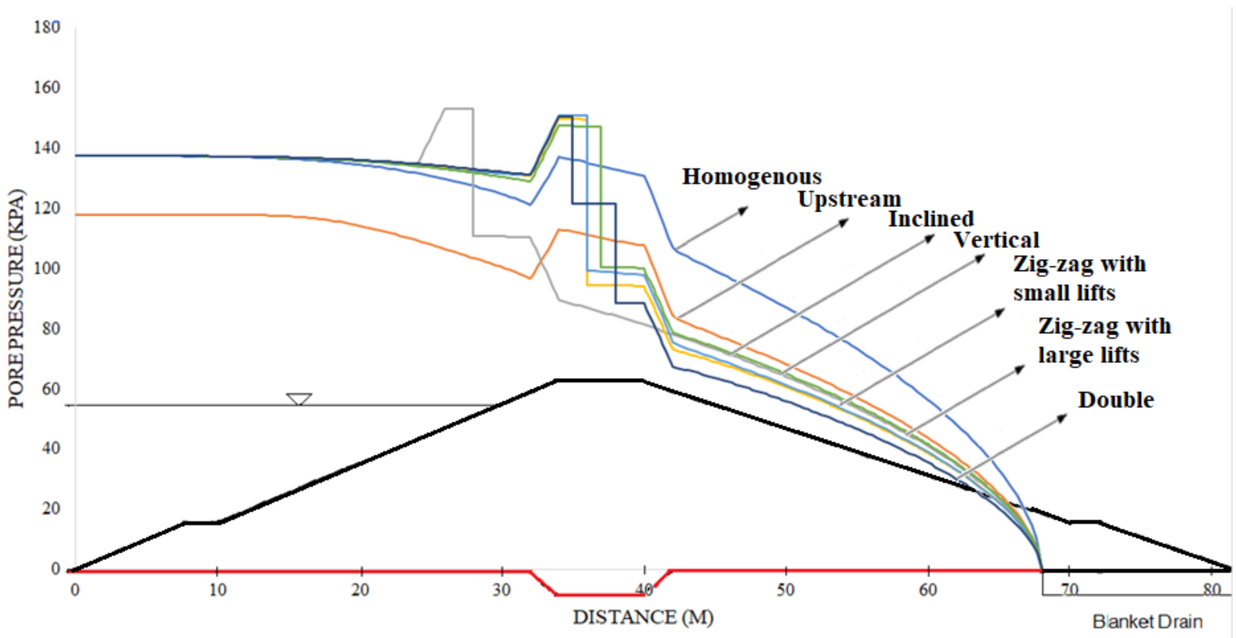


Figure 3.9 Pore Pressure Distribution of Different Geomembrane Systems along the Bottom Red Line of the Embankment Dam (GeoStudio 2018)

3.3.2 Transient Analysis

Placing of a geomembrane within an earth dam would cause excess pore pressures at the upstream side because the geomembrane liners do not permit water to seep through to the downstream side. To evaluate the effects of internal geomembrane systems on the pore pressure distribution along the upstream side of the dam, transient seepage analysis was conducted to simulate the rapid drawdown of the reservoir including the instantaneous drawdown and drawdown at a rate. It is important to note that a vertical geomembrane configuration was used in the case of rapid drawdown for simplicity.

Instantaneous drawdown analysis cannot happen in the field although this assumption is generally made for the embankment dams. On the other hand, the drawdown in time is a much more realistic analysis compared to the instantaneous case (GeoSlope International 2015). In this study, upstream boundary conditions were modified for both instances of instantaneous and rapid drawdown with time. Details of the rapid drawdown analyses are described in the following sections.

3.3.2.1 Instantaneous Drawdown

Two-dimensional (2D) transient analysis was performed to simulate the instantaneous drawdown case in the earthen dam. The initial pore water pressures that are required to perform transient analysis were gathered from the parent steady-state analysis. The water level in the reservoir was at 14 m at the beginning. In this analysis, all the water in the reservoir was removed instantaneously by using the constant boundary condition that was selected as an elevation of 0. Even though the boundary condition was constant, the dissipation of the excess pore pressure in the embankment dam took some time.

As can be seen from the Figure 3.10a, the pore pressure along the upstream side of the earth dam was very high when the geomembrane with a defect was placed in the dam core. Although the reservoir was emptied instantaneously, the excess pore pressure in the dam body was still very high on day 3 and day 45 due to the slow dissipation of water in the cohesive soil (Figure 3.10b and Figure 3.10c).

3.3.2.2 Drawdown at a Rate

To perform a more realistic rapid drawdown analysis, a reasonable drawdown rate per day should be first assumed for the transient seepage analysis. There is a commonly accepted value about a secure drawdown rate for a reservoir of an embankment dam. It is one foot (0.30 m) per

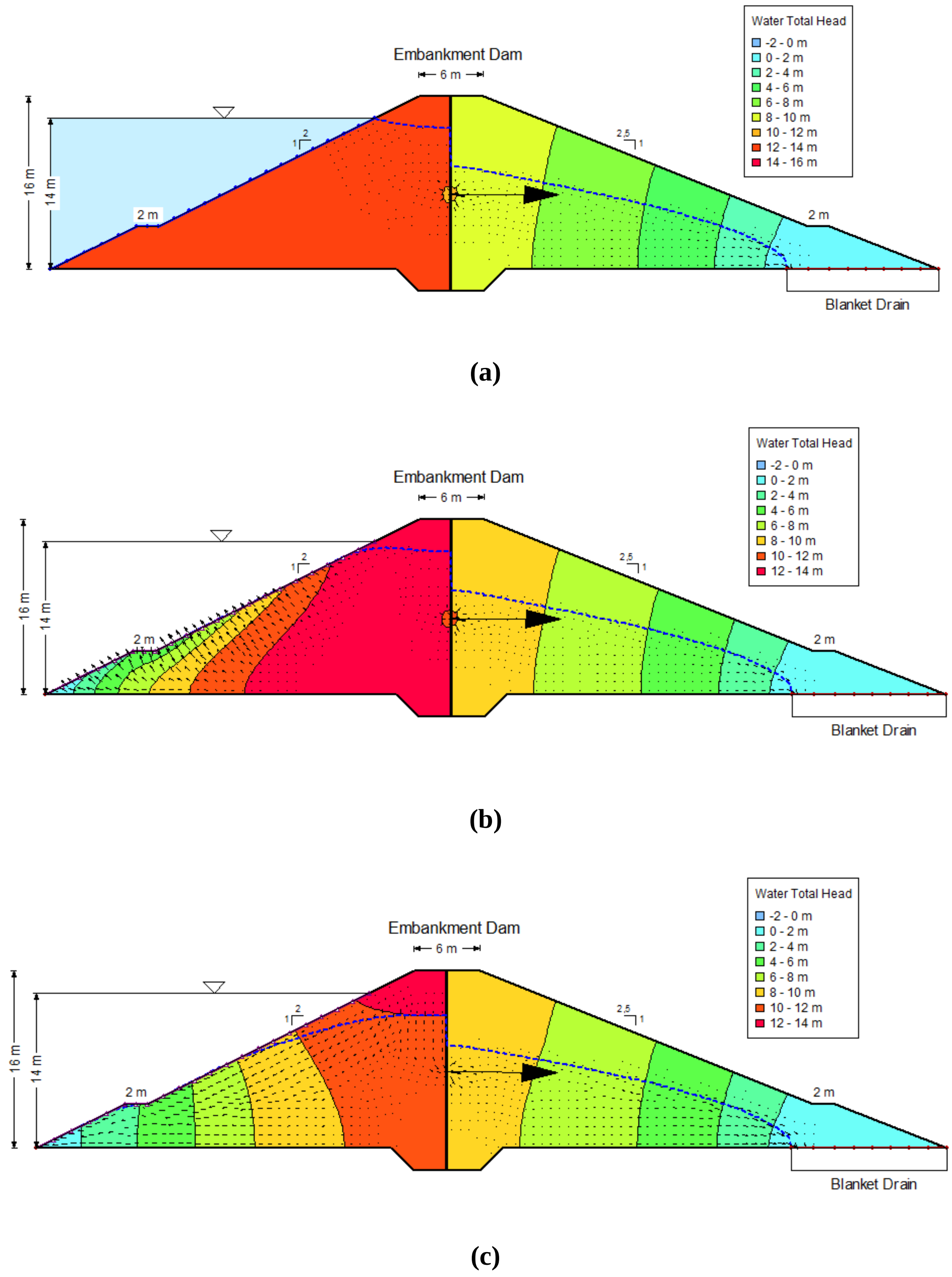


Figure 3.10 Pore Pressure Distributions: a) at the Beginning, b) Day 3, and c) Day 45 in the Case of Instantaneous Drawdown (GeoStudio 2018)

day. However, Beenenga et al. (2016) have performed comprehensive research about the safe drawdown rate per day by investigating the regulations and design guidance. As a result, the acceptable drawdown rate has been found to range from six inches to one foot per day in embankment dams. In this study, the drawdown rate was selected as 6 inches (0.15 m) per day.

Simulations of the rapid drawdown with time were performed by using a vertical geomembrane core configuration. The boundary condition for the upstream face was selected as a function in SEEP/W. The drawdown curve was created by using the data point function in SEEP/W (Figure 3.11). The total head was selected as 14 m (reservoir level) at time 0 and 0 at 93 days. The reason why the transient analysis was performed for 93 days is that 14 m high reservoir level at a drawdown rate of 0.15 m per day is removed in 93 days. It should be noted that eventually the reservoir was completely drained as in the case of instantaneous drawdown.

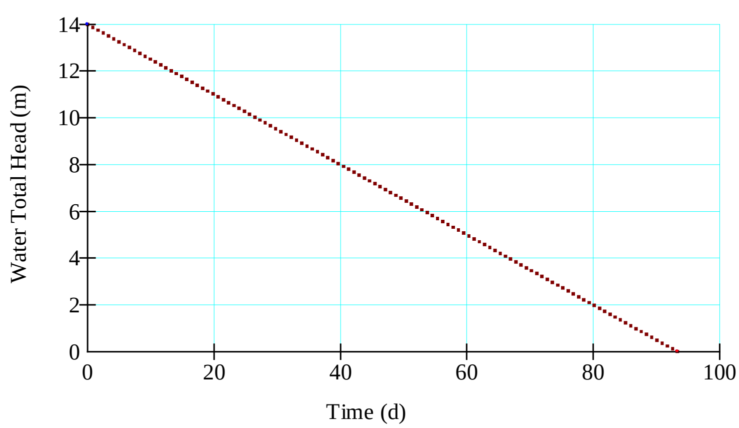
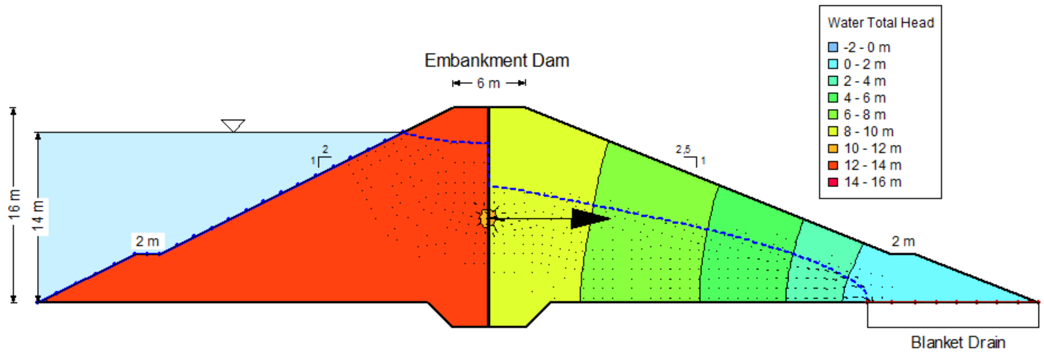
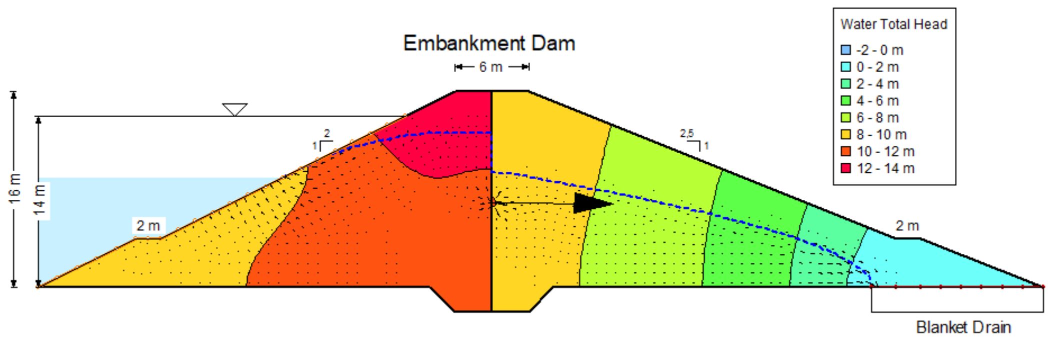


Figure 3.11 The Change of Water Total Head in Time as a Function of Upstream Boundary Condition (GeoStudio 2018)

Figure 3.12b and Figure 3.12c demonstrate the total head distributions on day 34 and day 100 respectively. As expected, the dissipation of excess pore pressure in embankment fill (i.e., silty clay) was at a slower rate than that of the reduction of water level in the reservoir.



(a)



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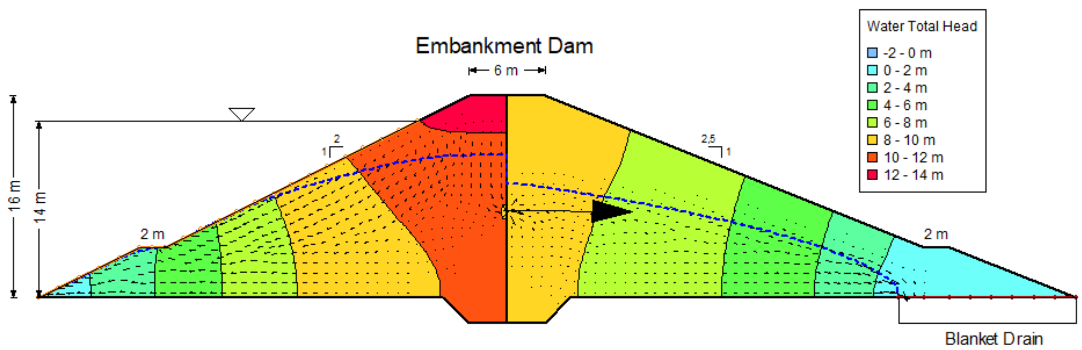


(c)

Figure 3.12 Pore Pressure Distributions: a) at the Beginning, b) Day 34, and c) Day 100 in the Case of Rapid Drawdown at a Rate (GeoStudio 2018)

3.4 Stability Analysis of Embankment Dams Associated with Internal and Upstream Geomembrane Systems

Seepage analysis is usually performed to calculate pore pressure distribution, water fluxes and water velocity in dams. However, the determination of pore water pressure distribution along the body of dam is the priority in seepage analysis since slope stability analyses of embankment dams are generally conducted by using the zero-pressure line that is determined through seepage analyses (GeoSlope International 2015).

In this study, limit-equilibrium analysis was performed to evaluate the effect of leakage through geomembrane liners on the stability of the upstream and downstream slopes of the earth dam. Slope stability calculations for the slopes of the earth dam with a geomembrane liner were performed in SLOPE/W which is a limit equilibrium software for the stability analysis of earth structures (Geo-Slope 2012). There are a number of slope stability analysis methods in SLOPE/W such as Bishop's Simplified, Janbu's Simplified, Spencer, Morgenstern-Price, etc. However, Morgenstern-Price is a more rigorous method compared with other methods of slope stability analysis according to Stark (2018). Therefore, Morgenstern-Price method which satisfies both force and moment equilibrium was selected for the slope stability analysis. Also, zero-pressure line, critical slip surfaces, and a number of slices are required to perform stability analysis in SLOPE/W. Pore water pressure conditions were gathered from the parent seepage analyses in each case. In SLOPE/W, there are many options to define the slip surfaces. In this study, the entry and exit method was used to find the most critical slip surface for both the upstream and downstream slopes of the dam. In this specification, users determine the entry and exit locations of trial slip surfaces. The red line segments shown in Figure 3.13 demonstrate the entry-exit zones (Geo-Slope 2012). It should be noted that the ground zone for entry and exit specification was determined by considering the possible slip surfaces that could occur in the embankment dam. Finally, the number of slices were modified until there was no change in the results of factors of safety for different sceneries.

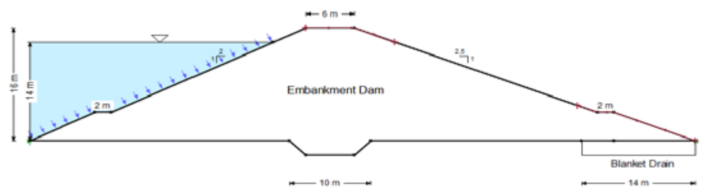


Figure 3.13 Entry and Exit Areas for the Determination of Trial Slip Surfaces (GeoStudio 2018)

U.S. Army corps of engineers recommend that slope stability analysis in embankment dams be performed for different types of conditions, which are: during and end-of-construction, steady-state seepage and sudden drawdown. In this study, stability analyses were performed at, (1) the end of construction for upstream and downstream face, (2) steady-state for the downstream face, and (3) rapid drawdown for the upstream face. A vertical geomembrane configuration was used for the cases of the end of construction and rapid drawdown for simplicity while all seven configurations, explained in Chapter 3.3, were modeled to assess the stability of the embankment dam in steady-state conditions. The required minimum factors of safety that are recommended for different conditions are shown in Table 3.3 (USACE 2003).

Table 3.3 Minimum Required Factors of Safety for Embankment Dams (USACE 2003)

Analysis Condition	**Required Minimum Factor of Safety**	**Slope**
End of Construction	1.3	Upstream and Downstream
Long-term (Steady-state seepage)	1.5	Downstream
Rapid drawdown	1.1-1.3	Upstream

Soil shear strength parameters (cohesion and angle of friction) are key components that affect the factor of safety for the slopes of embankment dams. In this study, average engineering properties of compacted silty clay used in simulations were gathered from the Water Resources Technical Publication – Design of Small Dams (Reclamation 1987). More than 1500 soils tests were performed in the engineering laboratories from 1960 to 1982 in Denver, Colorado. The soil samples were collected from 17 Western States. Minimum, average and maximum shear strength values of silty clay from the Western United States are shown in Table 3.4. For silty clay in this study, a cohesion of 6 kPa and an angle of friction of 28^{o} were assumed for simplicity. On the other hand, a homogenous dam, a geomembrane on the upstream face of the dam and a geomembrane within the dam were modeled with minimum, average and maximum value of the shear strength parameters determined by Bureau of Reclamation to understand the effects of shear strength parameters on the distribution of factors of safety for downstream slope (Appendix C). As the values of shear strength parameters used in limit equilibrium analysis increase, the impact of geomembrane liners on factors of safety of the dam slopes changed as well.

Table 3.4 Average Engineering Properties of Silty Clay (Reclamation 1987)

USCS Soil Type	**Shear Strength (Effective Stress)**		**Values Listed**
	Cohesion (kPa)	**Angle of Friction (degrees)**	
CL	6.2	8	Minimum Value
	71.1	25.1	Average of All Values
	164.1	33.8	Maximum Value
	31		Total Number of Tests

Stability analysis at the end of construction and rapid drawdown cases should be performed for undrained and fully drained conditions if incomplete drainage is expected. (USACE 2003). In the applications of geomembrane liners, upstream slopes of dams are generally constructed with highly permeable materials. Also, geomembrane liners are usually associated with drainage systems (Giroud 2016). For those reasons, drained shear strength parameters in terms of effective stresses were used in all analyses including the end of construction, rapid drawdown and long-term steady state (Table 3.5).

It is important to note that the dam configuration is exactly the same as that used in seepage analysis except for the rapid drawdown case. Upstream slopes of 1V:2.5H and 1V:3H were also used for the rapid drawdown of the reservoir to understand the effect of the upstream slope on the factor of safety.

Table 3.5 Shear Strength Parameters of the Embankment Fill for Slope Stability Analysis

Soil (Silty Clay)	**Cohesion, C (kPa)**	**Angle of Friction, φ (º)**
End of construction	6	28
Steady-state seepage	6	28
Rapid drawdown	6	28

Seven different dam configurations including homogenous, geomembrane on the upstream face and five different internal systems were modeled in SLOPE/W for long-term seepage. On the other hand, only the vertical geomembrane within the core was simulated to evaluate the performance of the internal system for the cases of the end of construction and rapid drawdown for the sake of simplicity.

3.4.1 Stability of the Upstream Slope

3.4.1.1 End of Construction

As previously mentioned, drained shear strength parameters may not be applicable at the end of construction condition in this embankment dam due to silty-clay (CL) with a permeability as low as $5x10^{-8}$ m/s. However, the upstream and internal geomembrane liners are usually associated with highly permeable materials. Therefore, drained shear strength parameters in terms of effective stresses can be used in case of the end of construction. In this study, SLOPE/W was used to calculate the factor of safety of the upstream slope of the embankment dam with a vertical geomembrane core.

The upstream slope of the embankment dam had a factor of safety of 1.361 at the end of construction which is higher than the value of 1.3 recommended by the U.S. Army Corps of Engineers.

3.4.1.2 Rapid Drawdown

Rapid lowering of the reservoirs of the embankment dams can cause upstream stability issues during service life due to the slower dissipation of excess pore pressure in cohesive soils (Beenenga et al. 2016). Consequently, upstream slope stability analysis for internal systems should be carefully considered in the case of rapid drawdown due to the high pore pressure stored in the upstream side. On the other hand, in the case where the rapid drawdown of the dam is a critical concern, the use of geomembranes within the dams provide more beneficial solutions against the risk of geomembrane uplift (Giroud 2016).

To understand the effect of rapid drawdown on dam stability when the geomembrane is placed within the dam, the vertical geomembrane with a defect configuration was simulated. It should be noted that the factors of safety were almost same during time in the case of unlined dam.

Parent pore water pressure distributions that were simulated in SEEP/W were used for the upstream slope stability in SLOPE/W. The boundary conditions for each case are explained in the following sections.

Upstream slope stability is highly dependent on the geometry of the embankment dam and the permeability of the soil. In this model, the embankment dam has an upstream slope of 1V:2H, which is quite steep when the geomembrane is used on the upstream face of an embankment dam according to USSD (2011) (Table 3.6). Consequently, the upstream slope of 1V:2.5 and 1V:3H were simulated to evaluate the effect of the inclination of the slope on the distribution of factor of safety during the time in rapid drawdown conditions.

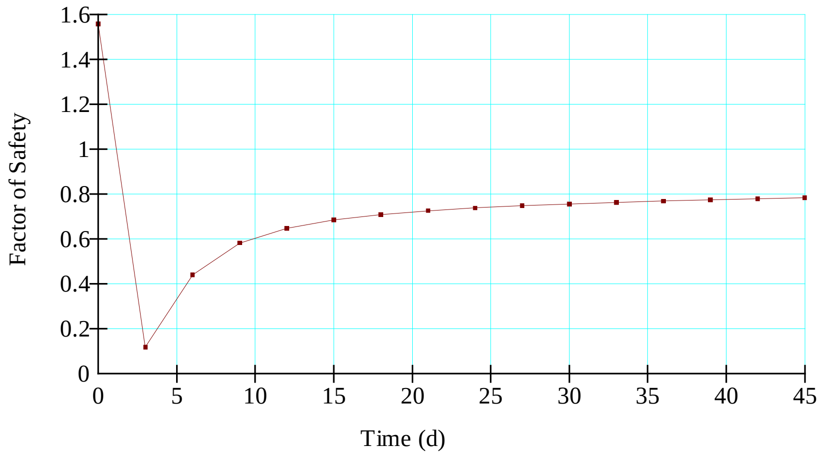
Table 3.6 Typical Slopes for Embankment Dams Associated with Geomembrane Liners on the Upstream Face (USSD 2011)

Material	**Typical Slope (Horizontal:Vertical)**
Clay	2.5:1 to 3.5:1
Sandy clay and silt	2.0:1 to 3.0:1
Sand and gravel	2.0:1 to 2.5:1
Rockfill	1.5:1 to 2.0:1

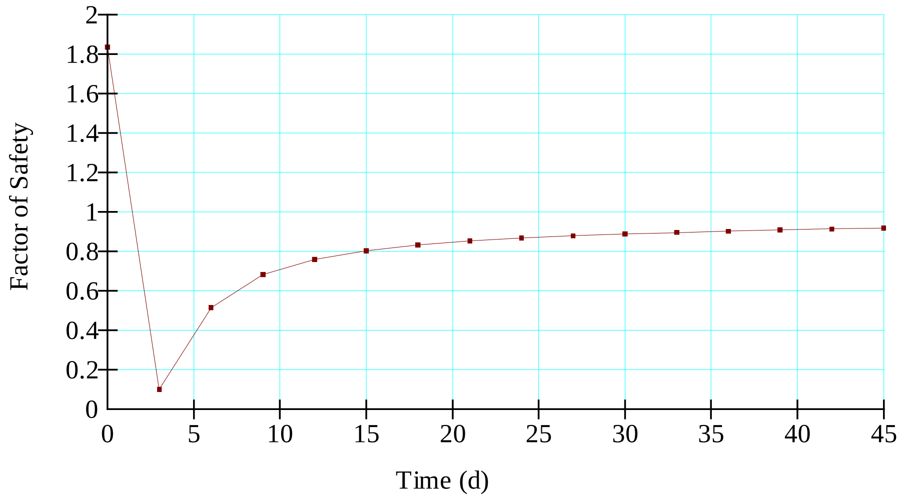
3.4.1.2.1 Instantaneous Drawdown

In the case of instantaneous drawdown, slope stability analysis was performed in SLOPE/W by using phreatic line gathered from the parent seepage analysis. Figure 3.14 shows the variation of factors of safety for the upstream slopes of 1V:2H, 1V:2,5H and 1V:3H over time in the case of instantaneous drawdown.

As expected, the factor of safety for the upstream slope dropped greatly when the reservoir was emptied suddenly. When the pore pressure dissipates in time, the factors of safety increased substantially, but it was still far less than the recommended factor of safety of 1.1. This trend was same for the flatter upstream slopes of 1V:2.5H and 1V:3H. However, it is important to note that instantaneous drawdown is an unusual case that would not happen in the field.

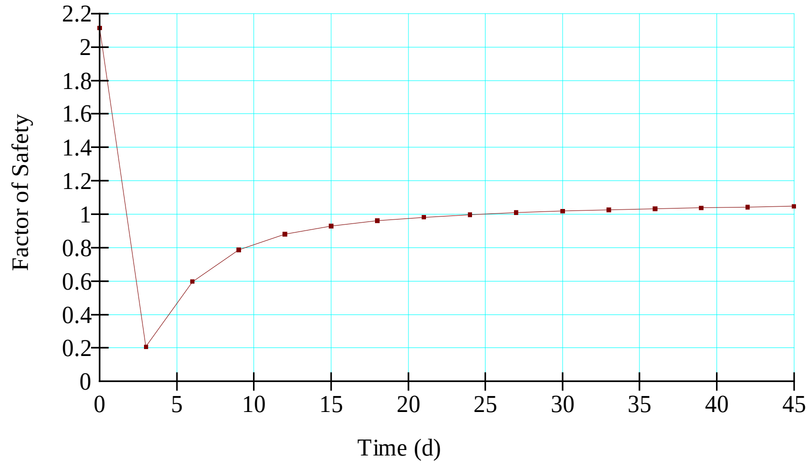


(a)



(b)

Figure 3.14 Distribution of the Factors of Safety for the Upstream Slope of: a) 1V:2H, b) 1V:2.5H, and c) 1V:3H Over Days for Instantaneous Drawdown (GeoStudio 2018)



(c)

Figure 3.14 (Continued)

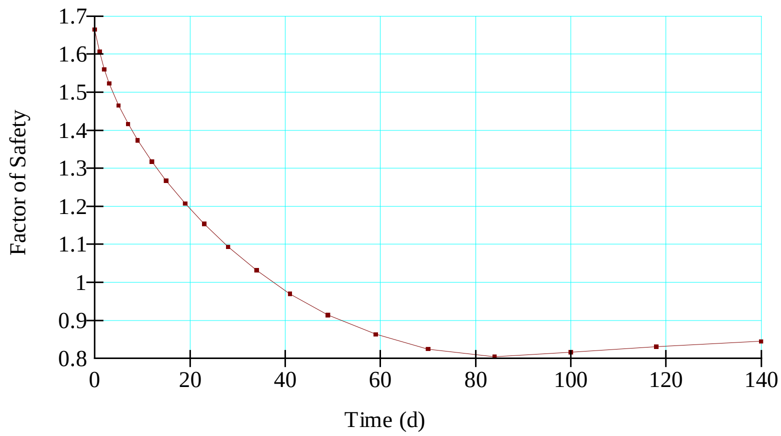
3.4.1.2.2 Drawdown at a Rate

The risk of upstream slope failure in the rapid drawdown condition is a significant concern when the embankment materials are cohesive soils. The drop of the reservoir level is generally faster than the dissipation of pore pressure in cohesive soils. As a result, the shear strength of the fill materials can be reduced, and this situation could end up with the failure of the upstream slope. In this study, parent seepage analysis which was drawdown at a rate was selected for the pore water pressure distribution in SLOPE/W.

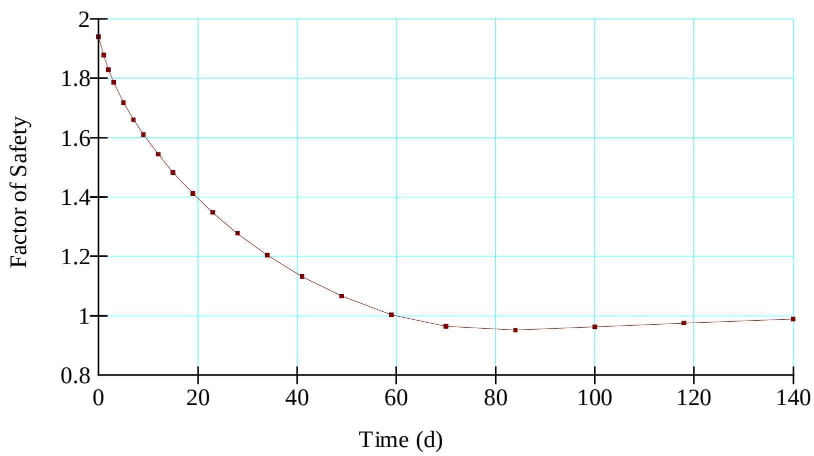
The distribution of factors of safety during the time is given in Figure 3.15. It is seen that the factors of safety dropped in time when the reservoir was removed at a rate of 15 cm per day. At the end of 93 days, the reservoir was drained completely. After 93 days, factors of safety started to increase because of the dissipation of pore pressures.

For the case of the upstream slope of 1V:2H, the factors of safety were becoming less than the required value of 1.1 after 30 days as can be seen in Figure 3.15a. When the upstream slope of

1V:2.5H was simulated, the factor safety again dropped below the recommended factor of safety of 1.1 after 50 days (Figure 3.15b). On the other hand, the factor of safety for the upstream slope of 1V:3H did not drop below the recommended value of 1.1, which made the upstream face of the dam safe (Figure 3.15c).

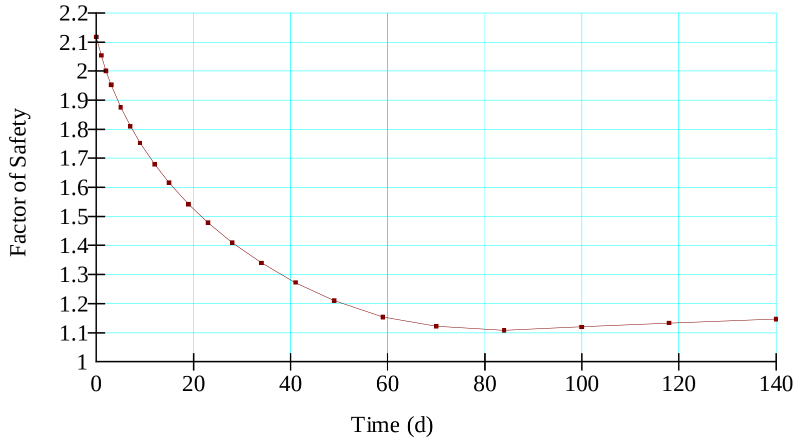


(a)



(b)

Figure 3.15 Distribution of the Factors of Safety for the Upstream Slope of: a) 1V:2H, b) 1V:2.5H, and c) 1V:3H Over Days for Drawdown at a Rate (GeoStudio 2018)



(c)

Figure 3.15 (Continued)

3.4.2 Stability of the Downstream Slope

3.4.2.1 End of Construction

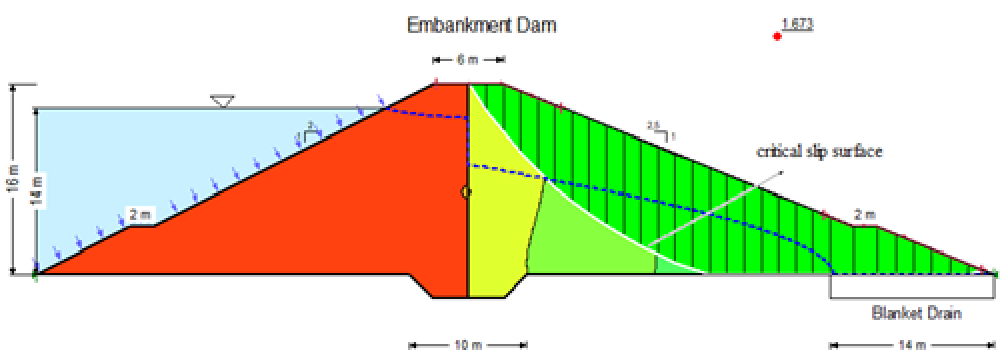
SLOPE/W was also used for the end of construction condition to analyze the stability of the downstream slope of the embankment dam with a vertical geomembrane. Drained shear strength parameters were used in this analysis.

The downstream slope of the embankment dam had a factor of safety of 1.648 at the end of construction which is higher than the value of 1.3 recommended by the U.S. Army Corps of Engineers.

3.4.2.2 Long-term (Steady-State Seepage)

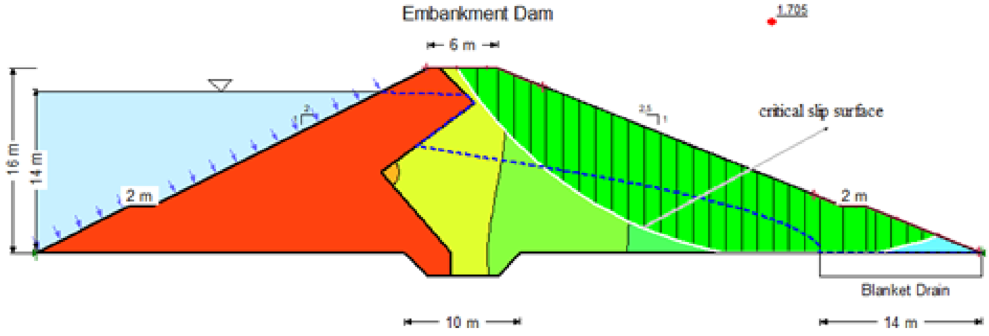
Steady-state seepage analysis is generally performed for the long-term stability of the downstream slope of the embankment dams because, in the long run, dams will mostly be under the condition of steady-state seepage conditions. In this study, limit-equilibrium analysis was performed to evaluate the performance of internal and upstream geomembrane systems with respect to the stability in earthen dams. Parent steady-state seepage analyses described in Section 3.3.1 were used in SLOPE/W for the pore water pressure distribution along the different domains. As for the strength, long-term conditions were analyzed using drained shear strengths parameters. Once more, the Morgenstern-Price analysis type and entry-exit specification for the trial slip surfaces were used in slope stability analysis.

The critical failure surfaces for the all internal geomembrane systems with a defect located at the central location can be seen in Figure 3.16. None of the critical slip surfaces crossed the geomembrane liners in the stability analyses. It is important to note that the bottom of the slip surface did not enter the bottom of the dam because it was assumed that the dam was on bedrock. Therefore, all the critical slip surfaces followed the bedrock surface until they completed the continuous circular segment. Additionally, the critical slip surfaces of the unlined and upstream geomembrane system are demonstrated in Appendix D.



(a)

Figure 3.16 Critical Slip Surfaces of the Embankment Dam with Internal Geomembrane Systems: a) Vertical, b) Zig-Zag with Large Lifts, c) Zig-Zag with Small Lifts, d) Inclined, e) Double (GeoStudio 2018)



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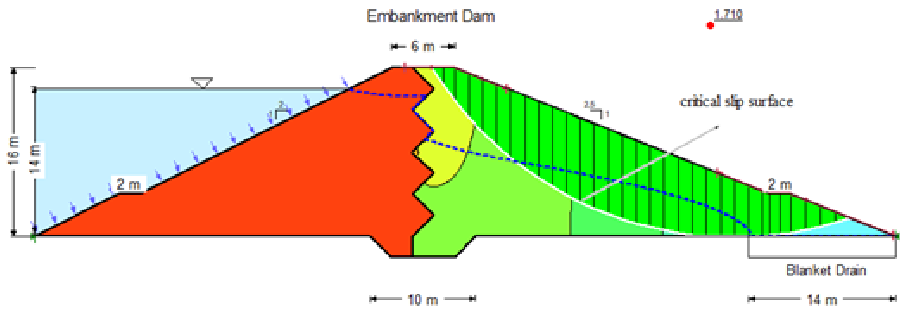

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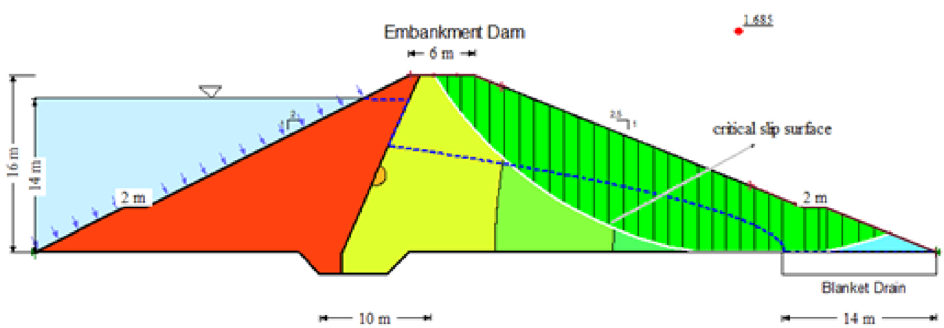

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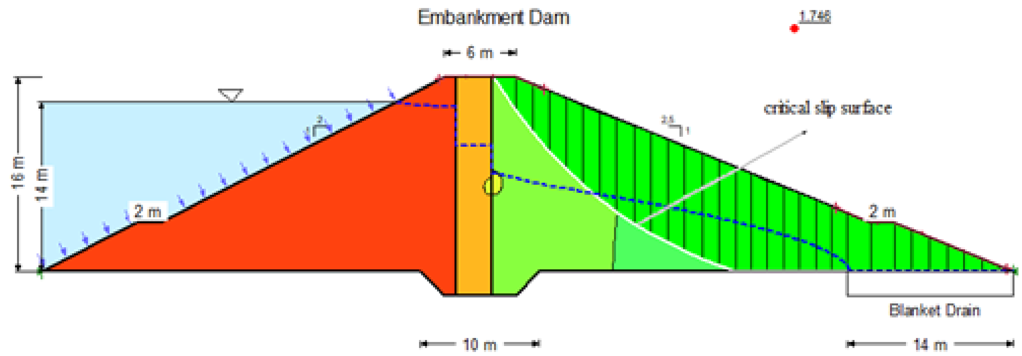
Figure 3.16 (Continued)



(e)

Figure 3.16 (Continued)

The factors of safety for all types of applications performed in slope stability analysis of the embankment dam with and without a geomembrane liner are shown in Table 3.7. The embankment dam without a geomembrane liner (unlined) has a factor of safety of 1.47, which is less than the value of 1.5 that is recommended by the U.S. Army Corps of Engineers for the long-term condition. However, the factor of safety for the embankment dam was significantly affected by the presence of a geomembrane liner placed either on the upstream face or within the dam. All the factors of safety for the embankment dam with the geomembrane liners that have defective seams or not are greater than the recommended value of 1.5. Regarding the slope stability analysis of the downstream slope, internal geomembrane systems produced slightly higher factors of safety than the upstream geomembrane systems. It should be noted that the highest factor of safety occurred in the case of double geomembrane application.

Table 3.7 Factors of Safety for the Downstream Slope of the Embankment Dam Associated with Geomembrane Systems with a Defective Seam or Seams Located in Different Places and Frequencies

Status of Defective Seam	**Factor of Safety**						
	Homogenous	**Upstream**	**Core**				
			Inclined	**Vertical**	**Zig-zag with Large Lifts**	**Zig-zag with Small Lifts**	**Double***
Unlined	1.470	-	-	-	-	-	-
No damage	-	1.830	-	1.833	-	-	-
Middle	-	1.646	1.683	1.669	1.706	1.710	1.746
Low	-	1.762	1.712	1.682	1.713	1.713	-
High	-	1.632	1.777	1.803	1.814	1.825	-
Two Defective Seams	-	1.589	1.608	1.612	1.633	1.640	-

**It was assumed that both geomembrane liners have defects in double liner systems.*

The location of the defective seam had a significant impact on the factor of safety of the downstream slope. For internal geomembrane systems, the highest value of factor of safety was observed when the defective seam occurred at a high location. Also, the minimum value of factor of safety was seen when the defective seam occurred at a middle location. On the other hand, the upstream geomembrane system showed a completely different trend. The highest value for the factor of safety in the upstream system was at a location when the defective seam occurred at a low elevation. The factor of safety becomes lower smaller when the position of the defective seam was higher elevations on the upstream slope.

When two defective seams were modeled in each configuration, the factors of safety for most of the configurations were still higher than the recommended value of 1.5. It is important to note that the zig-zag geomembrane configurations with either small or large lifts had the highest factor of safety of among all applications expect the double liner system when the defective seam occurred at the middle.

For this study, increasing the geomembrane thickness from 1 to 5 mm has no effect on the pore pressure distribution along the embankment dam (Appendix E). Therefore, the factors of safety for downstream slope were almost the same for the thickness of geomembranes ranging from 1 to 5 mm. Even if the thickness increased to 10 mm which is unrealistic, the factors of safety changed very slightly (Table 3.8).

Table 3.8 Factors of Safety of the Downstream Slope of the Embankment Dam with Different Geomembrane Thicknesses

Geomembrane Thickness (mm)	The factor of Safety for Downstream Slope	
	Internal Geomembrane System*	Upstream Geomembrane System
1	1.667	1.647
3.5	1.669	1.649
5	1.670	1.650
10	1.672	1.652

**The configuration of vertical geomembrane was modeled to represent the internal geomembrane systems.*

To assess the effect of geomembrane permeability on factors of safety for downstream slope, the analysis was performed with different hydraulic conductivities in the configuration of zig-zag geomembrane with large lifts. As previously mentioned, the hydraulic conductivity of geomembranes can be less than 10^{-14} (when intact). In SVOFFICE Help Manual, it is suggested that the hydraulic conductivity of the geomembrane and the adjacent regions in finite element analysis should be within a specific range because a solution may have some limitations in terms of accuracy after 7 orders of the magnitude (Fredlund et al. 2018).

In this analysis, the hydraulic conductivity of the geomembrane decreased from 10^{-10} to 10^{-17} m/s (Table 3.9). The results show that the factors of safety for the downstream slope of the embankment dam changed very slightly when the hydraulic conductivity of geomembrane was within or higher than six orders of magnitude of the hydraulic conductivity of the adjacent soil. After six orders, there was almost no change in the factors of safety for the downstream slope (Figure 3.17). Also, same trend was observed when the soil permeability was changed to 5×10^{-10} m/s.

Table 3.9 Factors of Safety of the Downstream Slope with Different Geomembrane Permeability

Soil Permeability (m/s)	**Geomembrane Permeability (m/s)***	**The factor of Safety for downstream slope**
5×10^{-8}	10^{-10}	1.477
	10^{-11}	1.526
	10^{-12}	1.643
	10^{-13}	1.692
	10^{-14}	1.701
	10^{-15}	1.702
	10^{-16}	1.702
	10^{-17}	1.702

**The configuration of zig-zag with large lifts was modeled for different geomembrane permeability*

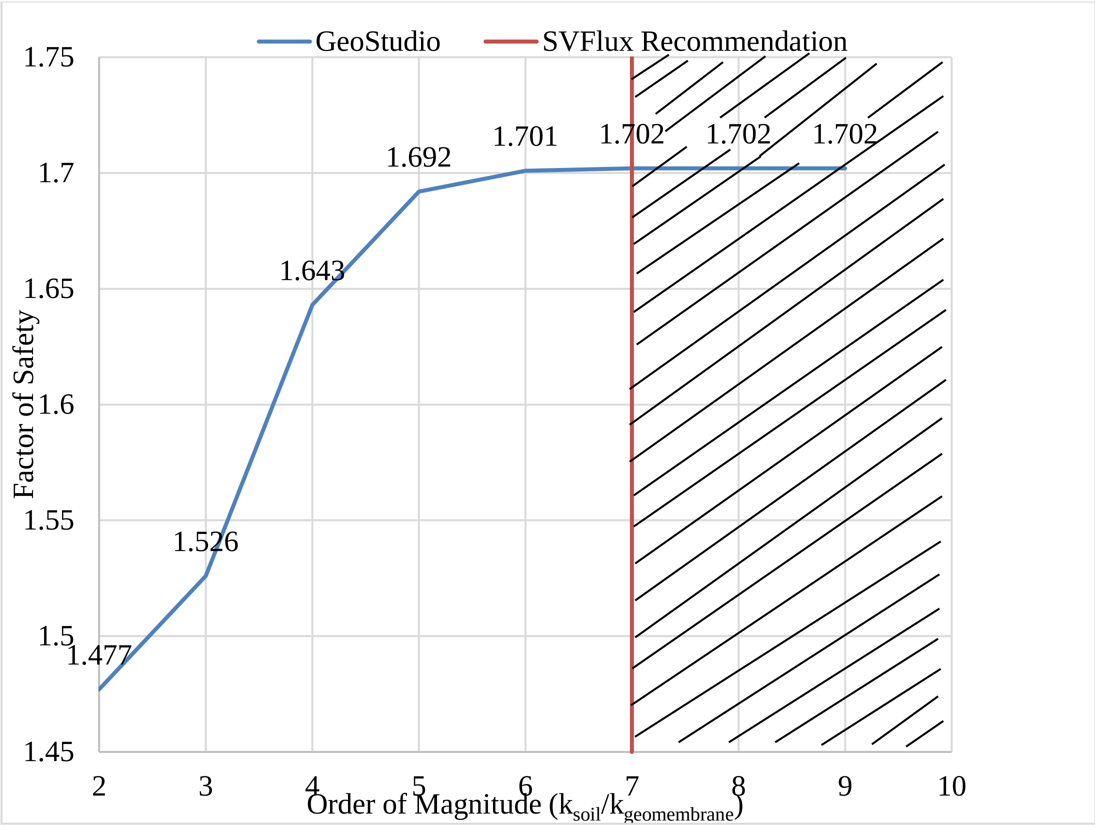


Figure 3.17 Factor of Safety versus Difference of Hydraulic Conductivities Between the Embankment Fill and the Geomembrane

CHAPTER 4: DISCUSSION, SUMMARY, AND RECOMMENDATIONS

4.1 Discussion

Internal geomembrane systems are one of the most effective ways to lower the elevation of the zero-pressure lines in earthen dams. For this study, two-dimensional (2D) finite element analysis was used to model geomembrane systems in embankment dams. The geomembrane systems were analyzed under the conditions of rapid drawdown, end of construction and long-term. This study aims not only to evaluate the leakage through internal and upstream geomembrane systems with defects located at different heights but also to compare the performance of those systems with respect to the stability in earthen dams. Also, this study provides a better understanding of how geomembrane parameters (e.g., thickness and permeability) will affect the factors of safety of the downstream slope of a dam.

Previous studies have shown that placing a geomembrane on the upstream face of a dam has positive impacts on dam performance with respect to stability. According to Weber & Zornberg (2008), the factor of safety for the downstream slope of a dam can be slightly increased if a geomembrane liner is placed on the upstream face of a dam. The increase in the factor of safety was not significant in that study because of the conservative defect modeling. Results of this study support and augment these findings by showing that the increase in factors of safety for the downstream slope of a dam can be significant for upstream geomembrane systems depending on the location, frequency, and size of the defect. It is also shown that the use of a geomembrane liner within an embankment dam could significantly resolve the stability issues of the embankment dam by increasing the factor of safety for the downstream slope.

The selection of thickness and permeability of the geomembrane liners is important in the design stages of embankment dams. It is shown that a geomembrane thickness with a typical ranging from 1 to 5 mm will more or less have the same performance in earth dams with respect to stability when they are placed in the dam core. On the other hand, it is important to note that increasing the geomembrane thickness will have positive impacts on the mechanical properties of geomembranes such as tensile behavior, tear and puncture resistance. Additionally, the permeability of geomembranes has significant effects on the performance of the embankment dam. For this study, the factor of safety for the downstream slope increased when the hydraulic conductivity of vertical geomembrane decreased from 10^{-10} m/s to 10^{-14} m/s.

Rapid drawdown would also be a significant concern in the case of internal geomembrane systems due to the excessive pore pressures developed on the upstream side. For this study, different upstream slopes were performed in the rapid drawdown condition. An upstream slope of 1H:3V was sufficiently stable under rapid drawdown at a specified rate case when stability analysis in the slope of 1H:2V and 1H:2.5 yielded a lower factor of safety than the recommended value of 1.1. Therefore, the upstream slope should be carefully considered in internal geomembrane systems when rapid drawdown is a critical concern in the dam performance. This study also contributed to understanding the performance of internal geomembrane systems in embankment dams. With respect to upstream slope, it is shown that internal geomembrane systems are as effective as upstream geomembrane systems in lowering the phreatic surface in the body of a dam and increasing the factor of safety for downstream slope. It should be noted that three-dimensional (3D) finite element analysis, including practical examples of the use of geomembranes in earthen dams, would be a logical step for future research to evaluate the leakage through circular defects in geomembrane liners.

4.2 Summary of Research Findings

This thesis research is a beneficial step in the study of leakage through internal geomembrane liners within earth dams and the comparison of the internal and upstream geomembrane systems with respect to stability of dams. Conclusions from the research that was based on numerical analysis are listed follows:

- The hydraulic conductivity of the geomembrane liner modeled in finite element analysis should be within seven orders of magnitude lower than the hydraulic conductivity of adjacent embankment fill. A solution may not be possible after seven orders of magnitude.
- When the geomembrane is placed either on the upstream slope or within the embankment dam, the elevation of the zero-pressure line lowers. As a result, the factor of safety against the stability of the embankment dam increases significantly.
- Internal geomembrane systems provide slightly higher factors of safety for the downstream slopes of the embankment dams than the upstream geomembrane systems when two defective seams occur.
- The use of geomembranes within the core could cause upstream slope stability problems with respect to rapid drawdown due to excessive pore pressures developing on the upstream side of the earth dam. In this study, upstream slope of 1V:3H or flatter slopes performed well in the case of drawdown at a rate.
- Slope stability analysis performed with the typical values of geomembrane thicknesses range of values (1 to 5 mm) yield almost the same factors of safety for the downstream slope of the embankment dam. Even though thick geomembranes increase the cost, they

would minimize the risk of occurrence of defects. Therefore, all these aspects should be carefully considered.

- As the angle of friction of the embankment soil used in limit equilibrium analysis increase, the effect of geomembrane liners on factors of safety for the downstream slope relatively increases. On the other hand, the geomembrane liners become less efficient with respect to the stability of the downstream slope when the cohesion of the embankment fill increases. Therefore, geomembrane systems in embankment dams can be more effective in cohesionless soils.
- The location of the defective seam has a significant impact on the factor of safety of the downstream slope. In the case of upstream geomembrane systems, the factor of safety for the downstream slope is the highest when the defective seam occurs at a relatively low location, whereas in the case of internal geomembrane systems, the highest factor of safety occurs when the defective seam is at a higher location.
- The factor of safety for the downstream slope can be increased by using double geomembrane liners, but the increase may not be significant.

4.3 Recommendations for Future Research

Verification of the results of seepage analysis and slope stability analysis is crucial. Therefore, it is recommended that the results of this study be verified by using another computer software that can perform a limit-equilibrium analysis.

A simple embankment dam was analyzed in this research. More complex dams, especially ones with the drainage accessories behind the geomembrane liners, could be modeled in finite element analysis.

For more realistic results, it is recommended that circular geomembrane holes be modeled in three-dimensional (3D) finite element analysis to evaluate the leakage through geomembrane liners within the embankment core.

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APPENDICES

Appendix A: Pore Pressure Distribution of the Homogenous Dam and the Upstream Geomembrane System

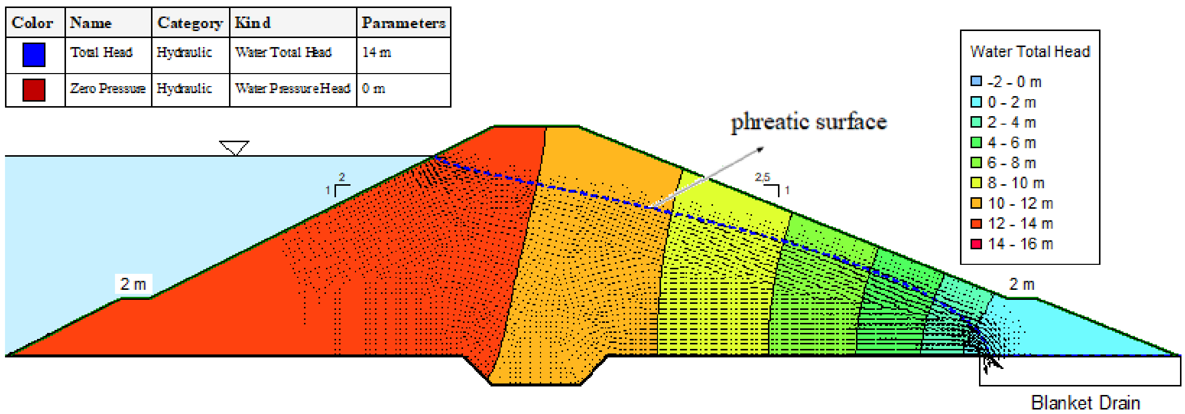

Figure A.1 Demonstration of the Phreatic Line and Total Head Distribution of Homogenous Dam

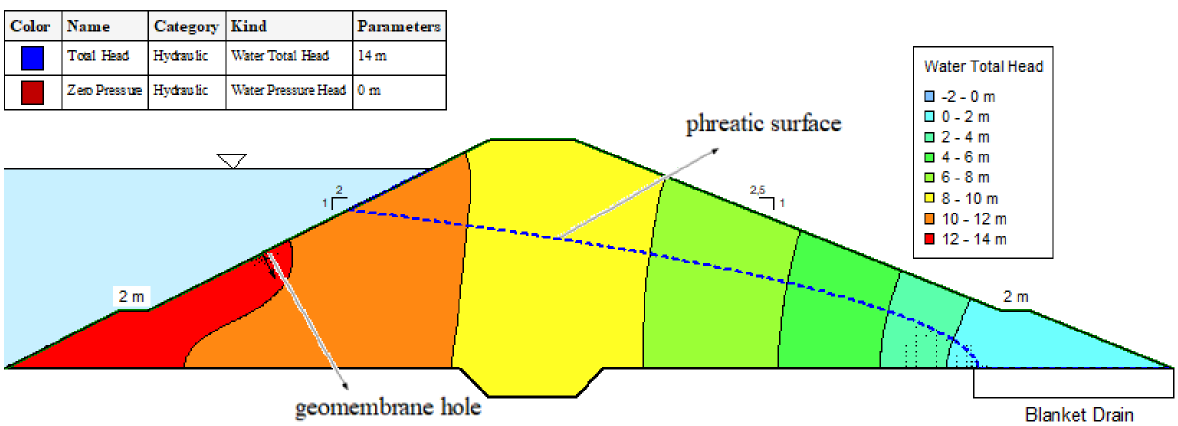

Figure A.2 Demonstration of the Phreatic Line and Total Head Distribution of Homogenous Dam with a Geomembrane on the Upstream Face

Appendix B: The Elevations of Phreatic Lines of Different Geomembrane Systems with a Defect

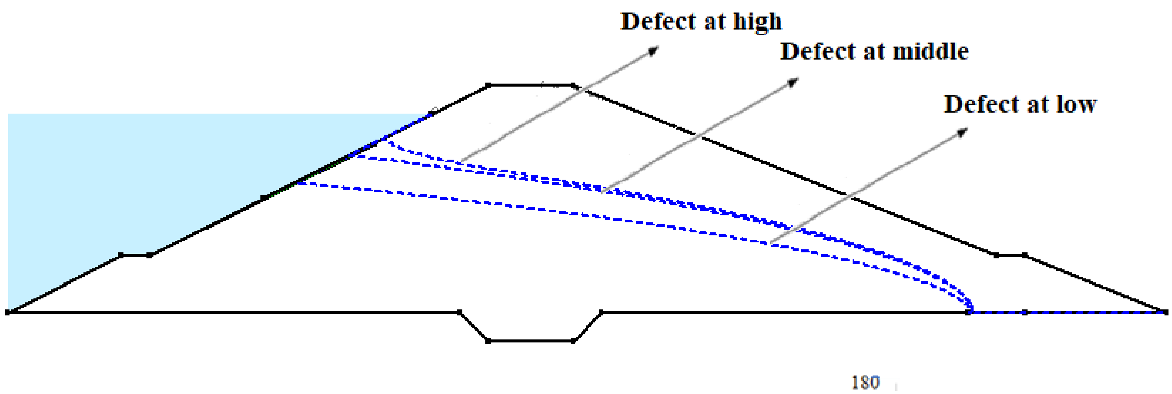

Figure B.1 The Elevations of Zero Pressure Lines in the Embankment Dam with a Defect Located at Low, Middle, and High in Upstream Geomembrane Systems

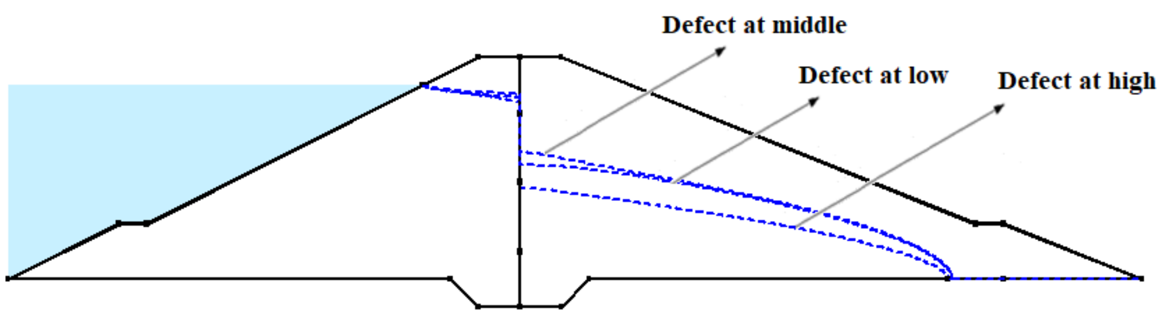

Figure B.2 The Elevations of Zero Pressure Lines in the Embankment Dam with a Defect Located at Low, Middle, and High in Internal Geomembrane Systems

Appendix C: The Effect of Soil Parameters on Factors of Safety for an Embankment Dam with a Geomembrane Liner

Table C.1 The Factors of Safety of the Downstream Slope of the Embankment Dam with a Vertical Geomembrane with Minimum, Average and Maximum Value of the Shear Strength Parameters Determined by Bureau of Reclamation

Geomembrane Status	Soil Properties				
	γ(kN/m^3)	Cohesion (kPa) / Angle of Friction (°)	6.2	71.1	164.1
			Factor of Safety		
Homogenous (unlined)	18	8	0.544	2.705	5.807
		25.1	1.328	3.487	6.585
		33.8	1.804	3.969	7.072
Upstream		8	0.594	2.87	6.09
		25.1	1.475	3.746	7.015
		33.8	2.015	4.282	7.549
Vertical		8	0.598	2.776	5.903
		25.1	1.494	3.738	6.804
		33.8	2.041	4.238	7.359

Table C.2 Percentage Increase in Factor of Safety Compared with Homogenous Case for All Shear Strength Values

Slopes of the Dam	Cohesion (kPa) / Angle of Friction (°)	Percentage Increase in Factor of Safety Compared with Homogenous Case		
		6.2	71.1	164.1
Upstream	8	9.2	6.1	4.9
	25.1	11.1	7.4	6.5
	33.8	11.7	7.9	6.7
Internal	8	9.9	6.3	1.7
	25.1	12.5	7.2	3.3
	33.8	13.1	6.8	4.1

Appendix D: Critical Slip Surfaces of the Homogenous Dam and Upstream Geomembrane System

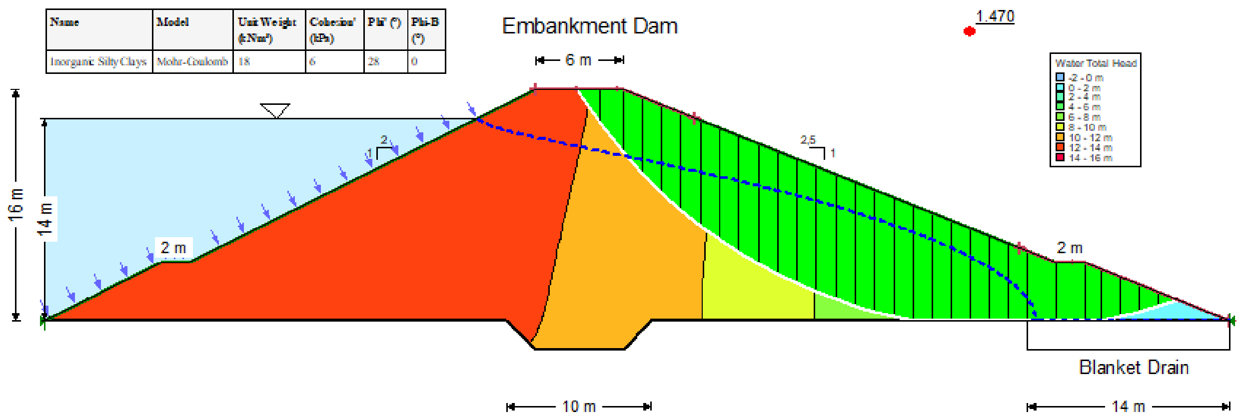

Figure D.1 Critical Slip Surface of the Unlined Embankment Dam

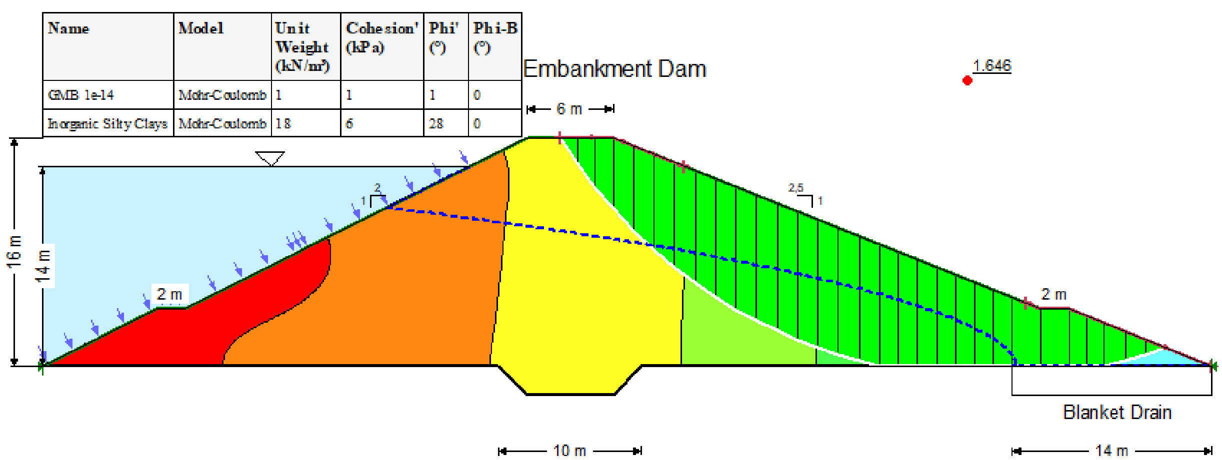

Figure D.2 Critical Slip Surface of the Embankment Dam Associated with Upstream Geomembrane Systems

Appendix E: Pore Pressure Distribution of Internal Geomembrane Systems with Different Thicknesses along the Downstream Side

Table E.1 Comparison of Pore Pressure Distributions When the Different Geomembrane Thicknesses are Placed within Embankment Dams

Geomembrane Thickness Modeled in Finite Element Analysis					
1 mm		**3.5 mm**		**5 mm**	
Distance (m)	Water Pressure (kPa)	Distance (m)	Water Pressure (kPa)	Distance (m)	Water Pressure (kPa)
0	82.110301	0	82.011091	0	81.88499
0.7027027	80.904128	0.7027027	80.808175	0.702703	80.68438
1.4054054	79.808006	1.4054054	79.714409	1.405405	79.59253
2.1081081	78.678659	2.1081081	78.586829	2.108108	78.4668
2.8108108	77.513128	2.8108108	77.422572	2.810811	77.30437
3.5135135	76.310325	3.5135135	76.22096	3.513514	76.10458
4.2162162	75.071903	4.2162162	74.983664	4.216216	74.86912
4.9189189	73.799555	4.9189189	73.71234	4.918919	73.59965
5.6216216	72.494618	5.6216216	72.408367	5.621622	72.29755
6.3243243	71.158023	6.3243243	71.072697	6.324324	70.96378
7.027027	69.790263	7.027027	69.705839	7.027027	69.59886
7.7297297	68.391412	7.7297297	68.307883	7.72973	68.20289
8.4324324	66.961152	8.4324324	66.878524	8.432432	66.77556
9.1351351	65.498806	9.1351351	65.417094	9.135135	65.31621
9.8378378	64.00335	9.8378378	63.922581	9.837838	63.82384
10.540541	62.473429	10.540541	62.393635	10.54054	62.29709
11.243243	60.907356	11.243243	60.828574	11.24324	60.73429
11.945946	59.303096	11.945946	59.225365	11.94595	59.1334
12.648649	57.65824	12.648649	57.581601	12.64865	57.49202
13.351351	55.969959	13.351351	55.894454	13.35135	55.80731
14.054054	54.234947	14.054054	54.160614	14.05405	54.07599
14.756757	52.449344	14.756757	52.376222	14.75676	52.29417
15.459459	50.608649	15.459459	50.53677	15.45946	50.45736
16.162162	48.707612	16.162162	48.637	16.16216	48.56031
16.864865	46.740067	16.864865	46.670754	16.86487	46.59684
17.567568	44.69874	17.567568	44.630785	17.56757	44.55973
18.27027	42.574887	18.27027	42.508405	18.27027	42.44029
18.972973	40.357783	18.972973	40.292975	18.97297	40.22792
19.675676	38.033997	19.675676	37.971173	19.67568	37.90934
20.378378	35.586433	20.378378	35.525975	20.37838	35.46755

Table E.1 (Continued)

Geomembrane Thickness					
1 mm		**3.5 mm**		**5 mm**	
Distance (m)	Water Pressure (kPa)	Distance (m)	Water Pressure (kPa)	Distance (m)	Water Pressure (kPa)
21.081081	32.992635	21.081081	32.934974	21.08108	32.8802
21.783784	30.221751	21.783784	30.168556	21.78378	30.11775
22.486486	27.234481	22.486486	27.184487	22.48649	27.13803
23.189189	23.961792	23.189189	23.917439	23.18919	23.87584
23.891892	20.299001	23.891892	20.261097	23.89189	20.22507
24.594595	16.027141	24.594595	15.997154	24.5946	15.96768
25.297297	10.79657	25.297297	10.771277	25.2973	10.7553
26	0	26	0	26	0

Appendix F: Verification of the Factors of Safety with Impervious Geomembrane Modeling

Table F.1 The Highest Factor of Safety for Downstream Slope with Internal and Upstream Geomembrane Systems

	Impervious Modeling		**Region Modeling**	
	Upstream Geomembrane System	Vertical Geomembrane System	Upstream Geomembrane System	Vertical Geomembrane System
The Factor of Safety of Downstream Slope	1.669	1.736	1.646	1.669

Appendix G: The Effect of Hole Sizes on Factors of Safety for the Downstream Slope in the Case of Vertical Geomembrane Application

Table G.1 The Distribution of the Factors of Safety with Different Size of Holes

Defect Size	Factors of Safety for Downstream Slope
	(Zig-zag with Large Lifts)
0.001m	1.648
0.01m	1.613
0.1m	1.588

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