Eric J. Tlachac

---

om: Heather M. Simon
Sent: Tuesday, September 14, 2010 9:40 AM
To: Rabins, Jaime
Cc: Mark Kelly; Maria Race
Subject: RE: Powerton Bypass Basin Relining

Jaime,

Per our conference call a few moments ago, I am sending this email to clarify the design basis for the geomembrane protection. As we attempted to convey in our August 9, 2010 email (see below), the 2 foot thickness requirement for soil over the geomembrane came from NRT's general HDPE geomembrane specification, which was originally written for landfill cover applications. We have refined this specification to better reflect the application and design we submitted for the MWG Powerton Bypass Basin Liner Replacement project. The 2 foot thickness requirement was eliminated based on the geomembrane protection measures built into the design (geotextiles, and cushion and warning layer materials), which are not typically used in landfill cover applications.

Further, the calculations attached to our September 10, 2010 email demonstrate that these geomembrane protection measures will adequately protect the geomembrane from anticipated loads during future dredging operations. We understand your concern that the manufacturer's guidance that this calculation was obtained from only references construction conditions. In typical geomembrane applications (landfills), it is assumed that geomembranes experience the highest loads during construction, and the manufacturer's guidance referenced below makes no mention of long-term conditions. However, the theory that the calculations are based upon can be applied for long-term conditions.

If you have any further questions, please feel free to contact me.

ncerely,

Heather M. Simon, PE
Environmental Engineer
Natural Resource Technology, Inc.
262.522.1207

From: Rabins, Jaime [mailto:Jaime.Rabins@Illinois.gov]
Sent: Monday, September 13, 2010 11:38 AM
To: Heather M. Simon
Subject: RE: Powerton Bypass Basin Relining

The 8 psi that you referenced appears to have come from Section 5(F)(4) which is a standard that applies when deploying the liner . There is no indication that the standard is acceptable during operations over the long term. Do you have any documents from the manufacturer which show that 8 psi will suffice in lieu of 2 ft of material standard when operating the liner, not just during deployment/construction?

Jaime Rabins
Environmental Protection Engineer, Industrial Unit
Permit Section
Division of Water Pollution Control
Illinois Environmental Protection Agency

ph: 217-524-3035
x: 217-782-9891
aime.Rabins@Illinois.gov

EXHIBIT
633

From: Heather M. Simon [mailto:hsimon@naturalrt.com]
Sent: Friday, September 10, 2010 2:19 PM
To: Rabins, Jaime
Cc: Mark Kelly; Maria Race
Subject: RE: Powerton Bypass Basin Relining

Jaime,

Attached are our calculations to determine the overburden stress on the liner based on 18-inch warning and cushion layer and rubber-tired vehicle. As stated in the geomembrane manufacturer's *Installation Quality Assurance Manual* (attached), a contact pressure directly on the geomembrane of "less than 8 psi" is acceptable. Our calculations indicate that the direct pressure on the geomembrane is less than 8 psi.

If you have additional questions, please contact me.

Sincerely,

Heather M. Simon, PE
Environmental Engineer
Natural Resource Technology, Inc.
262.522.1207

From: Rabins, Jaime [mailto:Jaime.Rabins@Illinois.gov]
Sent: Wednesday, August 18, 2010 10:58 AM
To: Heather M. Simon
Subject: RE: Powerton Bypass Basin Relining

If your client plans on using rubber tired vehicles and you have less than the minimum 2 ft. of cover specified, will the liner manufacturer certify that the proposed cover is sufficient to meet there specifications?

Jaime Rabins
Environmental Protection Engineer, Industrial Unit
Permit Section
Division of Water Pollution Control
Illinois Environmental Protection Agency

ph: 217-524-3035
fax: 217-782-9891
Jaime.Rabins@Illinois.gov

From: Heather M. Simon [mailto:hsimon@naturalrt.com]
Sent: Monday, August 09, 2010 5:08 PM
To: Rabins, Jaime
Cc: Maria Race; Mark Kelly
Subject: RE: Powerton Bypass Basin Relining

Jaime,

Section 02600 provided in the permit application is a general specification used for landfill applications. The construction specification for the MWG basin liner project was further refined to reflect the cover materials to be placed over the HDPE liner. The requirement in Section 02600 3.12(B)(4) provided in the permit application was omitted in the construction specification.

The CA6 material above the 12-inch cushion layer has a higher shear strength than materials that typically cover geomembrane liners such as self-compacting granular soils (i.e., sand). The CA6 will support the anticipated loads associated with basin maintenance activities.

As I mentioned on the phone, during placement of the cushion layer a minimum of 12-inches of cushion material is required to be maintained between the equipment and the liner to satisfy Section 02600 3.12 (B)(3) specification.

you have further questions or comments pertaining to the permit application, please feel free to contact me.

Sincerely,

Heather M. Simon, PE
Environmental Engineer
Natural Resource Technology, Inc.
262.522.1207

----- Forwarded by Maria Race/Chicago/EMG/EIX on 08/09/2010 02:50 PM -----
From: "Rabins, Jaime" <Jaime.Rabins@Illinois.gov>
To: Maria Race <MRace@MWGen.com>
Date: 08/09/2010 02:46 PM
Subject: Powerton Bypass Basin Relining

Maria,

The application proposes a 1 foot cushion layer and a six (6) inch warning layer over the HDPE liner. Since Midwest Generation uses mechanical devices such as loaders and trucks to remove ash from its impoundments, following specifications for liner protection is critical to maintaining liner integrity. It appears the proposed cushion and warning layers may not comply with Section 02600 High Density Polyethylene (HDPE) Geomembrane, Subsection 3.12(B) (3) and (4) specifications, submitted by Midwest Generation with the application.

Midwest Generation must at a minimum, demonstrate that they will meet the requirements for liner protection specified in the materials, referenced above, that were submitted with the application.

Jaime Rabins
Environmental Protection Engineer, Industrial Unit
Permit Section
Division of Water Pollution Control
Illinois Environmental Protection Agency

ph: 217-524-3035
fax: 217-782-9891
Jaime.Rabins@Illinois.gov

BY: KJB DATE: 9/3/10 CLIENT MWG
CHKD. BY: HMS DATE: 9/10/10 PROJECT/TASK 1965.5/
SUBJECT: Overburden Stress on Geomembrane from 18-inch Soil Cover and Tri-axal Truck PAGE: 1 OF: 3

NATURAL
RESOURCE
TECHNOLOGY

Reference: GSE Lining Technology Geomembrane Protection Design Manual.

Equation: $$\sigma_{geomembrane} = \frac{m \times W \times I_{OL} \times I_{IF}}{2 \times A_g} + \gamma_{soil} \times d$$

$\sigma_{geomembrane}$ = Overburden pressure of geomembrane.

m = Load distribution factor (psi)

W = operating weight (lbs)

A = Area of tire at geomembrane surface (in^2)

d = Depth of soil layer over geomembrane (in.)

γ_{soil} = Unit weight of soil overlying the geomembrane (lbs/in.^{3})

I_f = Impact factor

I_o = Overload factor

a = width of tire

b = length of equipment tire = 1/10 (circumfrence of tire)

Secondary Equation: $A_g = (a + d) \cdot (b + d)$

BY: KJB DATE: 9/3/10 CLIENT MWG

CHKD. BY: HMS DATE: 9/10/10 PROJECT/TASK 1965.5

SUBJECT: Overburden Stress on Geomembrane from 18-inch Soil Cover and Tri-axal Truck PAGE: 2 OF: 3

NATURAL
RESOURCE
TECHNOLOGY

Given/Assumptions:

$d = 18 \text{ in.}$

$m = 1/10$ – 10 wheels distributing load based on Tri-axal Truck

$W = 65{,}000 \text{ lbs.}$ – tri-axal truck is 23,000 lbs, plus 42,000 lbs. of material.

$a = 11 \text{ inches}$ – Tire 11R24.5 (common truck tire; 11 in width)

$b = \frac{1}{10}(2\pi r) = \frac{1}{10}\left(2\pi \frac{d}{2}\right) = \frac{1}{10}(\pi d)$ – Tire 11R24.5

$b = 7.697 \text{ inches}$ (common truck tire; 24.5 in diameter)

$\gamma_{12\text{-inch layer}} = 125 \text{ lb/ft}^3 = 0.0723 \text{ lb/in}^3$ Assume value

$\gamma_{6\text{-inch layer}} = 135 \text{ lb/ft}^3 = 0.0781 \text{ lb/in}^3$ Assume value

$\gamma_{Soil} = \left(2/3(0.0723 \text{ lb/in}^3) + 1/3(0.0781 \text{ lb/in}^3)\right) = 0.0743 \text{ lb/in}^3$

$I_f = 0.67$; from reference

$I_o = 1.3$; from reference

$A_g = (a+d)(b+d) = (11 \text{ in} + 18 \text{ in})(7.697 \text{ in} + 18 \text{ in}) = 745.2 \text{ in}^2$

BY: KJB DATE: 9/3/10 CLIENT MWG
CHKD. BY: HMS DATE: 9/10/10 PROJECT/TASK 1965.5
SUBJECT: Overburden Stress on Geomembrane from 18-inch Soil Cover and Tri-axal Truck PAGE: 3 OF: 3

$$\sigma_{geomembrane} = \frac{m \times W \times I_{DL} \times I_{if}}{2 \times A_g} + \gamma_{soil} \times d$$

$$\sigma_{geomembrane} = \frac{\left(\frac{1}{10}\right) \times (65{,}000\text{ lbs.}) \times (1.3) \times (0.67)}{2 \times (745.2\text{ in.}^2)} + \left[(0.0743\text{ lb/in}^3)(18\text{ in.})\right]$$

$$\sigma_{geomembrane} = \frac{5{,}661.5\text{ lbs.}}{1{,}490.2\text{ in.}^2} + 1.337\text{ lb./in.}^2$$

$$\sigma_{geomembrane} = 3.7986\text{ lbs./in}^2 + 1.337\text{ lb/in}^2$$

$$\sigma_{geomembrane} = 5.136\text{ psi}$$

GSE

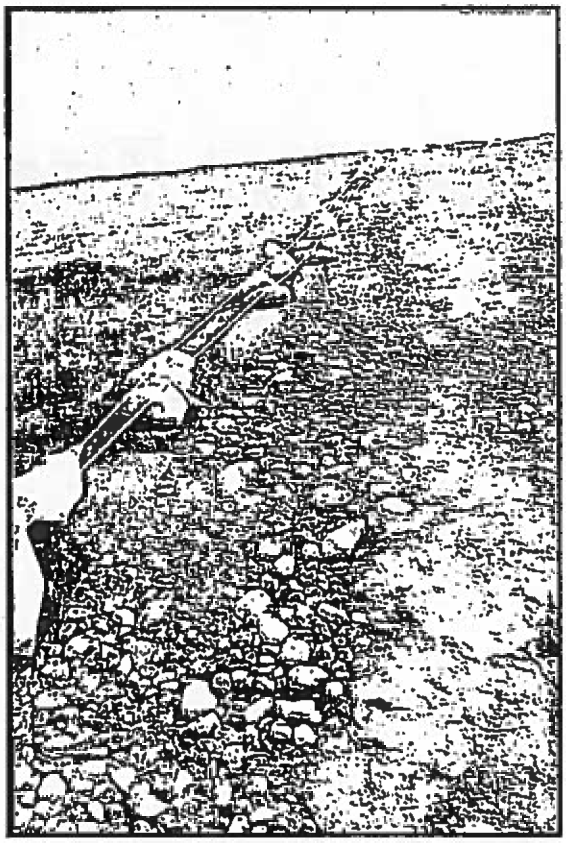
Geomembrane Protection
Design Manual

Co-Authors:

Dhani Narejo, Ph.D.
GSE Lining Technology, Inc.
and
Greg Corcoran, P.E.
GeoSyntec Consultants, Inc.

First Edition

Geomembrane Protection Design Manual



Co-Authors:

Dhani Narejo, Ph.D.
GSE Lining Technology, Inc.
and
Greg Corcoran, P.E.
Geosyntec Consultants, Inc.

First Edition

Preface

The objective of this manual is to provide a comprehensive design methodology for the protection of geomembranes from puncture using nonwoven needlepunched geotextiles. The design recommendations are applicable to most of the commercially available smooth geomembranes and nonwoven needlepunched geotextiles.

The design method was developed at the Geosynthetic Institute (GSI), Drexel University, by Dr. Dhani Narejo, Dr. Robert Koerner and Dr. Ragui Wilson-Fahmy. Since the initial publication of the method in 1996, a limited amount of additional research and testing on various aspects of geomembrane protection has appeared in published literature. The manual includes most of the published information relevant to the design method. The manual can be regarded as state-of-the-art on geomembrane protection.

A number of people at GSE contributed to the final organization of this manual. Jackie Nguyen and Adrian Baxter developed the format and figures. Ed Zimmel and Boyd Ramsey reviewed the manual and provided valuable comments. In the end this manual is the result of collaboration of a number of individuals from both GSE and Geosyntec Consultants.

A design methodology, no matter how comprehensive the information, can not be a substitute for sound engineering judgment. The equations reported in this manual should be used with full understanding of the assumption made and resulting limitations of the method.

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Preface

1. Introduction

2. Design Variables

3. Design Method

4. Specifications For Cushion Geotextiles

5. Design Examples

Chapter 1
INTRODUCTION

1.1 Definition of Geomembrane Puncture

Geomembrane puncture may be defined as a penetration, perforation, gouge, or cut in the geomembrane caused by an underlying or overlying object. The most common source of geomembrane puncture is aggregate or soil particles, but it is not uncommon for geomembranes to be challenged by objects such as sticks, glass, worker's boots and equipment tires. The puncture of a geomembrane is the result, invariably, of a stress concentration at the point of contact between the geomembrane and the culprit object. Therefore, preventing geomembrane puncture is primarily about preventing the stress concentration at the interface of concern. This is illustrated graphically in Figure 1.1.

Geomembrane puncture may be a concern both during the installation or construction phase as well as over the service life of a geomembrane. Moreover, for certain type of projects, the construction phase may be the most critical as far as geomembrane puncture is concerned. This is usually true for geomembranes in landfill cap systems where long term service loads are relatively small. For other types of projects, geomembrane puncture may be a bigger concern over the service life. This is the case, for example, for landfill lining systems where service loads tend to be much larger than those for landfill caps. Any mechanism employed for the protection of a geomembrane must take into consideration loads and interface conditions from the start of an installation to the end of service life of a project.

1.2 Definition of Geomembrane Protection

The primary purpose of using geomembrane liners is one or both of the following:

1. Prevention of harmful fluids and gases from being released into the atmosphere or ground water, or
2. Containment of a liquid, for example water, otherwise harmless to the atmosphere.

Geomembrane protection may be defined as the use of mechanisms, techniques and materials to prevent geomembrane puncture to the extent that the primary function of geomembrane as outlined above is not compromised. Implicit in this definition is the recognition that the required protection for a geomembrane is a function of risk associated with a leak resulting from the puncture. For municipal and hazardous waste landfills or liquid containment lagoons, for example, there is a significant risk of environmental damage from a leak in the geomembrane. For canal liners and cooling ponds for power projects, the risk associated with environmental damage may be small. However, leakage in ponds has been known to creation of an unstable geotechnical situation, aside from the economic impact of loss of fluid. Thus, in addition to environmental damage, the risk of economic loss must be considered.

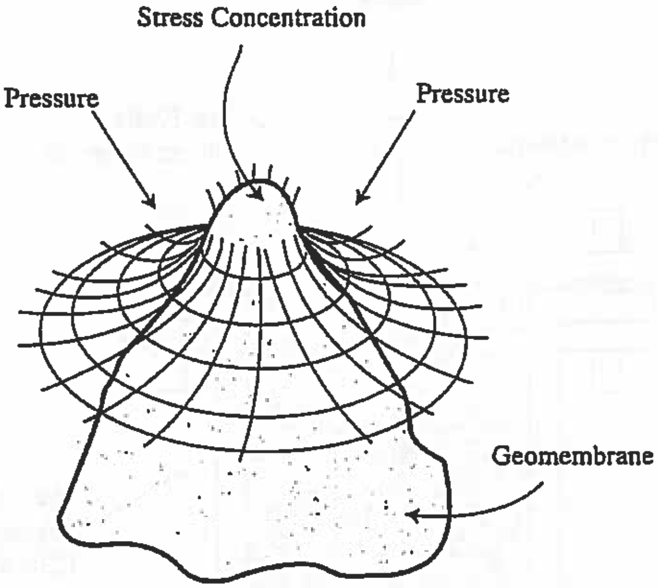


Figure 1.1 Illustration of Stress Concentration in Geomembranes Due to Puncturing Objetcs (from Koerner, 1998).

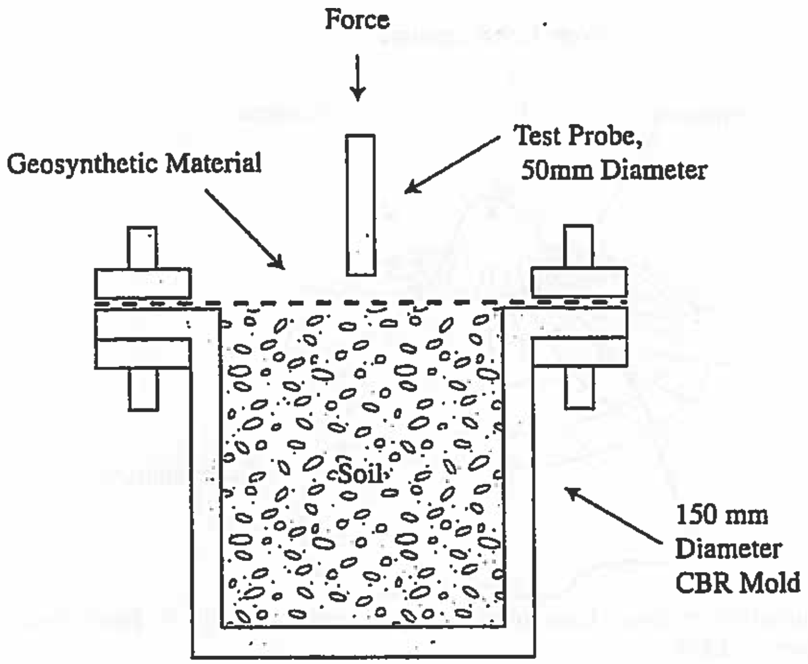
1.3 Evaluation of Protection Requirements for Geomembranes

The test methods available for the determination of the puncture strength of Geosynthetics may be grouped into the following three categories:

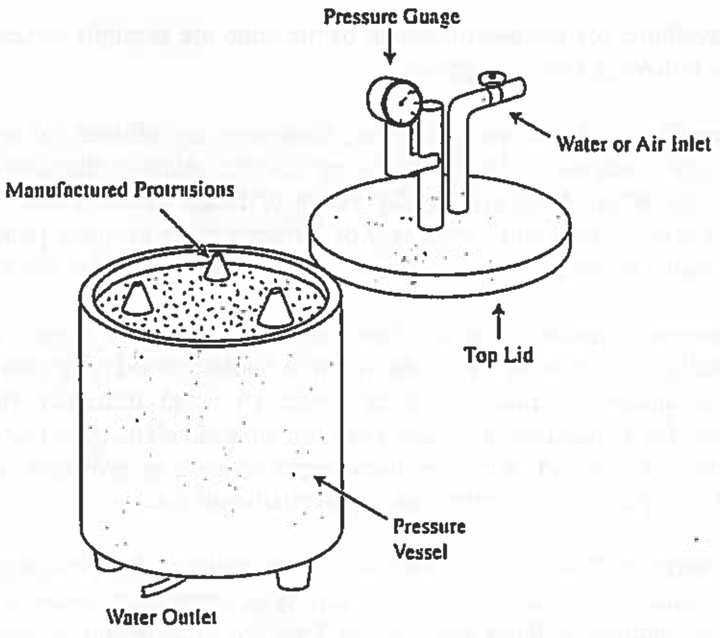
1. **Index Puncture Tests.** As the name implies, these tests are utilized for quality control or conformance testing purposes. These tests do not directly relate to the field behavior of the material being evaluated. A general configuration of index puncture tests is illustrated in Figure 1.2(a). Table 1.1 provides a summary of different types of index puncture tests based on the size and shape of the probe and the size of the specimen (Narejo, 1994).

2. **Quasi-Performance Puncture Tests.** These tests replicate only certain aspects of field conditions. Usually the limitation lies in the use of a manufactured protrusion rather than the actual soil. The quasi-performance puncture tests are used primarily for research and development and for comparing puncture behavior or protection performance of different types of materials. A general layout of these types of tests is provided in Figure 1.2(b). Table 1.1 lists two types of these tests currently available for use.

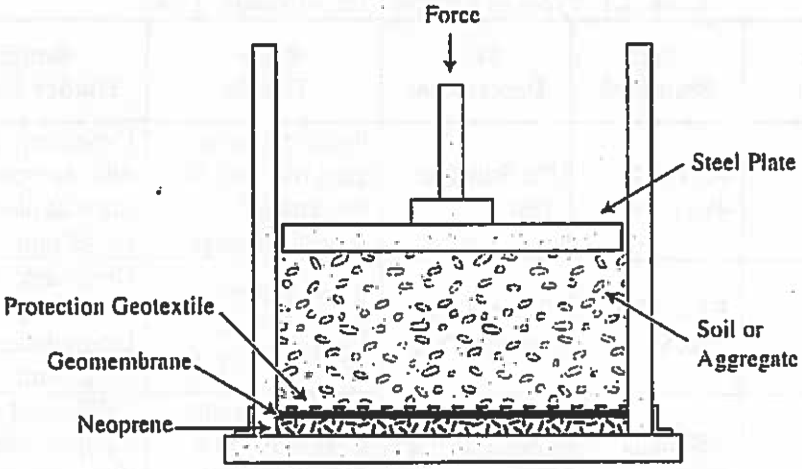
3. **Performance Puncture Tests.** These tests are used to replicate field conditions as closely as possible. The applied overburden pressure, soil type, protection material and boundary conditions are all similar to those expected in field for a particular project. Figure 1.2(c) provides a typical setup for the performance puncture tests. Table 1.1 includes a brief description of the performance puncture test.



(a) CBR Index Puncture Test.



(b) Quasi-Performance Puncture Test



(c) Performance Puncture Test.

Figure 1.2 Various Types of Puncture Tests.

1.4 Puncture Behavior of Different Types of Geomembranes

Geomembranes may be grouped into the following three categories on the basis of their stress-strain behavior:

1. Flexible
2. High Density
3. Reinforced

Flexible geomembranes exhibit high strains without a clear yield point. Examples include several types of polyethylene geomembranes – including linear low density polyethylene (LLDPE) and very low density polyethylene (VLDPE) - with a density lower than 0.94 grams/cm^3. In general, these geomembranes may be grouped together and called Very Flexible Polyethylene (VFPE). High Density Polyethylene (HDPE) geomembrane has a density higher than 0.94 grams/cm^3. The stress-strain behavior of High Density Polyethylene (HDPE) geomembranes is characterized by a distinct yield point at a very low strain. The tensile behavior of reinforced geomembranes, for example, Reinforced Chlorosulphonated Polyethylene (CSPE-R), is governed by the woven textile scrim. The typical stress-strain behavior of each of these geomembranes is provided in Figure 1.3.

The difference in the stress-strain behavior of these geomembranes is clearly reflected in their puncture behavior. For a given set of design conditions, the susceptibility of geomembranes to puncture increases with an increase in stiffness. Thus HDPE being the least flexible, requires the highest protection. Figure 1.4 provides failure pressures for HDPE, VFPE and CSPE-R geomembranes in Truncated Cone Puncture Test performed in accordance with ASTM method

Table 1.1 Types of Puncture Tests (Narejo, 1994)

Test Type	Test Standard	Test Description	Probe Details	Sample Holder Details
Index	ASTM D 4833	Pin Puncture Test	8 mm diameter steel rod with flat end and 45° chamfered edge	Concentric plates with an open internal diameter of 45 mm
Index	FTM 101C M2065	Tapered Pin Puncture Test	8 mm diameter steel rod with hemispherical tip	Concentric plates with an open internal diameter of 25 mm
Index	ASTM D 6241	CBR Puncture Test	50 mm diameter steel rod with a 45° chamfered edge	CBR mold with an open internal diameter of 150 mm
Quasi-Performance	ATM D 5514	Hydrostatic Truncated Cone Puncture Test	Three truncated cones placed 250 mm center to center	600 mm diameter hydrostatic pressure vessel
Quasi-Performance	ASTM D 5494	Pyramid Puncture Test	Three sided pyramids truncated 1 mm from top	550 mm diameter hydrostatic pressure vessel
Performance	CEN	Performance Puncture Test	Site specific soil	Minimum 300 mm

D 5514 (Hullings and Koerner, 1991). It is seen that for a given cone height, HDPE and CSPE-R geomembranes fail at significantly lower pressures than a VFPE geomembrane.

Of various geomembranes currently available in the industry, HDPE provides the highest chemical resistance to a large number of pollutants encountered in municipal and hazardous waste streams. Therefore, HDPE geomembranes are liners of choice for municipal and hazardous waste containment applications. The protection of HDPE geomembranes need not be technically challenging or cost prohibitive. The design method presented in this manual provides a simple step by step approach to calculate mass per unit area of nonwoven needlepunched geotextiles for site specific design conditions. The design method was developed primarily for smooth HDPE geomembranes. However, the use of the method for geomembranes other than HDPE results in conservative design recommendations.

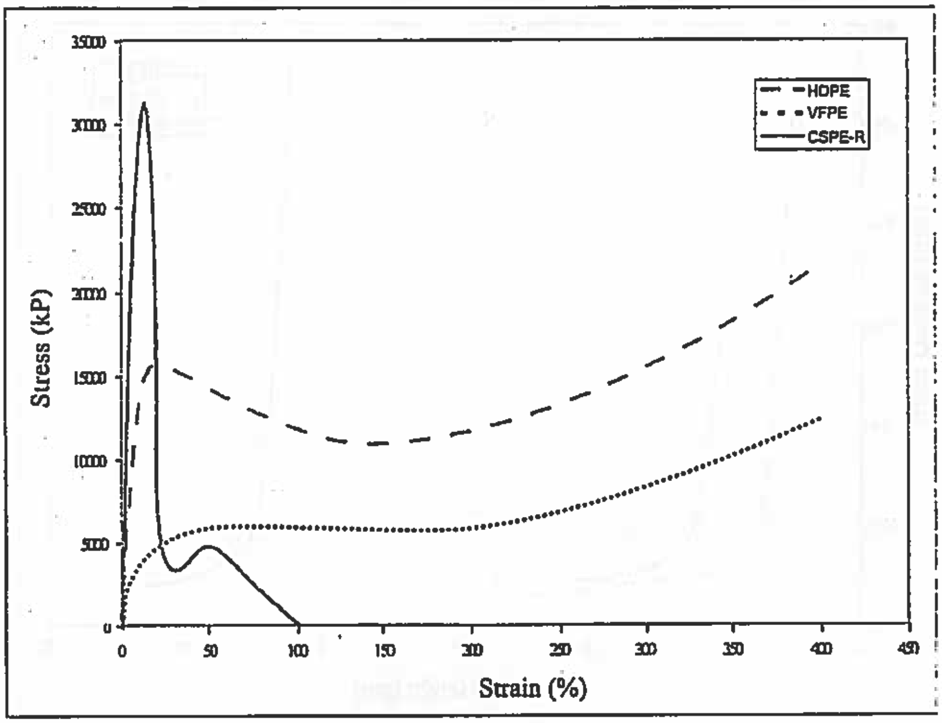


Figure 1.3 Stress Strain Behavior of Various Types of Geomembranes.

1.5 Types of Protection Materials

It is possible to use a number of different materials for the protection of geomembranes. Examples of materials used in the past include various types of nonwoven needlepunched geotextiles, scrim-reinforced nonwoven needlepunched geotextiles, soil-filled matts, Geosynthetic Clay Liners (GCLs), shredded tire matts and select soil. The description and performance of some of these materials can be found in articles by Von Maubeuge, et. al. (1993), Narejo & Koerner (1994), Narejo & Shettima (1994), Kirschner & Kreit (1994) and Muller-Rochholz & Asser (1994).

This manual provides a design method for the calculations of mass per unit area of nonwoven needle punched geotextile for a given set of design conditions. Research by the author has shown that the type of polymer does not affect the protection performance of nonwoven needlepunched geotextiles (Narejo, 1994). Therefore, the design method can be used for both polypropylene and polyester geotextiles.

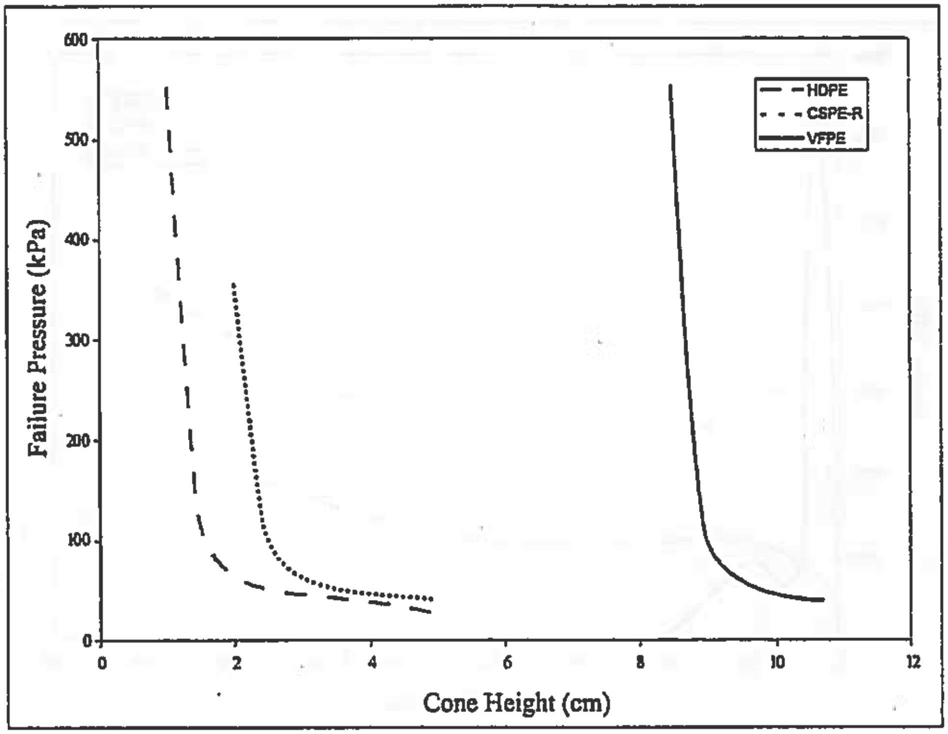


Figure 1.4 Hydrostatic Truncated Cone Failure Pressure for Various Geomembranes at 25 mm Cone Height (modified from Hullings and Koerner, 1991).

Chapter 2
DESIGN VARIABLES

2.1 Effective Protrusion Height

The effective protrusion height is the maximum dimension of the largest soil, aggregate, or any other object, to which a geomembrane liner may be exposed. The effective protrusion height depends, primarily, on two factors: size and arrangement. Two types of arrangements are possible for objects in the vicinity of a geomembrane: isolated and grouped. Each of these scenarios is discussed in detail in the following sections.

2.1.1 Isolated Protrusions

Isolated protrusions act more or less alone when interacting with a geomembrane in the puncture mode. An example is a stone underlying a geomembrane placed on a relatively level surface as indicated in Figure 2.1. The full exposed size of the stone in this case can challenge the geomembrane. The effective protrusion height, H', in this case is equal to the maximum exposed object dimension as indicated in the figure. Conservatively, H' may be assumed to be equal to the diameter of the largest size particle in the subgrade as determining the exposed dimensions of particles over the life of a project may be difficult.

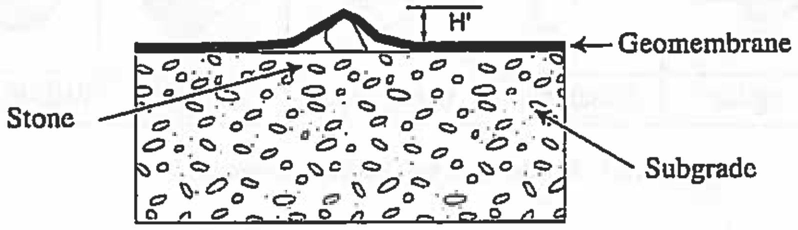


Figure 2.1 Effective Protrusion Height for the Case of Isolated Objects.

2.1.2 Grouped Protrusions

Grouped objects are close enough to interact with each other when challenging a geomembrane. An example is a drainage aggregate layer placed on top of a geomembrane. In such cases only a limited part of the full size of a particle can interact with the geomembrane because of the proximity of the surrounding particles. Practically, the adjoining particles "hide" part of each other. This is explained graphically in Figure 2.2. For the case of grouped particles, the effective protrusion height, H', is approximated as half of the maximum particle size. This approximation is based on performance puncture testing with isolated and grouped protrusions. Particle size analysis according to ASTM Method D 422 can be used to determine the maximum dimensions of protrusions.

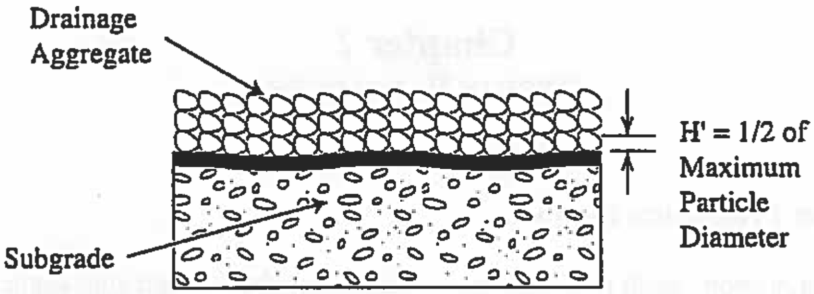


Figure 2.2 Effective Protrusion Height in the Case of Grouped Objects.

2.2 Protrusion Shape

For the purpose of geomembrane puncture protection, particle shape can be described by angularity. Angularity is a measure of sharpness of corners of a particle. Although a quantitative measurement of angularity is possible (Krumbein, 1941), for the design method presented here it is adequate to obtain a qualitative description as provided in Figure 2.3.

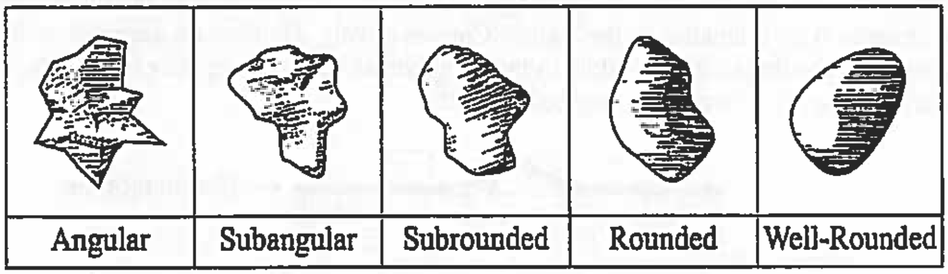


Figure 2.3 Angularity of Soil Particles (Sowers, 1979).

On the basis of the effect of shape on geomembrane protection requirements, soil particles can be placed into the following three categories:

Group I – Angular

Group II – Subangular and Subrounded

Group III – Rounded and Well Rounded

The design engineer should consider the angularity carefully as well rounded aggregate may become angular during installation, handling or excavation. When in doubt, it may be desirable to perform the calculations assuming angular stone.

2.3 Type of Overburden Stress

The overburden stress on a geomembrane comes primarily from two sources: construction equipment and overlying media such as waste, water or soil. The total stress on the geomembrane is the summation of stress from various sources at any given time.

2.3.1 Stress from Construction Equipment

The stress on a geomembrane from construction equipment depends upon the type of vehicle, load on the vehicle, type of wheels and depth of soil cover over the geomembrane. Typically two types of vehicles are used for the placement of soil or aggregate over a liner: a track type dozer for spreading the stone and a rubber tired vehicle (truck or LTV) for transporting the stone. Calculation of pressure on a liner for each of these cases is explained below.

2.3.1.1 Tracked Vehicles

Assuming a 2:1 pressure distribution as indicated in Figure 2.4, stress over the geomembrane can be calculated as follows:

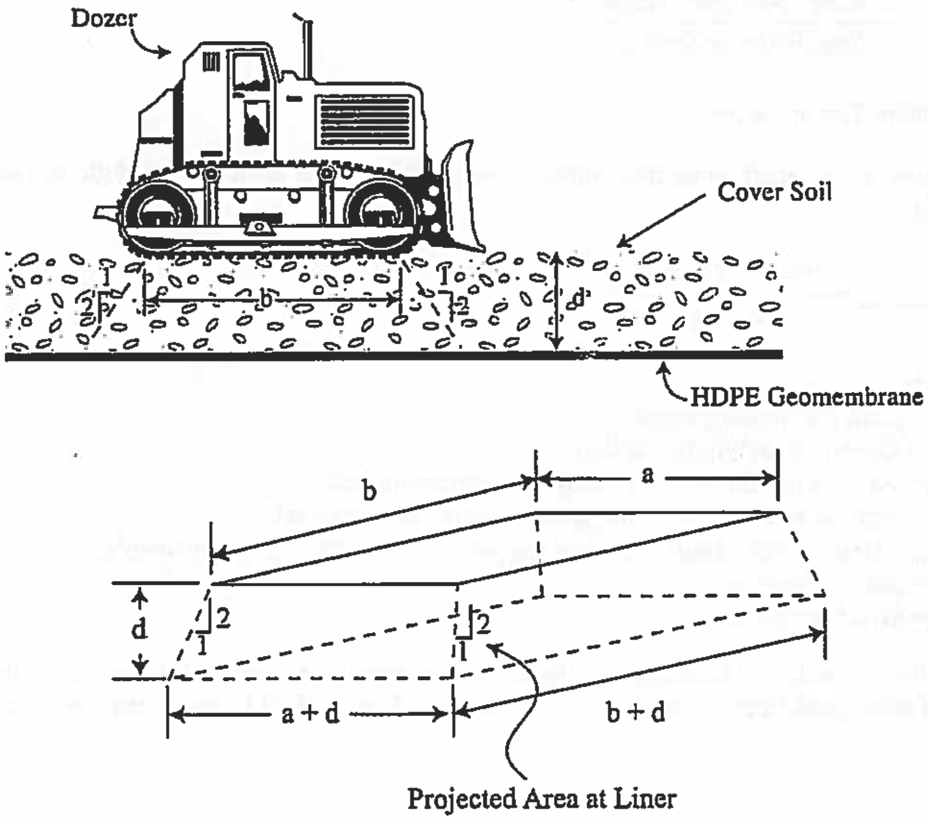


Figure 2.4 Calculation of Stress on Geomembrane for Track Type Vehicles.

$$\sigma_{Geomembrane} = \frac{W}{2 \times A_g} + \gamma_{soil} \times d \tag{2.1}$$

Where,
W = Operating weight of dozer (kg or lbs) from Table 2.1,
A_g = Area of track (m^2 or $inch^2$) at geomembrane surface,
d = Depth of soil layer over the liner (m or inches), and
γ_{soil} = Unit weight of soil overlying the liner (kN/m^3 or $lbs/inch^3$).

Projected area over the geomembrane can be calculated as follows:

$$A_g = (a+d) \times (b+d) \tag{2.2}$$

Where,
a = width of track (m or inches), and
b = length of track (m or inches).

For Caterpillar dozers in Table 2.1, length of track (b) can be calculated as:

$$b = \frac{Contact\ Area\ from\ Table\ 2.1}{Shoe\ Width\ in\ Table\ 2.1} \tag{2.3}$$

2.3.1.2 Rubber Tire Vehicles

Pressure over the geomembrane from rubber tired vehicle can be calculated as follows (see also Figure 2.5):

$$\sigma_{Geomembrane} = \frac{m \times W \times I_{OL} \times I_{if}}{2 \times Ag} + \gamma_{soil} \times d \tag{2.4}$$

Where
m = Load distribution factor,
W = Operating weight (kg or lbs),
A_g = Area of tire (m^2 or $inch^2$) at geomembrane surface,
d = Depth of soil layer over the geomembrane (m or inches),
γ_{soil} = Unit weight of soil overlying the geomembrane (kN/m^3 or $lbs/inch^3$),
I_{if} = Impact factor, and
I_{ol} = Overload factor.

For the values of m, I_{if} and I_{ol}, equipment manufacturer should be consulted. However, in the absence of other guidelines, a value of 0.67 for m and 1.3 for each of I_{ol} and I_{if} may be assumed.

Table 2.1 Operating Ground Contact Pressure for Track-Type Tractors (Caterpillar Performance Handbook, Edition 31).

Model	Shoe Width (mm)	Contact Area (m^2)	Operating Weight		Ground Contact Pressure	
			Kg	lb	kPa	psi
D6R	560	2.92	18,200	40,000	61	8.9
	610	3.18			56	8.1
D7R	510	2.94	25,077	55,300	82	11.9
	560	3.24			75	10.8
	610	3.53			69	10.0
	660	3.82			64	9.3
D8R	560	3.59	37,580	82,850	101.1	14.7
	610	3.91			92.8	13.5
	660	4.23			85.9	12.5
	710	4.55			79.7	11.6
D9R	560	3.86	48,840	107,670	121.1	17.5
	610	4.24			110.8	16.1
	685	4.74			98.7	14.3
	760	5.26			88.8	12.9
D10R	610	4.74	65,400	144,200	135.7	19.7
	710	5.52			116.2	16.9
	800	6.22			103.1	15.0
D11R	710	6.31	104,600	230,100	162.4	23.6
	810	7.20			142.4	20.7
	915	8.13			126	18.3

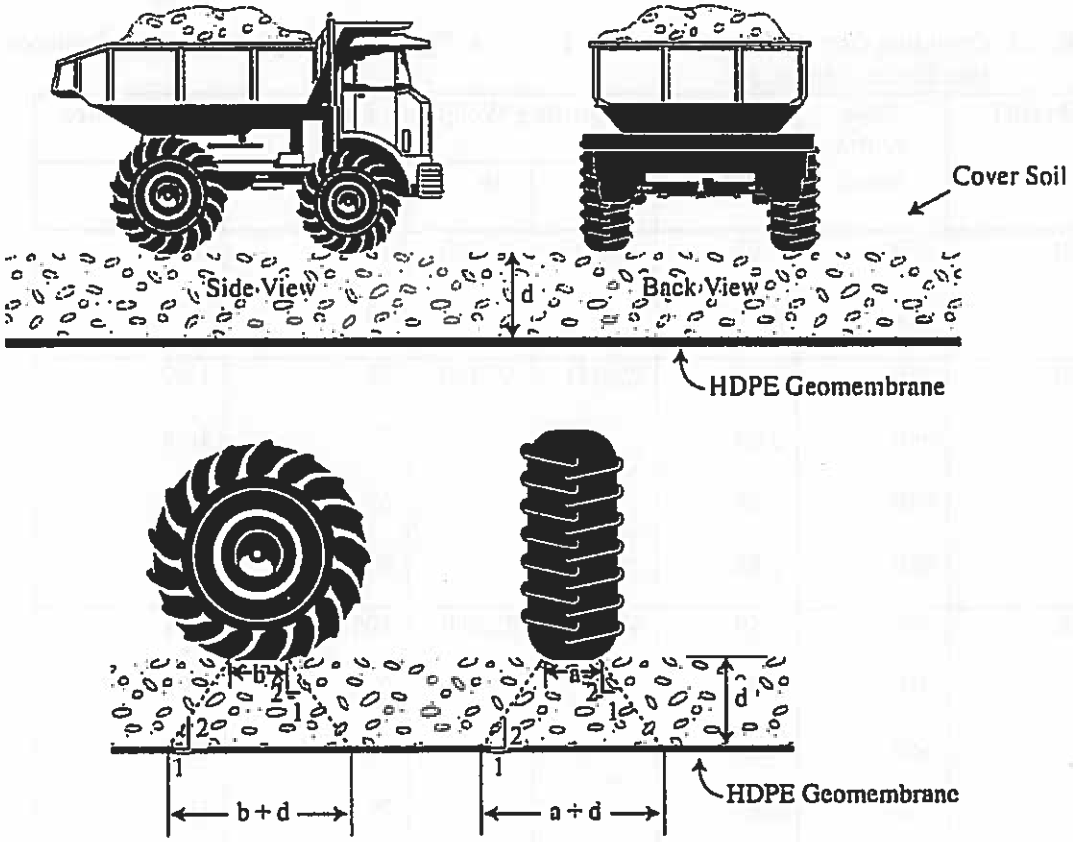


Figure 2.5 Stress Over Liner from Rubber Tire Vehicles.

2.3.2 *Stress from Infinite Media*

Stress from infinite media, such as soil, waste or water, can be calculated as:

$$P = \gamma \times h \tag{2.5}$$

Where

P = Stress (kPa or psi)

γ = Unit weight (kN/m^3 or $lbs/inch^3$), and

h = Depth of the material overlying the geomembrane (m or inches)

Table 2.2 Approximate Unit Weights of Various Materials.

Material	Unit Weight (kN/m^3)	Unit Weight (lb/ft^3)
Soil	15 to 20	100 to 130
Water	9.8	62.5
Municipal Solid Waste	9 to 26	60 to 170
Steel	77	490
Concrete	24	160

Chapter 3
DESIGN METHOD

3.1 Protecting Geomembranes from Puncture During Installation

Puncture of geomembranes during installation can occur from both subgrade conditions and overlying soil. Each of these two concerns is discussed in the following sections.

3.1.1 Geomembrane Puncture from Subgrade

Geomembranes should be placed on subgrades free of coarse particles, earth clods, uneven areas, ruts, roots, debris and wood pieces. The following steps should be followed to ensure that a geomembrane is not damaged from underlying surface during installation:

a) Any survey stakes, if used, should be pulled out of the soil surface. Breaking off of the survey stakes at the ground surface is not recommended.
b) Insitu soil or compacted clay liner must be smooth drum rolled to achieve the necessary compaction and to ensure that particles coarser than 1 cm (3/8 inches) do not protrude from the surface.
c) Alternately, where the preparation of the surface, as recommended above, is not feasible, a cushioning material should be placed between the geomembrane and the subgrade to protect the geomembrane from puncture.
d) A qualified and certified Construction Quality Assurance (CQA) inspector and the geomembrane installer must inspect and approve the surface prior to the placement of the geomembrane.
e) No vehicular traffic should be allowed on top of an installed geomembrane. However the use of light equipment, such as ATVs, approved by the project engineer, CQA inspector and installer, may be allowed.
f) Workers with sharp shoe soles, or shoes with treading that can trap stones, should not be allowed to traverse directly on top of the geomembrane.

3.1.2 Geomembrane Puncture from Overlying Soil

A soil cover or aggregate drainage layer is almost always placed over the geomembrane. For example, an aggregate drainage layer is typically placed over the primary geomembrane in a landfill liner system (see Koerner, 1998, pp. 551 for details). The placement of these overlying materials is typically performed using construction equipment such as trucks and bulldozers. For this reason puncture of geomembrane is of greater concern during the placement of overlying soil than the installation of the geomembrane itself. The following recommendations should be followed to ensure that the geomembrane is well protected during the placement of overlying soil:

a) Soil particles coarser than 1 cm (3/8 inch) should never be placed directly on a geomembrane without first placing a suitable nonwoven needlepunched geotextile as a protection layer.
b) Sudden breaking and turning of vehicles over the geomembrane should be avoided.
c) A minimum soil cover of thickness proposed in Table 3.1 should be maintained at all times between the tires or treads of the equipment and the geomembrane.

Table 3.1 Recommended Minimum Soil Cover Thickness Over Geomembranes for the Operation of Construction Equipment.

Equipment Ground Pressure		Recommended Minimum Lift Thickness, m (in.)	
kPa	psi	meter	inches
< 70	< 10	0.30	12
70 - 140	10-20	0.60	24
> 140	> 20	0.90	36

A number of researchers have evaluated geomembrane protection requirements during the construction process by building test pads. The methodology followed for such an evaluation can be summarized as follows:

a) A subgrade is prepared to the site-specific compaction and moisture content requirements.
b) A sample of the desired geomembrane is placed over the subgrade.
c) A nonwoven needlepunched protection geotextile is placed over the geomembrane.
d) A controlled thickness of overlying material is placed on top of the geomembrane.
e) Construction equipment, such as a truck or a dozer with a known weight, is moved over the soil a fixed number of times to simulate traffic during the construction project.
f) At the completion of the desired number of passes, soil overlying the geotextile is carefully removed. Coupons of geotextile and geomembrane are removed and observed visually for signs of damage and tested in a laboratory for changes in the physical or mechanical properties.

A study of the type described above was performed by Reddy et. al. (1996) to determine protection requirements for AASHTO # 8 (12 mm max diameter) stone. The conclusion of this study was to use a minimum of 270 gram/m^2 (8 oz. per square yard) nonwoven needle punched geotextile for the protection of a 1.5 mm (60 mil) thick HDPE geomembrane.

A similar study has been described by Richardson & Johnson (1998). They evaluated protection requirements for a 1.5 mm thick HDPE geomembrane under an AASHTO # 57 (max diameter 38 mm) stone. They recommend using at a minimum a 405 g/m^2 (12 oz. per square yard) nonwoven needlepunched geotextile to protect the geomembrane from damage by a # 57 stone.

A number of other researchers have performed similar testing for project-specific conditions. Generally, their recommendations have ranged from 270 grams/m^2 to 540 grams/m^2 (8 oz. to 16 oz.) geotextile depending on the type of soil and construction equipment.

Design recommendations provided in Table 3.2 are based on studies reported in the literature and authors own experience with protection requirements for HDPE geomembranes.

Table 3.2 Mass per Unit Area of Nonwoven Needlepunched Geotextile Recommended for Geomembrane Protection During Installation.

Maximum Stone Size		**Mass per Unit Area**	
(mm)	**(inch)**	**(g/m^2)**	**(oz/sq. yard)**
≤ 12	≤ 0.5	≥ 335	≥ 10
≤ 25	≤ 1.0	≥ 405	≥ 12
≤ 38	≤ 1.5	≥ 540	≥ 16
≤ 50	≤ 2.0	≥ 1080	≥ 32

3.2 Protecting Geomembrane from Puncture Due to Static Loads

The equations presented in this section were derived based on extensive quasi-performance and performance puncture testing. The final empirical relationship presented at the end of this chapter was obtained as follows:

a) An empirical equation relating truncated cone height and mass per unit area of a nonwoven needlepunched geotextile used as protection for a 1.5 mm (60 mil) HDPE geomembrane was obtained from Hydrostatic Truncated Cone Puncture Tests performed according to ASTM procedure D 5514.
b) The basic equation in (a) above was modified for the influence of geomembrane thickness.
c) The equation in step (b) above was modified for the influence of creep of the geomembrane and geotextiles.
d) The effect of type of overburden stress (hydrostatic vs. geostatic) on the equation in (c) above was evaluated.
e) The equation obtained from step (d) above was then adjusted for protrusion shape and arrangement.
f) Finally, the equation was modified for chemical and biological degradation of geomembranes and protection geotextiles.

All of the above work was performed by the author and other researchers at the Geosynthetic Institute, Drexel University, PA, using geotextiles from a number of different manufacturers. Thus the geotextile performance and the resulting design equations are representative of nonwoven needlepunched geotextiles manufactured and supplied in the US. The following sections provide details of each of the above steps.

3.2.1 Basic Equation

The failure pressure of a 1.5 mm (60 mil) thick HDPE geomembrane in Truncated Cone Puncture Test (ASTM D 5514) is related to the cone height H (mm) and the mass per unit area of a nonwoven needle punched protection geotextile M (grams/m^2) as indicated in Figure 3.1 (Narejo, et. al., 1996). The same relationship can be expressed mathematically as:

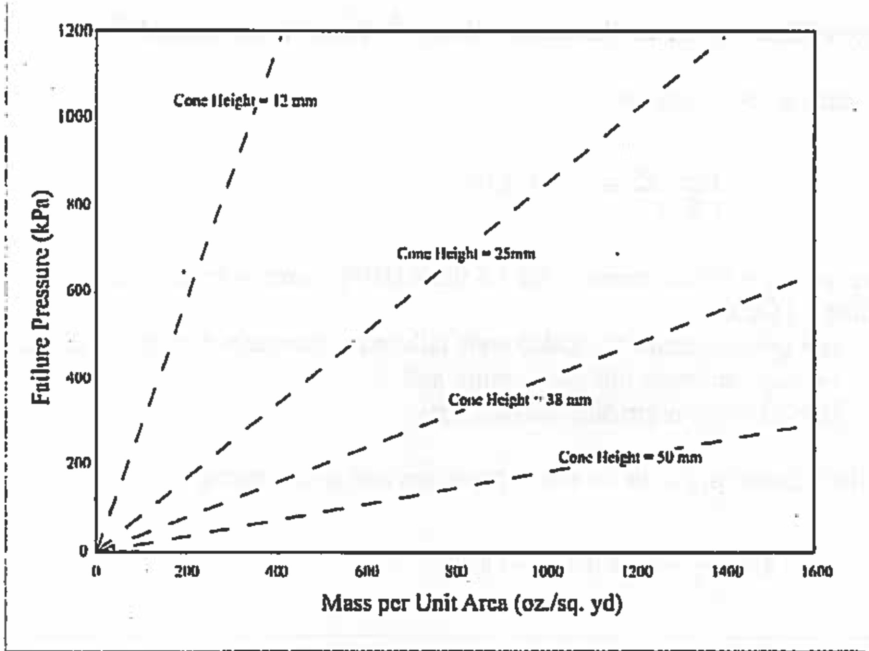


Figure 3.1 Short Term Test Results Obtained from Hydrostatic Truncated Cone Puncture Testing (Narejo et. al., 1996).

$$P_{1.5mm} = 450\frac{M}{H^2} \qquad (3.1)$$

Equation (3.1) is valid only for the following conditions:

a) hydrostatic pressure applied at the rate of 7 kPa (1 psi) per minute,
b) a 1.5 mm (60 mil) HDPE geomembrane, and
c) truncated cones used as protrusions, as indicated in Figure 1.2 (b).

Obviously, conditions on actual projects are always different from the test conditions used to derive Equation 3.1. Therefore, the equation must be modified to make it applicable to the design conditions typically encountered in the field. The following sections propose modifications to the above equation to derive the final empirical design equation.

3.2.1.1 Effect of Geomembrane Thickness

The influence of the geomembrane thickness on the failure pressures is indicated in Figure 3.2. It can be seen from the figure that the influence of geomembrane thickness on failure pressures is small above a cone height of 25 mm. However, geomembrane thickness becomes significant as cone height decreases below 25 mm. The failure pressure per unit thickness of the geomembranes (kPa/mm) is plotted in Figure 3.3 against cone height. The equation of the curve in Figure 3.3 can be written as:

Rate of change of failure pressure (kPa/mm) = $1.3x10^5$ (Cone Height in mm)$^{-2.4}$ (3.3)

Equation 3.3 can also be written as:

$$\frac{p_{1.5mm} - p_t}{1.5 - t} = 1.3x10^5 (H)^{-2.4} \tag{3.4}$$

Where, $p_{1.5\,mm}$ = failure pressure for 1.5 thick HDPE geomembrane, from Equation 3.1(kPa),

p_t = geomembrane truncated cone failure pressure at a thickness t (kPa),

t = geomembrane thickness (mm), and

H = effective protrusion height (mm).

Substituting the value of $p_{1.5mm}$ in the above equation, and re-arranging:

$$p_t = 450\frac{M}{H^2} - 1.3x10^5(1.5 - t)(H)^{-2.4} \tag{3.5}$$

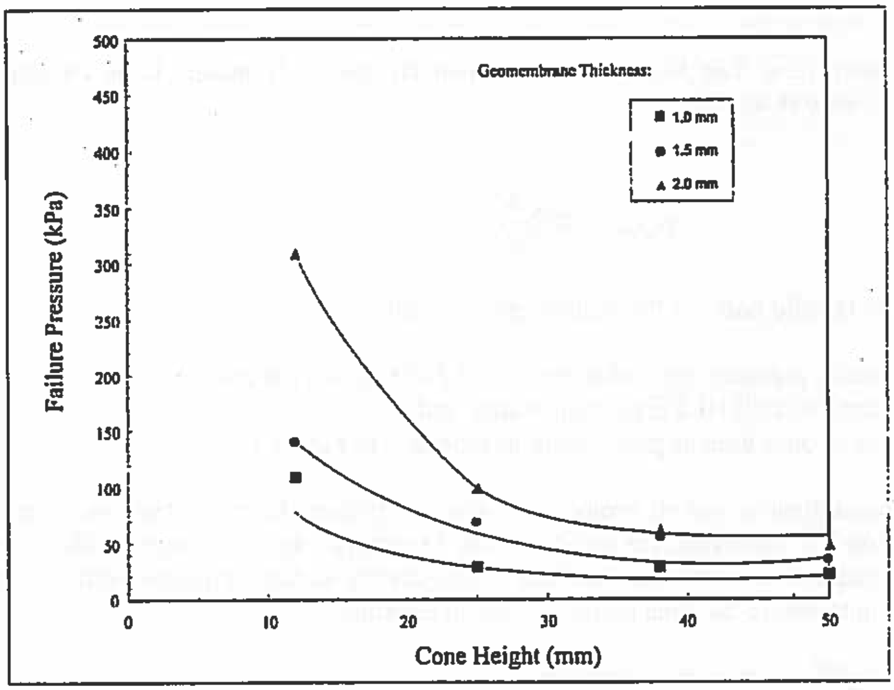


Figure 3.2 Influence of Geomembrane Thickness on Failure Pressures (Narejo et. al., 1996).

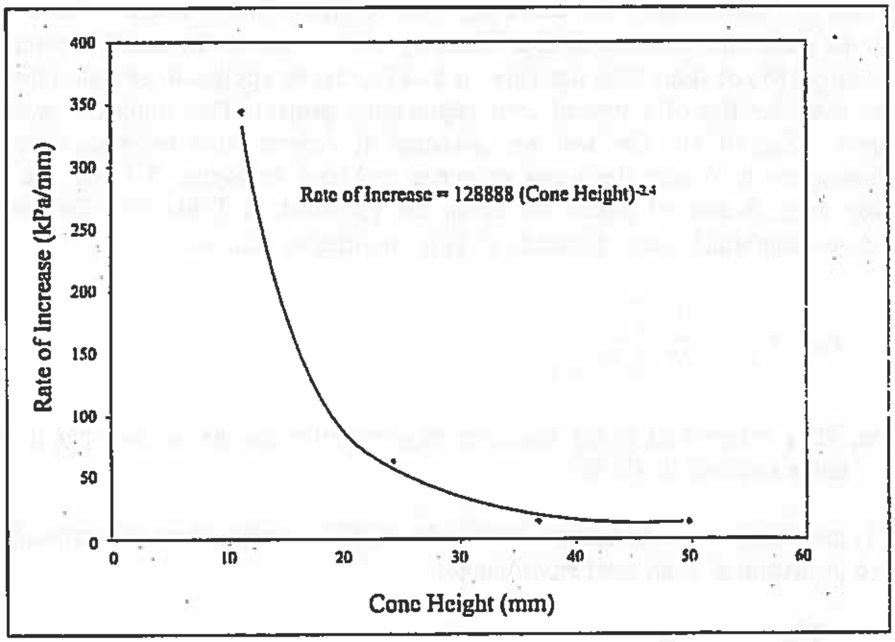


Figure 3.3 Rate of Change of Geomembrane Failure Pressure at Various Cone Heights.

$$\text{or, } p_{allow} = 450\frac{M}{H^2} - 1.3x10^5(1.5 - t)H^{-2.4} \qquad (3.6)$$

Note that Equation (3.6) reduces to Equation 3.1 for a geomembrane thickness of 1.5 mm. For other geomembrane thicknesses, there is small, and in many cases negligible, influence of geomembrane thickness on failure pressures. Therefore, the thickness effect in Equation 3.6 is ignored for further derivations. In those cases where a design engineer must consider the influence of thickness, the final equation can easily be modified using Equation 3.6. This is illustrated in a design example in Chapter 5.

3.2.1.2 Modification for Geotextile and Geomembrane Creep

As mentioned previously, Equation 3.1 is based on short term testing lasting only a few hours. Geomembranes and geotextiles are viscoelastic in nature. This means that time to failure is a function of rate of application of stress. To account for the effect of rate of application of stress on Equation 3.1, creep puncture tests were conducted using the same setup as short term hydrostatic truncated cone puncture test (ASTM D 5514). However, instead of increasing the pressure at the rate of 7 kPa per minute to failure, only a certain fraction of the failure pressure was applied and maintained. At this constant pressure, the time required to obtain a geomembrane puncture was noted. As an example, for a cone height of 25 mm and a protection nonwoven needlepunched geotextile of 270 grams/m^2, Figure 3.1 indicates an approximate failure pressure of 220 kPa when tested in accordance with ASTM D 5514 using short term conditions. A pressure of 75% (165 kPa), 50% (110 kPa), 25% (55 kPa) and 12% (26 kPa), respectively was applied to obtain the curve provided in Figure 3.4. It is seen that the curve is asymptotic to the x-axis at a pressure of approximately 10%. Thus for the conditions represented in Figure 3.4, only 10% of short term pressure, or 22 kPa, can be applied to prevent failure of the geomembrane over the life of a typical civil engineering project. This translates into a creep factor of safety, FS_{CR}, of 10. The test was repeated at various cone heights, pressures and protection geotextiles to obtain the types of curve provided in Figure 3.4. On the basis of puncture creep data, factors of safety for creep are provided in Table 3.3. To account for geotextile and geomembrane creep, Equation (3.1) is modified as follows:

$$p_{allow} = \left[450\frac{M}{H^2}\right]\left[\frac{1}{FS_{CR}}\right] \qquad (3.7)$$

Where, FS_{CR} = factor of safety for creep of geotextiles and geomembranes in puncture mode as given in Table 3.3.

Equation (3.7) provides long-term failure pressure for HDPE geomembrane over truncated cones (manufactured protrusions) in an inert environment.

3.2.1.3 Effect of Type of Pressure

Equation (3.7) is based on hydrostatic (water) pressure testing. A number of applications, including landfills, utilize waste or soil as the overburden medium. In such cases, the nature of the overburden pressure is geostatic rather than hydrostatic. To address this concern, a number of tests were performed using geostatic (soil) pressure (Narejo, et. al., 1996). Table 3.4 provides the data with geostatic pressure.

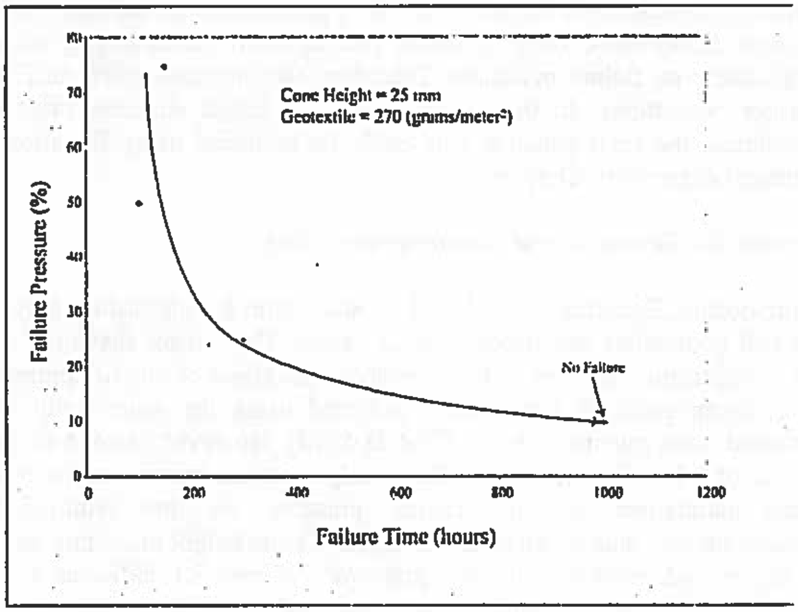


Figure 3.4 Graphical Explanation of Creep Factors of Safety.

Table 3.3 Factors of Safety for Creep Obtained from Long Term Puncture Testing (Modified from Narejo et. al., 1996).

NW-NP Geotextile Mass		**Effective Protrusion Height (mm)**		
g/m^2	oz./sq. yard	**≤38 (1.5")**	**≤25 (1.0")**	**≤12 (0.5")**
None	None	N/R	N/R	N/R
270	8	N/R	N/R	>1.5
335	10	N/R	N/R	1.4
405	12	N/R	N/R	1.4
540	16	N/R	1.5	1.3
675	20	N/R	1.4	1.2
810	24	1.5	1.3	1.2
950	28	1.4	1.3	1.1
1100	32	1.3	1.2	1.1
2000	60	1.2	1.1	1.0

Note: Values in shaded rows are extrapolated; NW-NP = Nonwoven Needlepunched; N/R = Not Recommended

Table 3.4 Geostatic Failure Pressures for a 1.5 mm HDPE Geomembrane with Various Nonwoven Needlepunched Geotextiles (from Narejo, et. al., 1996).

Geotextile Mass		**Failure Pressure (kPa) at Various Protrusion Heights**			
(g/m^2)	**($oz./yard^2$)**	**50 mm (2.0")**	**38 mm (1.5")**	**25 mm (1.0")**	**12 mm (0.5")**
None	None	240	310	450	700
270	8	380	510	>700	>700
540	16	580	>700	>700	>700
1080	32	>700	>700	>700	>700

A comparison of geostatic failure pressures (Table 3.4) with hydrostatic pressure in Figure 3.1 indicates an approximate advantage factor of 6 with the soil as the overburden medium. The higher failure pressures with soil are likely the result of soil arching. As the hydrostatic medium results in lower failure pressure, the design method based on hydrostatic testing is conservative. The authors recommend ignoring the influence of soil arching when making the design calculations for soil or waste overburden medium. Probably, in the future, after further research and testing, the influence of soil arching may be incorporated in Equation 3.7 through a modification factor. Presently, Equation 3.7 is recommended for use irrespective of type overburden medium.

3.2.1.4 Effect of Protrusion Shape and Arrangement

Equation (3.7) was derived on the basis of tests performed using truncated cones as indicated in Figure 1.2 (b). For the equation to be applicable to practical design cases, it must be modified to account for shape and arrangement of soil, aggregate or stones as discussed in Chapter 2. This was accomplished by performing tests on angular, sub-rounded and rounded stones of various sizes placed in the same manner as the truncated cones. The failure pressures thus obtained are provided in Figure 3.5. The geomembrane failure pressures are seen to decrease with an increase in angularity of the stones. On the basis of the test data in Figure 3.5, the modification factors to be incorporated in Equation 3.7 are provided in Table 3.5 (Narejo, et. al., 1996).

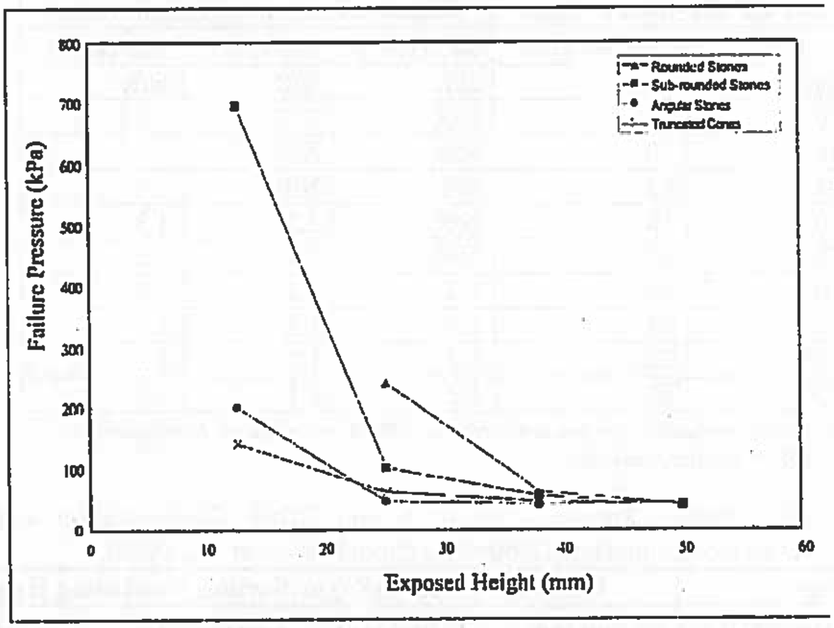


Figure 3.5 Influence of Stone Shape on Geomembrane Failure Pressures.

Table 3.5 Modification Factors for Shape of Stones.

Stone Shape	**Modification Factor MF_{PS}**
Angular	1.0
Subangular and subrounded	0.5
Rounded	0.25

To incorporate the effect of particle shape, Equation (3.7) can be modified as follows:

$$p_{allow} = \left[450\frac{M}{H^2}\right]\left[\frac{1}{MF_{PS} x FS_{CR}}\right] \tag{3.8}$$

Where, MF_{PS} = modification factor for particle shape.

Equation (3.8) represents the condition of isolated protrusions acting more or less independent of each other. This would be representative of an isolated stone protruding from a surface such as insitu soil or compacted clay liner. In some cases protrusions are placed so close together that their interaction can not be ignored. This is the case, for example, with a drainage layer placed on top of a geomembrane. To determine the influence of closely packed protrusions on geomembrane puncture, a number of tests were performed with AASHTO #3, 57 and 8 aggregate. For this purpose the truncated cones shown in Figure 1.2(b) were replaced by an aggregate layer. To the limit of the equipment, no failure of the geomembrane was noticed even without any protection geotextile. However, geomembrane yield was assumed to be the criteria for failure. Table 3.6 compares the truncated cone failure pressures from Figure 3.1 with yield pressures obtained in this case. It is seen that yield pressures with a layered soil are much higher than failure pressures with individualized stones in Figure 3.1.

The grouping advantage, as indicated in Table 3.6, is incorporated in Equation 3.8 by using a modification factor for packing density, MF_{PD}. Equation 3.8 can be written as:

$$p_{allow} = \left[450 \frac{M}{H'^2} \right] \left[\frac{1}{MF_{PS} x FS_{CR}} \right] \tag{3.8a}$$

Table 3.6 A Comparison of Geomembrane Failure Pressures with Truncated Cones and Assemblage of Stones.

HPTC Puncture Test		**Performance Puncture Test with Assemblage of Stones**			
Cone Height mm (in)	**Failure Pressure (kPa)**	**AASHTO Stone**			**Yield Pressure (kPa)**
		No	**d_{50} (mm)**	**d_{max} (mm)**	
50 (2.0)	35	3	38	50	70
38 (1.5)	55	57	12	38	170
25 (1.0)	69	8	10	25	690

Where,

H' = Effective protrusion size = $H x MF_{PD}$
H = Maximum protrusion size
MF_{PD} = Modification factor for packing density
= 1.0 for isolated stones
= 0.5 for packed stones

3.2.1.5 *Effect of Biological and Chemical Degradation*

Biological degradation is generally not a concern for polypropylene and polyester geotextiles and HDPE geomembranes. Therefore, effectively a factor of safety of 1.0 can be used for biological degradation.

Chemical degradation is a function of type and concentration of chemicals. A factor of safety of 1.0 to 2.0 has been suggested in the literature with a value of 2.0 applicable to aggressive environments and a value of 1.0 to more inert usage conditions (Koerner, 1998). For example, for potable water ponds and canal liners a value of 1.0 may be used. For containment of brine or diluted acids, a value of 2.0 is generally proposed. For landfill leachate an intermediate value of 1.5 is generally proposed. The reader is recommended to use these values with adequate caution and engineering judgment. Equation 3.8 may be modified for chemical and biological degradation as follows:

$$p_{allow} = \left[450\frac{M}{H'^2}\right]\left[\frac{1}{MF_{PS} x FS_{CR} x FS_{CBD}}\right] \qquad (3.9)$$

Where, FS_{CBD} = factor of safety for chemical and biological degradation.

Equation 3.9 is the final relationship for the calculation of allowable overburden pressure for an geomembrane protected by a nonwoven needlepunched geotextile of mass per unit area M grams/m^2. All terms in the equation and their values have been discussed in the forgoing sections.

3.3 Global Factor of Safety

A global factor of safety against the puncture of a geomembrane can be defined by Equation 3.10.

$$FS = \frac{p_{allow}}{p_{reqd}} \qquad (3.10)$$

Where, p_{allow} = as defined in Equation 3.9, and p_{reqd} is the site-specific overburden pressure discussed in Section 2.3.

The objective of a successful design method for protection of geomembranes should be to prevent the geomembrane puncture over the design life of a geomembrane liner system. This requires the use of a suitable value for global factor of safety in Equation 3.10 to offset the effect of various uncertainties in design, testing and installation. The authors suggest using a value of 3 in Equation 3.10 as a reasonable value against an actual puncture, defined as a hole, in the geomembrane.

It is well known that HDPE geomembranes yield much earlier in the stress-strain curve than the actual rupture (see stress-strain curves for various geomembranes in Chapter 2). Thus, although a global factor of safety of 3 in Equation 3.10 will prevent an actual puncture, it is quite possible that the yield of the geomembrane would still take place. Thus, much higher values of global factors of safety need to be used to ensure that the yield of the geomembrane over the design life is prevented. Koerner, et. al. (1996) performed theoretical analysis of yield of geomembrane and compared it with failure pressures from truncated cone puncture test. On the basis of this analysis, they suggest using global factors of safety against yield provided in Table 3.7.

Table 3.7 Proposed Values of Global Factors of Safety (modified from Koerner, et. al., 1996).

Effective Protrusion Height (mm)	Minimum Global Factor of Safety Against Yield	Minimum Global Factor of Safety Against Puncture
6 (0.25in)	3.0	3
12 (0.50in)	4.5	3
25 (1.0in)	7.0	3
38 (1.5in)	10.0	3

Chapter 4

SPECIFICATIONS FOR CUSHION GEOTEXTILES

4.1 Introduction

The design equation for the calculation of allowable pressure on a geomembrane- Equation 3.9 – is reproduced here as:

$$p_{allow} = \left[450\frac{M}{H'^2}\right]\left[\frac{1}{MF_{PS} x FS_{CR} x FS_{CBD}}\right]$$

where,

p_{allow} = allowable pressure on a geomembrane (kPa),
M = mass per unit area of nonwoven needlepunched geotextile (grams/m^2),
H' = effective protrusion height (mm),
FS_{CR} = factor of safety for creep,
FS_{CBD} = factor of safety for chemical and biological degradation, and
MF_{PS} = modification factor for protrusion shape.

Clearly, a value of mass per unit area, M, must be input in the above equation so as to calculate the allowable pressure on the geomembrane. Conversely, for a given value of allowable pressure, the mass per unit area may be calculated from the equation. In either case, a design engineer must ascertain that the geotextile mass being considered is commercially available at a reasonable cost. Since geotextiles are available from manufacturers in only certain mass denominations, specifying an odd geotextile mass may result in significantly higher cost as the geotextile would have to be custom-made for the project in question. The next section discusses nonwoven needlepunched geotextiles commonly manufactured and specified for geomembrane protection application.

4.2 Specifications for Cushion Geotextiles

Nonwoven needlepunched protection geotextiles are commonly available from manufacturers in the following mass denominations:

- 10 oz / yd^2 (335 g / m^2)
- 12 oz / yd^2 (405 g / m^2)
- 16 oz / yd^2 (540 g / m^2)
- 20 oz / yd^2 (675 g / m^2)
- 24 oz / yd^2 (810 g / m^2)
- 28 oz / yd^2 (950 g / m^2)
- 32 oz / yd^2 (1080 g / m^2)

Rather than specifying an odd geotextile mass, for example 13 oz/yd^2, the selction of one of the above geotextiles would result in a more cost-effective design.

The protection design equation (Equation 3.9) was derived on the basis of extensive quasi-performance and performance puncture testing. Both continuous filament and staple fiber nonwoven needlepunched geotextiles were used for the testing. Although, the equation is independent of the manufacturer of the geotextiles, certain minimum geotextile properties representative of the geotextiles originally tested, must be specified in the project documents. Table 4.1 lists MARV (minimum average roll values) properties recommended for protection geotextiles. It is recommended that, after performing design calculations, the design engineer select a geotextile from Table 4.1 and include relevant specifications in project construction documents.

Table 4.1(a) Recommended Minimum Average Roll Values (MARV) for Protection Nonwoven Needlepunched Geotextiles (SI Units).

Property[1]	**Test Method**	**Unit**	**Property Values**						
Mass per unit area	D 5261	g/m^2	335	405	540	675	810	950	1080
Thickness	D 5199	mm	2.6	2.9	4.1	4.8	6.6	7.9	8.5
Grab tensile strength	D 4632	kN	1.1	1.4	1.7	2.0	2.5	2.6	2.9
Grab tensile elongation	D 4632	%	50	50	50	50	50	50	50
Trapezoid tear strength	D 4533	kN	0.4	0.5	0.6	0.8	1.1	1.0	1.2
Pin puncture strength	D 4833	kN	0.80	0.9	1.1	1.2	1.8	1.9	2.1
UV resistance[2]	D 4355	%	70	70	70	70	70	70	70

(1) All values are MARV except UV resistance which is a minimum value.
(2) Evaluation of 50 mm (2.0 inch) strip tensile specimen after 500 hours of exposure.

Table 4.1(b) Recommended Minimum Average Roll Values (MARV) for Protection Nonwoven Needlepunched Geotextiles (English Units).

Property[1]	**Test Method**	**Unit**	**Property Values**						
Mass per unit area	D 5261	oz/yd^2	10	12	16	20	24	28	32
Thickness	D 5199	mils	105	115	165	190	260	310	345
Grab tensile strength	D 4632	lbs	260	320	390	460	580	590	660
Grab tensile elongation	D 4632	%	50	50	50	50	50	50	50
Trapezoid tear strength	D 4533	lbs	100	125	150	180	260	300	300
Pin puncture strength	D 4833	lbs	180	210	250	270	420	430	475
UV resistance[2]	D 4355	%	70	70	70	70	70	70	70

(1) All values are MARV except UV resistance which is a minimum value.
(2) Evaluation of 50 mm (2.0 inch) strip tensile specimen after 500 hours of exposure.

Chapter 5

DESIGN EXAMPLES

5.1 Example One

Determine effective protrusion height, H', for a layer of gravel of 38 mm maximum diameter placed on the surface of a geomembrane as a drainage layer.

Given:

H = Maximum protrusion height = 38 mm

Calculations:

$H' = MF_{PD} \times H$

As stone is placed as a layer, $MF_{PD} = 0.5$ (see Section 3.2.1.4).

$H' = 0.5 \times 38 = 19$ mm

Therefore, effective protrusion height = 19 mm.

5.2 Example Two

In Example 5.1, what is the mass per unit area of a nonwoven needle punched geotextile required to protect a 1.5 mm HDPE geomembrane from construction damage.

Given:

Maximum protrusion height = 38 mm

Calculations:

From Table 3.2, mass per unit area = 540 grams/m^2.

Therefore, a geotextile with a mass per unit area of 540 grams/m^2 is required to protect the geomembrane from installation damage.

5.3 Example Three

A D7 dozer is to spread drainage stone over a geomembrane. The minimum depth of stone between the geomembrane and the dozer tracks is 0.5 meters. Assume a unit weight of 20 kN/m^3 for the drainage stone. Calculate stress on the geomembrane from the dozer.

Given:

Stone unit weight = 20 kN/m^3

Soil lift thickness = 0.5 m

Dozer type = D7

Calculations:

From Table 2.1, operating weight of D7 dozer, W = 25077 kg

From Table 2.1, shoe width, a = 0.510 m

Using Equation 2.3, shoe length, b = 2.94/0.510 = 5.76 m
From Equation 2.2, projected area, $A_g = (a+d)(b+d)$
$A_g = (0.51+0.5)(5.76+0.5) = 6.3\ m^2$

Using Equation 2.1, stress on the geomembrane, $\sigma = \dfrac{25077}{2x6.3} + 20x0.5$

$\sigma = 2000\ kg/m^2 = 19.6\ kPa$

Therefore, the stress at the surface of the geomembrane will be about 20 kPa.

5.4 Example Four

A surface impoundment is to be constructed with a 1.5 mm thick HDPE geomembrane placed on an insitu compacted clay liner. The surface has been smooth drum rolled to prepare it for placing the geomembrane. However, after the compaction, the CQA (Construction Quality Assurance) inspector notices isolated 25 mm maximum diameter angular stones at the surface. The maximum height of liquid in the impoundment will be 15 meters and the unit weight of liquid is 9 kN/m³. Calculate the mass per unit area of a nonwoven needlepunched geotextile required to protect the geomembrane from puncture.

Given:

Unit weight of liquid, $\gamma = 9\ kN/m^3$
Height of waste, h = 15 meters
Geomembrane thickness, t = 1.5 mm
Maximum stone diameter = 25 mm

Calculations:

Using Equation 2.5, liquid overburden pressure = $p_{reqd} = \gamma h$
$p_{reqd} = 9 \times 15 = 135\ kN/m^2 = 135\ kPa$
Using Equation 3.9,

$$p_{allow} = \left[450 \frac{M}{H'^2}\right]\left[\frac{1}{MF_{PS} x FS_{CR} x FS_{CBD}}\right]$$

$H' = MF_{PD} \times H$
Since stones are isolated in this case, $MF_{PD} = 1.0$ (see Section 3.2.1.4)
$H' = 1 \times 25 = 25$ mm
From Section 3.2.1.5, $FS_{CBD} = 1.5$
From Table 3.5, $MF_{PS} = 1.0$ for angular stone
Inputting these values in the above equation for p_{allow},

$$p_{allow} = 450 \frac{M}{(25)^2}\left[\frac{1}{FS_{CR} \times 1.5}\right]$$

or, $p_{allow} = \dfrac{0.48M}{FS_{CR}}$

Substituting the values of p_{allow} and p_{reqd} in Equation 3.10,

$$FS = \frac{0.48M}{135xFS_{CR}}$$

From Table 3.2, minimum mass per unit area required to prevent construction damage with a protrusion size of 25 mm, M=405 g/m^2.
For this geotextile, from Table 3.3, FS_{CR} = 1.5 at a protrusion height of 25 mm
Therefore, FS = (0.48 x 405) / (135 x 1.5) = 0.96
The global factor of safety is less than a minimum value of 3 proposed in Table 3.7. From Table 4.1(a), try a geotextile with a mass of 1080 g/m^2. From Table 3.3, for this geotextile, FSCR = 1.2.
FS = (0.48 x 1080) / (135 x 1.2) = 3.2, OK

Therefore, for the example problem, a nonwoven needlepunched geotextile with a mass of 1080 grams/m^2 is required to prevent geomembrane puncture.

5.5 Example Five

An angular stone with a maximum size of 25 mm is to be placed on a 1.5 mm thick HDPE geomembrane. The thickness of stone layer is 1.0 meters and the unit weight is 20 kN/m^3. The height of waste above the drainage layer is 30 meters. The unit weight of waste is approximately 12 kN/m^3. The drainage layer over the geomembrane is to be placed using a D7 dozer with a minimum track width of 1.5 m. No other traffic except light ATVs will be allowed over the geomembrane. Assume that the subgrade has been carefully prepared such that there is no concern with puncture from under the geomembrane. Determine the mass per unit area of a nonwoven needlepunched geotextile required to prevent geomembrane puncture.

Given:

Unit weight of waste, γ = 12 kN/m^3
Unit weight of drainage stone = 20 kN/m^3
Height of waste, h = 30 meters
Thickness of drainage layer = 1.0 meters
Geomembrane thickness, t = 1.5 mm
Maximum stone size = H = 25 mm

Calculations:

Effective Stone Size, H', = MF_{PD} x H
Since stone is placed close together, MF_{PD} = 0.5
H' = 0.5 x 25 = 12.5 mm, assume 12.0 mm
Using Equation 2.5, waste overburden pressure = $p_{reqd} = \gamma h$
p_{reqd} = 12 x 30 + 1 x 20 = 380 kN/m^2 = 380 kPa
From Section 3.2.1.5, FS_{CBD} = 1.5

From Table 3.5, $MF_{PS} = 1.0$
From Equation 3.9,

$$p_{allow} = 450\frac{M}{(12.0)^2}\left[\frac{1}{FS_{CR} \times 1.5}\right]$$

or, $p_{allow} = \dfrac{2.0M}{FS_{CR}}$

Substituting the values of p_{allow} and p_{reqd} in Equation 3.10,

$$FS = \frac{2.0M}{380xFS_{CR}}$$

From Table 3.2, minimum mass per unit area required to prevent construction damage with a stone size of 25 mm, M=405 g/m^2.
For this geotextile, from Table 3.3, $FS_{CR} = 1.4$ at an effective protrusion height of 12 mm.

Therefore, FS = (2.0 x 405) / (380 x 1.5) = 1.4, which is less than a required value of 3.0.
Next, try a geotextile of 540 g/m^2 from Table 4.1. For this geotextile, $FS_{CR} = 1.3$ at a protrusion height of 12 mm.
FS = (2.0 x 540) / (380 x 1.3) = 2.2 which is less than 3.0.
Next try a geotextile of mass, M = 675 g/m^2 from Table 4.1. For this geotextile, $FS_{CR} = 1.2$.
FS = (2.0 x 675)/(380 x 1.2) = 3.0 which is OK
Thus at a minimum 675 g/m^2 nonwoven needlepunched geotextile is required for the protection of the geomembrane.

5.6 Example Six

For Example 5.5, calculate the factor of safety for a 1.0 mm thick HDPE geomembrane with a 675 g/m^2 nonwoven needlepunched geotextile.

For a 1.5 mm thick HDPE geomembrane, the equation for calculating p_{allow} is given below (Equation 3.9):

$$p_{allow} = \left[450\frac{M}{H'^2}\right]\left[\frac{1}{MF_{PS}xFS_{CR}xFS_{CBD}}\right]$$

The effect of thickness on p_{allow} is expressed by Equation 3.6. The above equation can be modified to incorporate the effect of thickness:

$$p_{allow} = \left[450\frac{M}{H'^2} - 1.3x10^5(1.5-t)H'^{-2.4}\right]\left[\frac{1}{MF_{PS}xFS_{CR}xFS_{CBD}}\right]$$

From Example 5.5,

$M = 675\ g/m^2$
$H' = 12.0\ mm$
$MF_{PS} = 1.0$
$FS_{CR} = 1.2$
$FS_{CBD} = 1.5$

Inputting the above values for the equation for p_{allow}:

$P_{allow} = 996\ kPa$

$$FS = \frac{996}{380} = 2.6$$

Thus the factor of safety for 1.0 mm HDPE geomembrane is less than the requirement of 3.

5.7 Example Seven

A mining company is to build a 90 meter deep heap leach pad over a 2 mm thick HDPE geomembrane. The geomembrane is placed over a GCL which rests over a well prepared subgrade. The maximum size of stone over the geomembrane is 12 mm (0.5 inch). Assume a unit weight of 18 kN/m^3 for the rock. Determine the mass per unit area of protection geotextile.

Given:

Unit weight of drainage stone = 18 kN/m^3
Height of rock, h = 90 meters
Geomembrane thickness, t = 2.0 mm
Maximum stone size = H = 90 m

Calculations:

Effective Stone Size, H', = MF_{PD} x H
Since stone is placed close together, $MF_{PD} = 0.5$
$H' = 0.5 \times 12 = 6.0$ mm
Using Equation 2.5, waste overburden pressure = $p_{reqd} = \gamma h$
$p_{reqd} = 18 \times 90 = 1620\ kN/m^2 = 1620\ kPa$
From Section 3.2.1.5, $FS_{CBD} = 1.5$
From Table 3.5, $MF_{PS} = 1.0$
From Equation 3.9, ignoring the advantage of geomembrane thickness,

$$p_{allow} = 450\frac{M}{(6)^2}\left[\frac{1}{FS_{CR}\times 1.5}\right]$$

or, $p_{allow} = \dfrac{8.3M}{FS_{CR}}$

Substituting the values of p_{allow} and p_{reqd} in Equation 3.10,

$$FS = \frac{8.3M}{1620xFS_{CR}}$$

From Table 3.2, minimum mass per unit area required to prevent construction damage with a maximum stone size of 12 mm, M=335 g/m^2.
For this geotextile, from Table 3.3, FS_{CR} = 1.4 at an effective protrusion height of 6 mm.

Therefore, FS = (8.3 x 335) / (1620 x 1.5) = 1.1, which is less than a required value of 3.0.
Next try a geotextile of 540 g/m^2 from Table 4.1. For this geotextile, FS_{CR} = 1.2 at a effective protrusion height of 6 mm.
FS = (8.3 x 540) / (1620 x 1.2) = 2.3 which is less than 3.0, however, may be sufficient for mining applications. To achieve a factor of safety of 3.0, probably a heavier geotextile is necessary.

5.8 Example Eight

An evaporation basin is to be built using a 1.5 mm HDPE geomembrane over a subgrade with maximum particle size of 12 mm. The depth of water in the evaporation basin is to be 6 m. The unit weight of water is to be 9.8 kN/m^3. Determine the mass per unit area of the protection geotextile.

Given:

Unit weight of drainage water = 9.8 kN/m^3
Height of water, h = 6.0 meters
Geomembrane thickness, t = 1.5 mm
Maximum stone size = H = 12 mm

Calculations:

Effective Stone Size, H', = MF_{PD} x H
Assuming isolated stones, MF_{PD} = 1.0
H' = 1.0 x 12 = 12 mm
Using Equation 2.5, waste overburden pressure = $p_{reqd} = \gamma h$
p_{reqd} = 6 x 9.8 = 58.8 kN/m^2 = 59 kPa
From Section 3.2.1.5, FS_{CBD} = 1.0
From Table 3.5, MF_{PS} = 1.0
From Equation 3.9,

$$p_{allow} = 450\frac{M}{(12)^2}\left[\frac{1}{FS_{CR} \times 1.0}\right]$$

or, $p_{allow} = \dfrac{3.1M}{FS_{CR}}$

Substituting the values of p_{allow} and p_{reqd} in Equation 3.10,

$$FS = \frac{3.1M}{59xFS_{CR}}$$

From Table 3.2, minimum mass per unit area required to prevent construction damage with a stone size of 12 mm, M=335 g/m^2.
For this geotextile, from Table 3.3, FS_{CR} = 1.4 at an effective protrusion height of 12 mm.

Therefore, FS = (3.1 x 335) / (59 x 1.4) = 12.5, which is more than a required value of 3.0.

Therefore, a 335 g/m2 geotextile is satisfactory.

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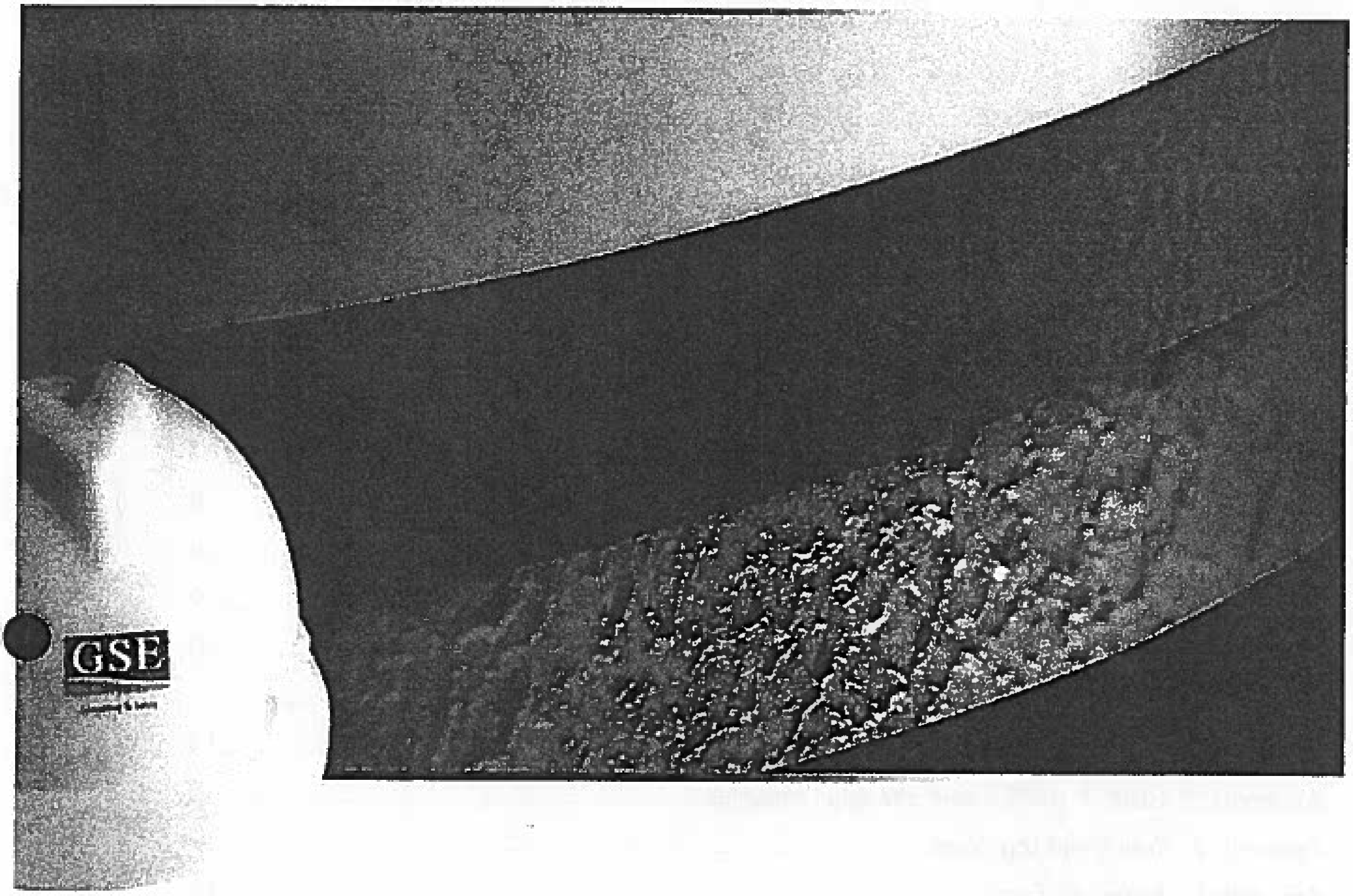
Installation Quality Assurance Manual



Geomembrane Products

GSE

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1.0 INTRODUCTION

This manual provides an overview of the GSE Installation Quality Assurance procedures consistent with industry accepted practices to ensure that the geomembrane products installed will perform for its intended purpose. In addition, all installation work will be performed in strict accordance per the customer's specifications. Please read the procedures below completely before you begin. If you need further clarification, contact the GSE Installation Department for assistance. Remember safety first and use safe practices always on every project.

2.0 STANDARD TEST METHODS

ASTM D 6392:	Standard Test Methods For Determining The Integrity Of Non-Reinforced Geomembrane Seams Produced Using Thermo Fusion Methods
ASTM D 5820:	Standard Practice For Pressurized Air Channel Evaluation of Dual Seamed Geomembranes
ASTM D 5641:	Standard Practice For Geomembrane Seam Evaluation By Vacuum Chamber
ASTM D 6497:	Standard Guide For Mechanical Attachment of Geomembrane to Penetrations or Structures
ASTM D 7240:	Standard Practice for Leak Location using Geomembranes with an Insulating Layer in Intimate Contact with a Conductive Layer via Electrical Capacitance Technique (Conductive Geomembrane Spark Test)
GRI Standard GM13:	Test Properties, Testing Frequency and Recommended Warranty for High Density Polyethylene (HDPE) Smooth and Textured Geomembranes
GRI Standard GM14:	Selecting Variable Intervals for Taking Geomembrane Destructive Seam Samples Using the Method of Attributes
GRI Standard GM17:	Test Properties, Testing Frequency and Recommended Warranty for Linear Low Density Polyethylene (LLDPE) Smooth and Textured Geomembranes
GRI Standard GM19:	Standard Specification for Seam Strength and Related Properties of Thermally Bonded Polyolefin Geomembranes

3.0 MATERIAL DELIVERY

A. Upon arrival on site, the GSE QA personnel will inventory all materials on the job site.

B. Roll numbers of geomembrane will be logged on the Inventory Check List (Appendix A) and cross-referenced with the Bill of Lading for materials supplied by GSE.

C. Copies of the Inventory Check List and signed Bill of Lading should be sent to the GSE's corporate headquarters while the QA personnel retains the original copies.

D. Any visible damage to roll materials should be noted on the roll and Inventory Check List.

4.0 EARTHWORK

A. The general contractor is responsible for preparing and maintaining the subgrade. The subgrade should be prepared and maintained per the job specifications.

B. The GSE site manager shall be responsible for assuring that the subgrade surface has been properly prepared for deployment of geosynthetics. After each day's deployment the Subgrade Surface Acceptance form (Appendix B) will be signed by all parties.

5.0 PANEL PLACEMENT

A. Each panel will be assigned a number as described below.

1. When there is one layer, panels may be designated with only a number, i.e...1, 2, 3, 4 etc.

2. When two or more layers are required, use a letter and number, i.e....
Primary Liner P1, P2, P3, P4 etc...
Secondary Liner S1, S2, S3, S4 etc...
Tertiary Liner T1, T2, T3, T4 etc...

B. This numbering system should be used whenever possible. Agreement to a panel numbering system should be made at the pre-construction meeting. However, it is essential that GSE and the owner representative and third party QA inspector agree.

C. Panel numbers shall be written in large block letters in the center of each deployed panel. The roll number, date of deployment and length (gross) should be noted below the panel number. All notes should be made, so that they are easily visible from a distance. On long panels it is beneficial to write information on both ends.

D. Panel numbers shall be logged on the GSE Panel Placement Log (Appendix C) along with the roll number and other information neccessary to complete the form.

E. If there is a partial roll left after deployment, it is important to write the last four digits of the roll number in several locations on the roll along with the estimated length for future identification.

F. Deployment of geomembrane panels shall be performed in a manner that will comply with the following guidelines:

1. Unroll geomembrane using methods that will not damage geomembrane and will protect underlying surface from damage. GSE Conductive should be installed with Conductive layer facing down.

2. Place temporary ballast, such as sangbags, on geomembrane that will not damage the geomembrane and to prevent wind uplift.

3. Personnel walking on geomembrane shall not engage in activities or wear shoes that could

damage it. Smoking is not permitted on the geomembrane.

4. Do not allow heavy vehicular traffic directly on geomembrane. Rubber tired and tracked ATV's and equipment are acceptable if contact pressure is less than 8 psi.
    a. Protect geomembrane in areas of heavy traffic by placing protective cover over the geomembrane.
    b. Prior to driving on any geomembrane layer, please check for sharp edges, embedded rocks, or other foreign objects that may protrude in the tires and tracks.
    c. Path driven on geomembranes shall be as straight as possible with no sharp turns, sudden stops or quick starts.
    d. Areas where driving occurs shall be continuously and thoroughly inspected throughout the deployment process by the contractor and the third party CQA.

6.0 TRIAL WELDS

A. Seaming apparatus shall be allowed to warm up a minimum of 10 minutes before performing trial welds.

B. Each seaming apparatus along with GSE welding technician will pass a trial weld prior to use. Trial welds to be performed in the morning and afternoon, as a minimum, as well as whenever there is a power shutdown.

C. Fusion or wedge welds will always be performed or conducted on samples at least 6.0 ft long. Extrusion welds will be done on samples at least 3.0 ft long.

Note: Always perform trial welds in the same conditions that exist on the job. Run the trial welds on the ground, not the installed liner. Do not use a wind break unless you are using one on the job.

D. Operating temperatures should be monitored while welding. The welding technician should verify that the equipment is capable of maintaining temperature while welding.

E. Sampling Procedure
1. Cut five 1.0 in wide specimens from the trial weld sample. Specimens will always be cut using a 1.0 in die cutter, so the peel values may be used for qualitative analysis.
2. When cutting coupons from the trial weld samples, the inside and outside tracks on the coupon should be identified to assist in troubleshooting problems in case the weld fails. The outside track will be defined as the track, which would be peeled if pulling the overlap exposed in a typical installation, or the seam that is closest to the edge of the top sheet. The inside track is the seam closest to the edge of the bottom sheet.

F. Cutter
1. Only cut one sample at a time to avoid damaging the die cutter.

2. Samples should be free of sand and grit prior to cutting sample.

3. Inspect the die edge weekly for nicks, dents or signs of dullness. Dullness of the cutting edge may damage the units.

4. Remove die when edge has been dulled and lightly reshape it with a medium hand file. When wear is excessive return it for a replacement die.

5. When the cutting board becomes deeply scored and/or interferes with coupon cutting it should be replaced.

6. To adjust the depth of the die cut into the cutting board, after replacing the cutting board or sharpening the die, 0.015 in washer shims can be added or removed between the cutting ram and the ram extension. Only add shims when cutting is difficult due to lack of depth of cut.

G. Trial Weld Testing
1. Allow coupons to cool prior to testing. Avoid separating the coupons while hot as failure of the sheet may be initiated and false readings indicated.

2. In extreme heat the coupons may need to be cooled, using water or an insulated cooler prior to peel testing. Lab conditions specify 70 degrees (plus or minus 4 degrees) Fahrenheit. Coupon temperatures greater than 70 degrees may result in lowered strengths.

3. Visually inspect the coupons for squeeze-out, footprint, pressure and general appearance.

4. Each of the five coupons will be tested in peel on the field tensiometer at a separation rate of 2 in per minute (for HDPE). Shear tests, in addition to the peel tests, will be performed.

H. Pass/Fail Criteria
1. Criteria for passing trial welds will be as follows:
   a. Seam must exhibit film tear bond (FTB). Trial welds should have no incursion into the weld.

   b. Peel and shear values shall meet or exceed the values as listed in Appendix D, Table 1 for HDPE smooth or textured sheet (@ 2 in/min).

   c. Peel and shear values shall meet or exceed the values as listed in Appendix D, Table 2 for LLDPE smooth or textured sheet (@ 20 in/min).

   d. Both tracks of fusion welded samples must pass for the trial weld to be considered acceptable. If any of the five coupons fail due to seam incursion (no FTB) or low strength values, the trial weld must be performed again.

e. The GSE QA personnel will give approval to proceed with welding after observing and recording all trial welds.

2. All trial weld data will be logged on the GSE Trial Weld Log (Appendix E).

3. When logging fusion welded peel values on the GSE Trial Weld Log indicate the values. for the outside track first, followed by the inside track.

4. Speed and temperature settings will be recorded for each machine trial weld as appropriate.

7.0 GEOMEMBRANE FIELD SEAMING

A. The seam number takes the identity of the panels on each side. The seam between panels 1 & 2 becomes seam 1/2.

B. Welding technicians will record their initials, machine number, date and time at the start of every seam and on the GSE Seam Log (Appendix F). The technician should also periodically mark temperatures along the seam and at the end of the seam.

C. Approved processes for field seaming and repairing are fusion welding and extrusion welding. All welding equipment shall have accurate temperature monitoring devices installed and working to ensure proper measurement.

D. Fusion welding shall be used for seaming panels together and is not used for patching or detail work. The GSE site manager shall verify that:

1. The equipment used is functioning properly.

2. All work is performed on clean surfaces and done in a professional manner. No seaming will be performed in adverse weather conditions.

E. Extrusion welding shall be used primarily for repairs, patching and special detail fabricating and may be used for seaming. The GSE site manager shall verify that:

1. Equipment used is functioning properly.

2. Welding personnel are purging the extrusion welders of heat degraded extrudate prior to actual use.

3. All work is performed on clean surfaces and done in a professional manner. No seaming will be performed in adverse weather conditions.

F. For seam preparation, the welding technician shall verify that:

1. Prior to seaming, the seaming area is free of moisture, dust, dirt, sand or debris of any nature.

2. The seam is overlapped properly for fusion welding.

3. The seam is overlapped or extended beyond damaged areas at least 4.0 in when extrusion welding.

4. The seam is properly heat tacked and abraded prior to extrusion welding.

5. Seams are welded with fewest number of unmatched wrinkles or "fishmouths".

G. No seaming will be performed in ambient air temperatures or adverse weather conditions that would jeopardize the integrity of the liner installation.

8.0 FIELD DESTRUCTIVE TESTING

A. Destructive seam tests shall be performed to evaluate bonded seam strength. The frequency of sample removal shall be one sample per 500 ft of seam, unless site specifications differ. Location of the destructive samples will be selected and marked by the QA technician or third party QA inspector. Field testing should take place as soon as possible after seam is completed.

B. Samples should be labeled in numerical order, i.e. DS-1, DS-2 etc....This should carry thru any layer and or multiple ponds, do not start numbering from 1 again. The size of samples and distribution should be approximately 12 in x 39 in (Size may vary depending on job requirements) and distributed as follows:

1. 12 in x 12 in piece given to QA technician for field testing.
2. 12 in x 12 in piece sent to the GSE's corporate headquarters for testing, if required.
3. 12 in x 12 in piece given to third party for independent testing or to archive.

NOTE: All samples will be labeled showing test number, seam number, machine number, job number, date welded and welding tech number.

C. The sample given to the QA technician in the field shall have ten coupons cut and be tested with a tensiometer adjusted to a pull rate as shown below. The strength of four out of five specimens should meet or exceed the values below, and the fifth specimen must meet or exceed 80% of the value below.

1. Seam must exhibit film tear bond (FTB). Welds should have ≤ 25% incursion into the weld.

2. Peel and shear values shall meet or exceed the values as listed in Appendix D, Table 1 for HDPE smooth or textured sheet (@ 2 in/min).

3. Peel and shear values shall meet or exceed the values as listed in Appendix D, Table 2 for LLDPE smooth or textured sheet (@ 20 in/min).

D. All weld destructive test data will be logged on the GSE Destructive Test Log (Appendix G).

E. When logging fusion welded peel values on the GSE Destructive Test Log, indicate the values for the outside track first, followed by the inside track.

F. Test results will be noted in the GSE Destructive Test Log as Pass (P) or Fail (F).

G. If a test fails, additional samples will be cut, approximately 10 ft on each side of the failed test, and retested. These will be labeled A (After) & B (Before). This procedure will repeat itself until a sample passes. Then the area of failed seam between the two tests that pass will be capped or reconstructed.

9.0 NON-DESTRUCTIVE TESTING

A. GSE shall non-destructively test all seams their full length using an air pressure or vacuum test. The purpose of this test is to check the continuity of the seam.

B. For air pressure testing, the following procedures are applicable to those seams welded with a double seam fusion welder.

1. The equipment used shall consist of an air tank or pump capable of producing a minimum 35 psi and a sharp needle with a pressure gauge attached to insert into the air chamber.
2. Seal both ends of the seam by heating and squeezing them together. Insert the needle with the gauge into the air channel. Pressurize the air channel to 30 psi. Note time test starts and wait a minimum of 5 minutes to check. If pressure after five minutes has dropped less than 2 psi then the test is successful (Thickness of material may cause variance).
3. Cut opposite seam end and listen for pressure release to verify full seam has been tested.
4. If the test fails, follow these procedures.
   a. While channel is under pressure walk the length of the seam listening for a leak.
   b. While channel is under pressure apply a soapy solution to the seam edge and look for bubbles formed by air escaping.
   c. Re-test the seam in smaller increments until the leak is found.
5. Once the leak is found using one of the proceedures above, cut out the area and retest the portions of the seams between the leak areas per 4a to 4b above. Continue this procedure until all sections of the seam pass the pressure test.
6. Repair the leak with a patch and vacuum test.

C. For vacuum testing, the following procedures are applicable to those seams welded with an extrusion welder.

1. The equipment used shall consist of a vacuum pumping device, a vacuum box and a foaming agent in solution.
2. Wet a section with the foaming agent, place vacuum box over wetted area. Evacuate air from the vacuum box to a pressure suitable to affect a seal between the box and geomembrane. Observe the seam through the viewing window for the presence of soap bubbles emitting from the seam.
3. If no bubbles are observed, move box to the next area for testing. If bubbles are observed, mark the area of the leak for repair per section 11.0 and re-test per section 9.0.

Note: If vacuum testing fusion welded seams, the overlap flap must be cut off to perform the tests

4. All non-destructive tests will be noted in the GSE Non-Destructive Logs (Appendixes H-I).

D. For spark testing GSE Conductive geomembranes, ASTM D 7240 will be the procedure, unless otherwise instructed by the engineer client.

10.0 DEFECTS & REPAIRS

A. All seams and non-seam areas of the geomembrane lining system shall be examined for defects.

B. Identification of the defect should be made using the following procedures:

1. For any defect in the seam or sheet that is an actual breach (hole) in the liner, installation personnel shall circle the defect and mark with the letter P along side the circle. The letter P indicates a patch is required.

2. For any defect that is not an actual hole, installation personnel shall circle the defect indicating that the repair method may be only an extruded bead and that a patch is not required.

3. Each suspect area that has been identified as repair shall be repaired in accordance with section 11.0 and in the non-destructively testing per section 9.0. After all work is completed, the GSE site manager will conduct a final walk-through to confirm all repairs have been completed and debris removed. Only after this final evaluation by the GSE site manager, the owner, and the agent shall any material be placed over the installed liner.

11.0 REPAIR PROCEDURES

A. Any portion of the geomembrane lining system exhibiting a defect that has been marked for repair may be repaired with any one or combination of the following procedures:

1. Patching - used to repair holes, tears, undispersed raw materials in the sheet.

2. Grind and Reweld - used to repair small sections of extrusion welded seams.

3. Spot Welding - Used to repair small minor, localized flaws.

4. Flap Welding - Used to extrusion weld the flap of a fusion weld in lieu of a full cap.

5. Capping - Used to repair failed seams.

B. The following conditions shall apply to the above methods:

1. Surfaces of the geomembrane which are to be repaired shall be prepared according to this section.

2. All surfaces must be clean and dry at the time of the repair.

3. All seaming equipment used in repairing procedures shall be qualified.

   4. All patches and caps shall extend at least 4 in beyond the edge of the defect, and all patches must have rounded corners.

   5. All cut out holes in liner must have rounded corners of 3.0 in minimum radius.

C. Patches should be labeled in numerical order, i.e. RP-1, RP-2, etc... This should carry through any layer and/or multiple ponds, and do not start with the number 1 again.

12.0 AS-BUILT DRAWINGS

As-built drawings are available per these items:

A. As-built drawings will be provided at the completion of the project.

B. AutoCad as-built drawings will be provided in either a printed version or by email in a PDF file.

C. As-built drawings will include geomembrane panels and panel numbers with the last four digits of the roll number.

D. Panel numbers and the full roll numbers will correspond with the GSE Panel Placement Log.

E. All destructive testing and repair locations will be placed on the as-built drawings.

If you require further information, please contact the GSE Installation Department directly.

Appendix A: Inventory Checklist

GSE Inventory Check List

Project: ______________ Site Mgr.: ______________ Date: ______________

Project #: ______________ QA Tech: ______________ Page: ____ of ____

Material	Roll #	Used	Material	Roll #	Used	Material	Roll #	Used	Material	Roll #	Used

Appendix B: Subgrade Surface Acceptance

Subgrade Surface Acceptance

Date: ____________

Project: ____________________ **Site Manager:** ____________________

Project #: ____________________

Location: ____________________ **Partial:** ____________ **Final:** ____________

This document only applies to the acceptability of surface conditions for installation of geosynthetic products. GSE does not accept responsibility for compaction, elevation or moisture content, nor for the surface maintenance during deployment. Structural integrity of the subgrade and maintenance of these conditions are the responsibility of the owner or earthwork contrator.

For GSE Lining Technology, LLC: For Owner / Contractor:

Acceptance Number: ____________ Area Accepted: ____________ s.f. Total Area Accepted to date: ____________ s.f.

Appendix C: Panel Placement Log

GSE Panel Placement Log

Project Name: ______________________________

Location: ____________________ Site Supervisor: ____________________

Job Number: ____________________ Type of Material: ____________________

Q.A. Tech.: ____________________ Sheet Thickness: ____________________

Panel Number	Roll Number	Deployment Date	Width (Feet)	Length (Feet)	Square Feet	Square Feet (Cumulative)	A/T 1	A/T 2

Appendix D: HDPE & LLDPE Seam Strength Properties

Table 1. HDPE Seam Strength Properties

Material (Mil)	Shear Strength (PPI)	Fusion Peel (PPI)	Extrusion Peel (PPI)
40	81	65	52
60	121	98	78
80	162	130	104
100	203	162	130

Table 2. LLDPE Seam Strength Properties

Material (Mil)	Shear Strength (PPI)	Fusion Peel (PPI)	Extrusion Peel (PPI)
40	60	50	48
60	90	75	72
80	120	100	96
100	150	125	120

Appendix E: Trial Weld Log

GSE Trial Weld Log

Project Name: ____________________
Location: ____________________
Job Number: ____________________
Q.A. Tech.: ____________________

Site Supervisor: ____________________
Type of Material: ____________________
Sheet Thickness: ____________________

Fusion (ppi)
Min. Peel _____
Min. Shear _____

Extrusion (ppi)
Min. Peel _____
Min. Shear _____

Trial No.	Date of Trial	Time of Trial	Technicians ID Number	Ambient Temp.	WELDER TYPE	Wedge Mass	Speed Preheat	Peel ppi	Peel ppi	Peel ppi	Peel ppi	Peel ppi	Shear ppi	Shear ppi	Shear ppi	Shear ppi	Shear ppi	Pass Fail

Appendix F: Seam Log

GSE Seam Log

Project Name: ____________________

Location: ____________________ Site Supervisor: ____________

Job Number: ____________________ Type of Material: ____________

Q.A. Tech.: ____________________ Sheet Thickness: ____________

Seam Number	Time of Weld	Date of Weld	Type of Weld	Length of Seam	Machine Number	Technician ID Number

Appendix G: Destructive Test Log

GSE Destructive Test Log

Project Name: ______________________
Location: ______________________
Job Number: ______________________
Q.A. Tech.: ______________________

Site Supervisor: ______________________
Type of Material: ______________________
Sheet Thickness: ______________________

Fusion (ppi)
Min. Peel ______
Min. Shear ______

Extrusion (ppi)
Min. Peel ______
Min. Shear ______

Sample Number	Date Welded	Seam Number	Technician ID Number	Machine Type & No.	Location	Peel ppi	Peel ppi	Peel ppi	Peel ppi	Peel ppi	Shear ppi	Shear ppi	Shear ppi	Shear ppi	Shear ppi	Pass/ Fail

Appendix H: Repair Log - Vacuum Test

GSE Repair Log - Vacuum Test

Project Name: ______________________________

Location: ______________ Site Supervisor: ______________

Job Number: ______________ Type of Material: ______________

Q.A. Tech.: ______________ Sheet Thickness: ______________

Repair Number	Weld Date	Machine Number	Tech ID	Location	Test Date	Tech ID	Pass/Fail

Appendix I: Non-Destructive Log - Air Test

GSE Non-Destructive Log - Air Test

Project Name: ____________________

Location: ____________________ Site Supervisor: ____________________

Job Number: ____________________ Type of Material: ____________________

Q.A. Tech.: ____________________ Sheet Thickness: ____________________

Seam Number	Test Date	Technician ID Number	Air Pressure Test		Test Result (P or F)	Location
			psi start	psi finish		

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