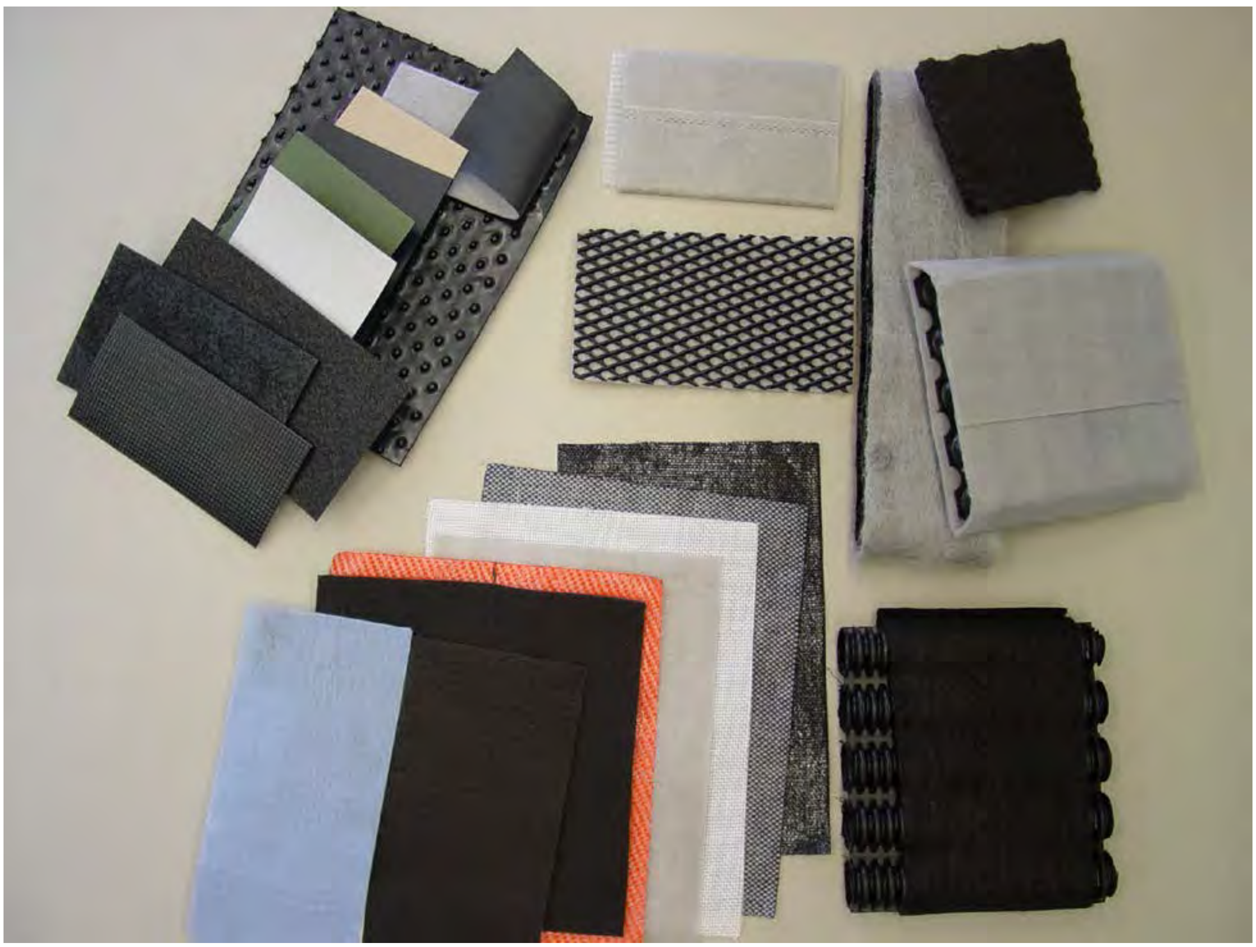
Geotextiles in Embankment Dams

Status Report on the Use of Geotextiles in Embankment Dam Construction and Rehabilitation



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Federal Emergency Management Agency

April, 2008

Preface

Geotextiles are used in a variety of applications in embankment dam construction and rehabilitation. Although policy varies, most practitioners in the United States limit the use of geotextiles to locations where there is easy access for repair and replacement (shallow burial), or where the geotextile function is not critical to the safety of the dam should the geotextile fail to perform.

In a limited number of cases, geotextiles have been used as deeply buried filters in dams in France, Germany, South Africa, and a few other nations. Most notable, is the geotextile installed as a filter for Valcross Dam which has been successfully performing for over 35 years. These applications remain controversial and are not considered to be consistent with accepted engineering practice within the United States. Because geotextiles are prone to installation damage and have a potential for clogging, their reliability remains uncertain. Many organizations forbid their use in embankment dams in critical applications where poor performance could lead to failure of the dam or require costly repairs. Due to the potential problems associated with using geotextiles in a dam, they should not be placed in embankment dams where poor performance could lead to failure of the dam.

It is the policy of the National Dam Safety Review Board that geotextiles should not be used in locations that are critical to the safety of the dam.

The above policy is explained in more detail in the policy section of this report. This report includes information about the policy of geotextile use in the United States, it reviews geotextiles against the larger backdrop of geosynthetic materials, discusses functional applications of geotextiles in embankment dams, reviews potential performance problems and causes, current design procedures, and construction practices. This report summarizes the current state of practice. Although design and construction procedures are discussed in detail and recommendations regarding good practice are made, this report is not intended to be used as a design manual. It does not contain the level of detail necessary for use as a design reference.

Embankment dams can be classified according to their hazard potential for causing damages downstream should they fail. Various State and federal agencies have different systems for rating the hazard classes of embankment dams. A single, universally accepted hazard classification system does not exist. All of the hazard classification systems group embankment dams into categories based on the potential impacts of a theoretical release of the stored water during a dam failure. However, the most common problem with all of these classification systems is the lack of clear, concise, and consistent terminology. The Federal Emergency

Management Agency (FEMA) has a hazard classification system that is clear and succinct, and this system was adopted for the purposes of this document. The reader is directed to FEMA 333, *Federal Guidelines for Dam Safety: Hazard Potential Classification Systems for Dams* (1998), for a complete version of their system. The FEMA document uses three hazard potential levels to classify embankment dams. These levels are summarized as follows:

- *Low hazard potential.*—Embankment dams assigned the low hazard classification are those where failure or misoperation results in no probable loss of human life and low economic and/or environmental losses. Losses are principally limited to the owner's property.

- *Significant hazard potential.*—Embankment dams assigned the significant hazard classification are dams where failure or misoperation results in no probable loss of human life, but can cause economic loss, environmental damage, or disruption of lifeline facilities, or can impact other concerns. Significant hazard potential classification dams are often located in predominantly rural or agricultural areas, but could be located in areas with population and significant infrastructure.

- *High hazard potential.*—Embankment dams assigned the high hazard classification are those where failure or misoperation will probably cause loss of human life.

Hazard potential classification	Loss of human life	Economic, environmental, lifeline losses
Low	None expected	Low and generally limited to owner
Significant	None expected	Yes
High	Probable—one or more expected	Yes (but not necessary for this classification)

Embankment dam hazard classifications are assigned based on their potential for causing downstream damage, but these classifications do not reflect in any way on the likelihood that the dam may fail. An embankment dam might be classified as having a low hazard potential based on the impacts a failure would have on the downstream area, but have a high probability of failure if it were in very poor condition. The hazard classification says nothing about the safety or condition of the structure.

The guidance in this document is considered valid technically without regard to the hazard potential classification of a particular embankment dam. However, some design measures that are commonly used for design of high and significant hazard embankment dams may be considered by some to be overly robust for use in low hazard dams. As an example, chimney filters that extend across the entire width of the embankment fill section are considered state of practice for high hazard embankment dams. Many smaller, low hazard embankment dams are constructed without this feature.

FEMA's National Dam Safety Program sponsored development of this document in conjunction with the Association of State Dam Safety Officials, Bureau of Reclamation, Natural Resources Conservation Service, and U.S. Army Corps of Engineers.

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The National Dam Safety Review Board (NDSRB) reviewed this document prior to issuance. The NDSRB has responsibility for monitoring the safety and security of dams in the United States, advising the Director of FEMA on national dam safety policy, consulting with the Director of FEMA for the purpose of establishing and maintaining a coordinated National Dam Safety Program, and monitoring of State implementation of the assistance program.

A number of additional engineers and technicians provided input in preparation of this document, and the authors greatly appreciate their efforts and contributions. The authors also extend their appreciation to the following agencies and individuals for graciously providing additional reviews, information, and permission to use their materials in this publication:

American Association of State Highway & Transportation Officials
American Concrete Institute
ASTM International
Association of State Dam Safety Officials, Lori Spragens and Sarah Mayfield
Federal Energy Regulatory Commission
Dr. J.P. Giroud
Industrial Fabrics Association International (publisher of *Geosynthetics* magazine)
International Geosynthetics Society
Mr. Robert Snow, D'applonia

United States Army Corps of Engineers

If geotextiles are not designed and constructed correctly, embankment dams may have an increased probability of failure. The particular design requirements and site conditions of each embankment dam and geotextile installation are unique. No single publication can cover all of the requirements and conditions that can be encountered during design and construction. They must be designed and approved by engineers experienced with all aspects of the design and construction of these structures.

The users of this document are cautioned that sound engineering judgment should always be applied when using references. The authors have strived to avoid referencing material that is considered outdated for use in modern designs. However, the user should be aware that certain portions of references cited in this document may have become outdated in regards to design and construction aspects and/or philosophies. While these references still may contain valuable information, users should not automatically assume that the entire reference is suitable for design and construction purposes.

Many sources of information were utilized in the development of this document, including:

- Published design standards and technical publications of the various federal and State agencies involved with the preparation of this document.

- Published professional papers and articles from selected authors, technical journals and publications, and organizations.

- Experience of the individuals and the Federal and State agencies involved in the preparation of this document.

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Suggestions for changes, corrections, or updates to this document should be directed to:

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Common Abbreviations

AASHTO, American Association of State Highway and Transportation Officials
AOS, apparent opening size
ASCE, American Society of Civil Engineers
ASDSO, Association of State Dam Safety Officials
ASTM, ASTM International
BIA, Bureau of Indian Affairs
CD-ROM, compact disc—read only memory
DOS, disc operating system
DVD, digital versatile disc
EAP, emergency action plan
EOS, equivalent opening size
FEMA, Federal Emergency Management Agency
FERC, Federal Energy Regulatory Commission
FHWA, Federal Highway Administration
GSI, Geosynthetics Institute
HDPE, high density polyethylene
ICODS, Interagency Committee on Dam Safety
ICOLD, International Commission on Large Dams
IGS, International Geosynthetics Society
NRCS, Natural Resources Conservation Service
O&M, operation and maintenance
OSHA, Occupational Safety and Health Administration
PDF, portable document format
P.E., professional engineer
PE, polyethylene
PI, plasticity index
POA, percent open area
PVC, polyvinyl chloride
Reclamation, Bureau of Reclamation
ROF, report of findings
USACE, U.S. Army Corps of Engineers
UV, ultraviolet

Conversion Factors
To the International System of Units (SI) (Metric)

Pound-foot measurements in this document can be converted to SI measurements by multiplying by the following factors:

Multiply	By	To obtain
acre-feet	1233.489000	cubic meters
cubic feet	0.028317	cubic meters
cubic feet per second	0.028317	cubic meters per second
cubic yards	0.764555	cubic meters
degrees Celsius (˚C)	1.8*(˚C+32)	degrees Fahrenheit (˚F)
degrees Fahrenheit	(˚F-32)/1.8	degrees Celsius
feet	0.304800	meters
gallons	0.003785	cubic meters
gallons	3.785412	liters
gallons per minute	0.000063	cubic meters per second
gallons per minute	0.063090	liters per second
inches	2.540000	centimeters
mils	0.025400	millimeters
pounds	0.453592	kilograms
pounds per cubic foot	16.018460	kilograms per cubic meter
pounds per square foot	4.882428	kilograms per square meter
pounds per square inch force	6.894757	kilopascals
pounds per square inch force	6894.757000	pascals

Websites

The following websites can provide additional information and publications related to geotextiles and embankment dams:

American Society of Civil Engineers: www.asce.org
Association of State Dam Safety Officials: www.damsafety.org
Bureau of Reclamation: www.usbr.gov
Bureau of Reclamation publications: www.usbr.gov/pmts/hydraulics_lab/pubs/index.cfm
Canadian Dam Association: www.cda.ca
Federal Emergency Management Agency: www.fema.gov
Geosynthetics Institute: www.geosynthetic-institute.org
Geosynthetica: www.geosynthetica.net
Industrial Fabrics Association International: www.ifai.com
International Commission on Large Dams: www.icold-cigb.net
International Geosynthetics Society: www.geosyntheticssociety.org
National Performance of Dams Program: www.npdp.stanford.edu/front.html
Natural Resources conservation Service: www.nrcs.usda.gov/technical/eng
Natural Resources conservation Service Publications: www.info.usda.gov/ced
U.S. Army Corps of Engineers: www.usace.army.mil
U.S. Army Corps of Engineers Publications: www.usace.army.mil/inet/usace-docs/eng-manuals
United States Society on Dams: www.ussdams.org

Introduction

Geotextiles are widely used in various engineering projects to perform one or more of their recognized functions. The principal functions of geotextiles are filtration, drainage, separation, reinforcement protection, and erosion control. The use of geotextiles in embankment dams has been in limited applications, largely in secondary roles where failure of the geotextile would not jeopardize the safety of the dam nor present a situation that would be difficult or costly to repair. The most common uses of geotextiles in embankment dams in the Unites States are:

- As a separator/filter between embankment material and a layer of riprap placed on the upstream slope or in a downstream discharge area.

- As a filter zone between riprap used to line watercourses and the underlying foundation soils.

- As a filter in a downstream trench drain where the coarse drainage layer does not meet filter requirements for the foundations soils.

Less common embankment dam applications are as a protective layer and drain placed in contact with an upstream waterproofing geomembrane, as an internal filter, and as an internal drain. Such applications are limited in number. Applications as internal filters and drains are considered to be outside the accepted standards for engineering practice in the United States.

This report reviews the status of the use of geotextiles in embankment dams. Geotextiles are a part of a broader group of engineering materials known as geosynthetics. Geosynthetics covers a variety of man-made materials including geotextiles, geomembranes, geonets, geogrids, etc., which are finding their way into embankment dam applications. This report includes information about the policy of geotextile use in the United States, it reviews geotextiles against the larger backdrop of geosynthetic materials, discusses functional applications of geotextiles in embankment dams, reviews potential performance problems and causes, current design procedures, and construction practices.

Geotextiles have been used as the sole method of providing filtration and drainage for some dam embankments constructed in France, Germany, and other foreign countries. Such applications are controversial, and are considered to be outside of accepted standards of engineering practice in the United States (Talbot, et al., 2000).

Although geotextile manufacture is a mature technology, current policy in the United States is that geotextiles are not an accepted component in a design where failure of the geotextile could lead to failure of the dam. They also **are not to be used** where the geotextile is not easily accessed for inspection and repair should it be needed because this could impose a significant economic barrier to achieving a timely repair.

The design and construction of geotextile elements for embankment dams are discussed in this report; however; this is not a design manual and should not be used as such. The Design Classification scheme in the table below is envisioned as a key element in a design process laid out at a conceptual level in this report. The table is intended to assist the designer in understanding the nature of a proposed geotextile application with respect to redundancy, access, and critical functionality of the application.

Classification of geotextiles in embankments by access and redundancy.

Design Classification	Access and Redundancy*	Critical or Non Critical **
A-critical or A-noncritical	Geotextile performs a function in internal locations in an embankment with limited or no access, once installed. There is no redundant natural design element present.	Likely to be a critical design element.
B-critical or B-noncritical	Geotextile performs a function in internal locations in an embankment with limited or no access, once installed. There is a redundant natural design element present.	Unlikely to be a critical design element.
C-critical or C-noncritical	Geotextile is installed in locations where it can be accessed without excessive cost and effort. There is no redundant natural design element present.	May or may not be a critical design element.
D-critical or D-noncritical	Geotextile is installed in locations where it can be accessed without excessive cost and effort. There is a redundant natural design element present.	Unlikely to be a critical design element.

*In filtration and drainage applications, redundancy may be difficult or impossible to achieve. The consequences of clogging of the geotextile, and of piping of fines through the geotextile need to be considered to determine if a redundant system is provided.
** Is failure of the dam possible given poor performance of the geotextile? Each dam is unique and, therefore, the critical nature of the application must be evaluated on a case by case basis.

Expansion of the roles geotextiles perform in dams as internal filters and drains would involve placing them materially deeper within the dam section exposing them to greater stresses and higher seepage gradients than those encountered in most other engineering applications. Geotextile design in the United States has not been tailored to the particular challenges posed by burial deep inside of a dam. There, it would no longer be practical to physically inspect key areas of the buried product, nor remove and replace it. For such an expansion of use to be realized it must be shown that geotextiles can be installed without damage, can endure the stresses of their environment, and will reliably perform their intended filtration and drainage functions for the design life of the dam. Designers are cautioned to consider the potential problems associated with using a geotextile as a critical design element in a non-redundant manner in a dam. It is the policy of the National Dam Safety Review Board that geotextiles should not be used in locations that are critical to safety and inaccessible for replacement.

A rational decision method that can help to determine if geotextiles are suitable could include the following steps:

- Assess the downstream hazard classification in the event of a dam failure including the likelihood for a change in that classification in the future.

- Identify the minimum design life and performance level expected of the dam.

- Select the materials, embankment cross-section, and construction control to achieve the expected level of safety and serviceability for the dam.

- Perform economic analyses to evaluate whether cost savings strongly favor a design employing geotextiles over more conventional dam building materials.

- Assign a Design Classification for the proposed geotextile application. Perform the design analysis and if suitable, select geotextiles meeting the design criteria.

- Identify all potential failure modes that the design element is proposed to protect against.

- Conduct failure mode analyses to predict the likely impact on the integrity of the dam for realistic variances in the performance of geotextiles.

- Revise the design to achieve the desired level of performance, geotextiles may not always be retained as being suitable to the design.

A rational design approach should be developed for geotextiles that focuses specifically on dams. While many federal and state agencies expressly restrict the use of geotextiles in dams, a fraction of the design review staffs of those same agencies have accepted designs that appear to be in conflict with existing policy. In some cases the policy is not clearly written and in others it is not written at all. Agencies should make efforts to clarify and communicate their policy about geotextile applications within embankment dams.

The principal driver for expanding the use of geotextiles in dams is the potential cost savings over conventional construction practices with granular materials. Government agencies and private concerns are struggling with the financial burden of managing portfolios of aging dams with deficiencies. A major cost in the retrofitting of such dams is providing processed construction material at remote project sites. Aggregate sources in the Unites States are becoming more limited in availability. Often the cost of producing the aggregate for a conventional drain or filter zone is dwarfed by the cost of transporting that material from the point of production to the job site. Readily transportable geotextiles offer the potential to replace whole layers of multi-staged filters and thereby materially reduce costs. However, the potential cost savings can not be allowed to compromise the safety and reliability of a dam. At present, the long term reliability of geotextiles used for internal filtration and drainage remains as a technology whose reliability has not been sufficiently demonstrated.

Geotextiles are not a panacea. They have their limitations which must be considered in design. There are a number of perceived material behaviors that practitioners in the dam engineering community expect in construction materials. One key element is a self-healing capacity that a multi-staged chimney drain of processed aggregate will survive displacements associated with construction and service loads for centuries without compromising its ability to perform its intended function. Geotextiles do not inspire such confidence. They come from the factory in rolls some 12-to 15-feet wide and in thicknesses measured in thousandths of a foot rather than feet. In the short term it is easy to imagine them failing as the result of excessive clogging, puncturing, rodent damage, inadequate hydraulic capacity, poor construction practices, or inadequate inspection. In the long term their strength, deformation and hydraulic properties are necessarily "predicted" based on accelerated aging testing that has been validated from samples with at most a few decades of service.

If money were no object engineers would naturally opt for the conventional solution. Embracing geotextiles can speed up the pace of addressing deficient dams and the clear threat they pose until remediated. To do that responsibly, the strengths and weaknesses of geotextiles must be recognized and designs prepared accordingly. Where geotextiles have gaping vulnerabilities, those vulnerabilities need to be identified so that the geotextile manufacturing industry and geosynthetic engineers can focus on addressing them. Finally, there are some applications where geotextiles can not demonstrate an ability to perform satisfactorily. In those instances the engineer has to acknowledge those limitations and choose another material to accomplish the desired function.

Chapter 1

Current Policy on the Use of Geotextiles in Embankment Dams

Some geotextile applications such as a protective cushion for a geomembrane, or as a separator/filter beneath riprap are well accepted in the U.S. dam engineering community. Other geotextile applications such as internal filtration, drainage, or as a crack stopper, are controversial and considered to be outside standard engineering practice in the United States for embankment dams. There is a continuing interest in expanding the use of geotextiles in U.S. dam construction and rehabilitation because of the significant cost savings potential; however; economic concerns can not be allowed to compromise dam safety. The reliability of geotextiles as internal filters or drains in a dam embankment has not been sufficiently established.

It is the policy of the National Dam Safety Review Board that geotextiles should not be used in locations that are critical to the safety of the dam.

1.1 Overview

Current policy in the U.S. federal sector, and some state regulatory agencies and among many private consultants, prohibits the use of geotextiles for stand alone applications and or in deeply buried locations in an embankment dam where poor performance could jeopardize the safety of the dam or require costly repairs to the dam.

Despite these objections, some states have no restrictions regarding the use of geotextiles in dams. Also, geotextiles have been employed worldwide in stand alone applications deep within embankment dams with good results so far and the projects have enjoyed significant cost savings by their use. The use of geotextiles for embankment filtration and drainage is mainly evident in France, Germany, China, and South Africa. A common factor in foreign practice regarding the use of geotextiles as filters and drains is the requirement that design must include large-scale hydraulic laboratory testing to evaluate filtration and permeability performance using the proposed geotextile materials and actual soils from the project site. The employment of a significant laboratory effort to evaluate filter and drain performance using site specific soils and simulated stress and flow conditions overcomes much of the uncertainty over how the proposed soil and geosynthetic system will behave. Such testing is also capable of revealing situations where geotextile performance will not be satisfactory and should not be used.

The following objections to the use of geotextiles for filtration and drainage have been put forth by the dam engineering community in the United States (ASDSO, 2003):

- A geotextile fabric will clog when water containing soil in suspension enters the filter face.
- Sand filters support the soil discharge face and prevent movement of fines that would clog the filter, geotextile fabrics do not support the soil discharge face as a granular filter does. Fabric needs to have intimate contact with the soil discharge face with distance between contact points similar to a granular filter, or soil particle movement will occur clogging the fabric. Coarse granular fill does not provide uniform pressure with close contact points as does a sand filter.
- When used inside the dam, fabrics will have very large soil pressures on both sides of the fabric that will hold it firmly in place with no chance to distribute stresses that are produced by differential movement within the soil mass along the plane of the fabric. When a crack occurs in the dam, it may tear the fabric in the plane of the crack.
- Geotextiles are easily damaged from equipment passing over the material, from protrusions in the underlying material, or from moving sheets of the fabric over a rough surface. Damage may not always be detected.
- Structural integrity of the dam is dependent on complete continuity of the filter drainage zone and when constructed with a fabric, it must be without holes, tears, or defects.
- Self healing characteristics of granular filters are not inherent in geotextile materials.

1.2 Federal Sector

A large number of Federal agencies are responsible for the operation, maintenance, and safety of dams which have been established upon public lands within the United States. The agencies include the Bureau of Reclamation, Bureau of Indian Affairs, Bureau of Land Management, Fish and Wildlife Service, National Park Service, Corps of Engineers, and Natural Resources Conservation Service. In addition, there are Federal agencies which have a regulatory role with respect to dam safety for facilities that are privately owned and operated. These regulatory agencies include the Corps of Engineers, Federal Energy Regulatory Commission, Office of Surface Mining, and Mine Safety and Health Administration. The policies of a few of these Federal agencies were investigated for this study as follows:

1.2.1 Bureau of Reclamation

The Bureau of Reclamation (Reclamation) has constructed more than 600 dams and reservoirs in 17 western states. The current agency policy is that geotextiles can be used in embankment dams, but not as a sole element in a critical application. For critical applications there must be a redundant system that will protect the dam should the geotextile fail to perform its design function.

The use of geotextiles in embankment dams is established by a written Design Standard (Bureau of Reclamation, 1992). The document states "If a geotextile is to be placed within an embankment where future access is extremely difficult, a backup system should be included in the design similar to conventional design methods without a geotextile. Thus if the geotextile failed to perform, the backup system would maintain the integrity of the dam while a permanent solution is sought."

1.2.2 Corps of Engineers

The Corps of Engineers began experimenting with use of geotextiles as filters below erosion control materials in conjunction with Bob Barrett of Carthage Mills in the late 1950's. By the 1970's, plastic filter cloth was being used extensively for erosion control applications. In some cases, problems were encountered which resulted in restrictions on use of these products. The current policy that has resulted from over 40 years of experience is summarized in Table 1

Table 1.1.—Corps of Engineers Policy Documents Related to Use of Geotextiles in Dams

Year	Reference	Title	Notes
1984	ETL 1110-2-286	Use of Geotextiles Under Riprap	Lessons learned from Tennessee-Tombigbee Waterway.
1986	EM 1110-2-1901	Seepage Analysis & Control for Dams, Appendix D - Filter Design	Use in inaccessible areas must be considered carefully. Fabrics should not be used as filters on upstream face or within embankment.
1992	EM 1110-2-1914	Relief Wells	Well filters should consist of

			natural material (i.e. Not geotextiles).
1992	ETL 1110-2-334	Grouted Riprap	Geotextiles are included as needed. Filters can consist of uniformly graded granular material with underlying geotextile. Never mentions dams.
1995	TM 5-818 (UFC 3-220-08FA)	Engineering Use of Geotextiles	Where duration is critical to life safety and where the geotextile is inaccessible, (e.g. earth dams), current practice is to use only geologic materials. Geotextiles should not be used on the upstream face of earth dams or within any inaccessible portion of the dam embankment. Geotextiles have been used in toe drains of dams. Caution advised for wrapping piezometers and relief wells.
1996	EP 1110-2-13	Dam Safety Preparedness	Definitions include geotextile filters, but never mentioned elsewhere.
2003	EM 1110-2-1902	Slope Stability	Casual mention of geotextile reinforcement.
2004	EM 1110-2-2300	General Considerations for Dams	Geotextiles should not be used in conjunction with relief wells. Geotextiles (filter fabrics) should not be used in or on embankment dams. Includes paragraph on geotextile use for embankment reinforcement. Geotextiles (filter fabrics) should not be used beneath riprap on embankment dams.
2004	EC 1110-2-6061	Safety of Dams - Policy & Procedures	Definitions include geotextile filters, but never mentioned elsewhere.

Although experience with geotextiles has been largely positive, the current policy includes restriction on use of geotextiles in critical applications. This has resulted in large part to experiences resulting from failures attributed to clogging and resulting loss of drainage efficiency. Publication ETL 1110-2-286 documents problems of clogging, tearing and puncturing experienced on the Tennessee – Tombigbee Waterway, where over 4 million square yards of geotextile were placed (primarily as a filter below riprap). Causeways along the Gulf of Mexico coast have experienced miles of armor failure by sliding that has been attributed to clogging (blinding) and pressure buildup beneath the geotextile from wave action. Many smaller applications have experienced loss of drainage efficiency in toe drain applications. Restrictions on use of geotextiles in dams are included in several criteria documents as noted in Table 1; but the restrictions are most specifically stated in TM 5-818, which includes the following quotes:

> Durability: "Where long duration integrity of the material is critical to life safety and where the in-place material cannot easily be periodically inspected or easily replaced if it should become degraded (for example filtration and/or drainage functions with an earth dam), current practice is to use only geologic materials (which are orders of magnitude more resistant to these weathering effects than polymers)."
>
> Filtration: "Since long-term experience is limited, geotextiles should not be used as a substitute for granular filters within or on the upstream face of earth dams or within any inaccessible portion of the dam embankment. Geotextiles have been used in toe drains of embankments where they are easily accessible if maintenance is required and where malfunction can be detected."

Table 1 does not include guidance which has been withdrawn, such as Engineer Technical Letter 1110-1-20, "Use of Filter Cloth around Subdrains", 1969. There are numerous research reports that have been published by the Corps of Engineers concerning use and applications of geotextiles that have not been summarized in Table 1. Some of these have been significant, such as:

- Technical Report S-72-7, "Development of Design Criteria and Acceptance Specifications for Plastic Filter Cloth", 1972.
- Technical Report HL-80-12, "Filter Fabric for Streambank Protection", 1980

There are also guide specifications that include use of geotextiles. The Corps guide specification CW02215 "Geotextiles used as Filters" was published in 1977. This has presently evolved into UFGS 02378. Current Unified Facilities Guide Specifications that include geotextiles as a major component of the section include:

UFGS 02332 Reinforced Soil Slopes
UFGS 02373 Geotextile
UFGS 02378 Geotextile Filters

UFGS 02380 Riprap
UFGS 02382 ACB Revetments
UFGS 02832 Segmental Concrete Retaining Walls

1.2.3 National Resource Conservation Service

The NRCS has an unwritten policy on the use of geosynthetics in dams at the present time. The policy does not permit the use of geosynthetics as an internal design component of a dam particularly as a filtering/drainage function. Geotextiles have been used extensively as a separator function placed between rock riprap and soil in rock-lined plunge pool basins and outlet channels downstream of concrete stilling basins. Geotextiles have also been permitted beneath riprap on the upstream slope of dams for wave protection. The use of geosynthetics for other functional purposes in dams requires agency review by National technical staff because its use is deemed to be a variance to design policy.

1.2.4 Federal Energy Regulatory Commission (FERC)

FERC's policy does not allow the use of geotextiles in inaccessible areas of embankment dams or their foundation. Geotextiles are not accepted in lieu of sands and gravels as bedding for riprap. Geotextiles have been permitted in drain trenches that are accessible if repairs are needed. If plugging of the drain filter occurs, the drain has to be replaced.

1.3 Private Sector

There is a diversity of opinion among private consulting engineering companies in the United States regarding the use of geotextiles as filters and drains. While views vary there is a majority position. The consensus among most design firms is that geotextiles should not be used for critical applications such as filtration and drainage where their failure could affect the integrity of the dam. A principal reason why these consultants will not use geotextiles for filtration and drainage is the liability that they would assume in their use. Geotextile filters and drains in dams are not considered to be a part of accepted engineering practice in the Unites States.

1.4 State Sector

A wide variation in policy is found at the State level. A questionnaire was submitted in 2006 to the regulatory agencies within the United States who are responsible for dam safety. The survey form and the results of the survey are provided as follows:

STATE SURVEY QUESTIONAIRE

NAME OF STATE PROGRAM: **40 Total Respondents**

JOB TITLE: ____

1. Does your state dam safety program have regulations that restrict or prohibit the use of geo-synthetics (specifically, geofabrics or geotextiles) in the design or construction of earthen embankment dams?
YES **4**
NO **36**

2. Has your state dam safety program implemented standards or guidelines that prescribe the use(s) of geo-synthetics in the design or construction of earthen embankment dams?
YES **8**
NO **32**

3. Within the past 5 years, have you or your state dam safety program approved design plans and specifications for construction or rehabilitation of an earthen embankment dam that incorporated the use of geo-synthetics as the *primary* mechanism for internal drainage (filter)?
YES **13**
NO **27**

4. Within the past 5 years, have you or your dam safety program approved design plans and specifications for construction or rehabilitation of an earthen embankment dam incorporating geo-synthetics as a *secondary or auxiliary* mechanism for internal drainage (filter)?
YES **25**
NO **15**

5. Do you have personal reservations against using geo-synthetics in the design or construction of earthen embankment dams?
YES **14** **Of those respondents indicating 'Yes', eight were**
NO **26** **were accompanied by some sort of written qualification explaining their answer**

If yes, please rate numerically 1-to-5 from the following list those factors that most influenced your opinion (1 = greatest):

- Lack of personal experience
- Too few examples of successful projects
- Insufficient technical support from the geo-synthetics industry
- Bad experience/ poor performance or failure
- Absence of engineering guidelines, specifications or standards

Based on the last question of the survey, the chart presented in figure 1.1 summarizes the response of those States' dam safety program representatives who indicated a reluctance to use geosynthetic materials in earthen embankment dams. Five (5) possible choices were available to the respondents. Please note that some respondents did not address all five choices. Each respondent was instructed to rank their selections in order of importance using the following criteria:

1) Primary reason not to use geosynthetics in earthen dams
2) :
3) :
4) :
5) Least reason not to use geosynthetics in earthen dams

As can be seen, the primary concern was very nearly evenly divided between all five choices available. That is, of the 14 respondents who expressed reservations against using geosynthetics in the design and construction of earthen dams, three listed as the *primary reason* for their reluctance the Lack of Personal Experience, three chose Too Few Examples of Successful Projects, three picked Insufficient Technical Support From the Geosynthetics Industry, and so on down the list.

However, the pattern did not follow as the priority decreased. For example, far more individuals expressed Poor Performance/Bad Experience as the *least reason* for not using geosynthetics as compared with the other four choices available.

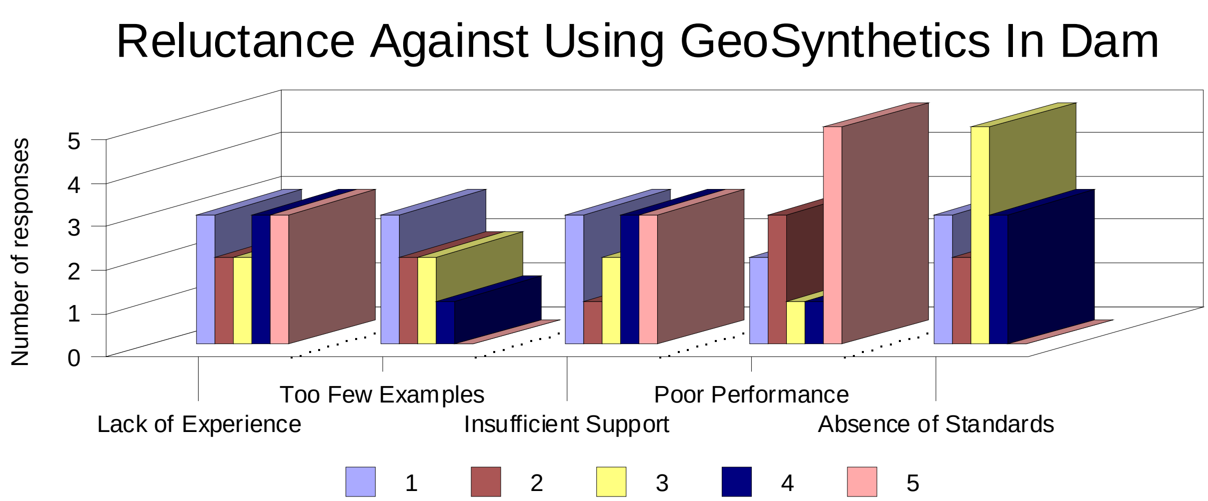


Figure 1.1.—Reluctance against using geosynthetics in dams

Chapter 2

Overview of Geosynthetics for Use in Embankment Dams

Geosynthetics have been used in dam construction and rehabilitation worldwide for well over 45 years and are currently being used at an ever increasing rate in a variety of functional applications in all types of dams including rock-fill, RCC, concrete gravity and embankment dam construction. Geosynthetics are not new to the dam construction and rehabilitation industry and in fact are considered a reliable and durable civil engineering material with proven performance in many exposed and buried applications. Geosynthetics are used in dam construction and rehabilitation, where they can be accessed if necessary, not only because they may be the only practicable choice for a specific application but also because they provide a viable and durable economic alternative to other types of conventional civil engineering materials. Since the first application of a geosynthetic in a dam in 1959 (Contrada Sabetta, Italy), geosynthetics have been installed on or in hundreds of dams worldwide.

Geosynthetics includes a myriad of materials used in civil engineering and geotechnical engineering (fig. 2.1). In fact, "geosynthetics engineering" is an accepted engineering discipline with BS, MS and PHD degrees offered in this fast growing and dynamic geotechnical related field. So, what is a geosynthetic? According to ASTM (2005), a geosynthetic is "a planar product manufactured from polymeric material used with soil, rock, earth or other geotechnical engineering related material as an integral part of a man-made project, structure, or system". Thus the term cross references "geo" (earth related) and "synthetic" (man made).

Geosynthetics include a wide variety of flexible, polymeric materials commonly referred to by generic names such as geomembranes, geotextiles, geonets, geonet composites, geomats, geocells, geogrids, geosynthetic clay liners, geocomposites, and geopipe. Geosynthetics can also include discrete elements such as polymeric fibers or yarns, which are mixed with soil for soil improvement. Geosynthetics can also be made from materials that are not synthetic polymers but rather biodegradable fibers and fabrics such as jute. Geosynthetics can also be made from a combination of polymeric or synthetic sheet or fiber and natural material (i.e. erosion control products and geosynthetic clay liners). In any case, the term "geosynthetic" is the generic name for all man-made polymeric and/or polymeric/natural combinations used in geotechnical engineering applications. The following are brief overviews of the most prominent types of geosynthetics. Details of each type can be found in publications such as Dr. Robert M. Koerner's book entitled "Designing with Geosynthetics" (2005a).

2.1 Functions of geosynthetics in dams

The functions of geosynthetics in dams are not unlike the functions of geosynthetics in all other civil/geotechnical engineering applications. The functions for geosynthetics are filtration, separation, planar drainage (transmission), reinforcement, fluid (liquid or gas) barrier, protection, and surface erosion control. All of these functions have been used in dam construction and rehabilitation. The International Geosynthetics Society (IGS) recognizes an eighth function called containment (for soil and sediments) but this is not used in dam construction. Table 2.1 illustrates the functions that will be discussed further in this section as well as examples of geosynthetics that are typically used to satisfy each function in design.

Table 2.1.—Geosynthetic Functions in Dams

Function of Geosynthetic	Typical Geosynthetics Used
Filtration of Soils Particles	Geotextile Nonwoven Geotextile Woven Geotextile Knitted (2 stage only)
Separation of Dissimilar Materials	Geotextile Nonwoven Geotextile Woven Geocomposite
Planar Drainage	Geotextile Nonwoven Geonet Geocomposite Geomat Structured Geomembrane (drain)
Reinforcement	Geotextile Nonwoven Geotextile Woven Geogrid Geocomposite
Fluid Barrier	Geomembrane GCL (limited) Geocomposite (with geomembrane)
Protection	Geotextile Nonwoven Geocomposite
Surface Erosion Control	Erosion Control Geocomposites Geocells Geomat

2.1.1 Filtration function (IGS symbol F)

A geotextile will perform a filtration function if it allows liquid (water) to pass while controlling the soil or particulate migration through the geotextile. The geotextile, therefore must be located between the soil being retained and the open drain material, perforated pipe or drainage geosynthetic (i.e. geonet). Typically, nonwoven needlepunched geotextiles are used. However, woven monofilament geotextiles have performed well and knit geotextiles have been used around perforated pipes as a two stage filter in combination with a primary sand filter layer.

2.1.2 Separation function (IGS symbol S)

A geotextile will perform a separation function if the geotextile is located between two dissimilar soils or between a soil and a man-made material and if the geotextile prevents mixing of the two dissimilar materials (i.e. a fine grain soil and a coarse soil) during mechanical agitation (i.e. pumping as in a road base). All types of geotextiles and composites (i.e. woven and nonwoven geotextiles as well as composites) that have minimum strength requirements can perform this function. This function was one of the earliest geotextile functions as it was utilized in unpaved road construction over soft soils for USDA Forest Service access roads.

2.1.3 Planar drainage (transmission) function (IGS symbol D)

A geosynthetic that is thick and permeable in its plane will provide a planar conduit for fluid (or gas) flow. This function of planar flow is usually performed by a geosynthetic designed for planar flow such as a geonet, geonet composite, structured (drain) geomembrane, thick coarse fiber geotextile, geocomposite (geomat) or wick drain. It is important to note that a geotextile is often used as a filter prior to fluid entering a transmissive geosynthetic (i.e. wick drains and geonet composites)

2.1.4 Reinforcement function (IGS symbol R)

A geosynthetic that allows stress transfer from a soil or adjacent material to the geosynthetic provides structural reinforcement. Thus soil layers on slopes or within walls can be reinforced with geosynthetics specifically designed for taking stress. This will improve the stability of slopes or walls. Geogrids are products specifically designed for this function although woven and nonwoven geotextiles have been used where lower stress transfer is required.

2.1.5 Liquid barrier function (IGS symbol B)

A geosynthetic of very low permeability will provide an effective barrier to fluid migration from one area to another as in an upstream lining on the face of a dam. It should be noted that geomembranes are the only geosynthetic that can perform this function. GCL's, although exhibiting low permeability once hydrated, allow fluid migration.

2.1.6 Protection function (IGS symbol P)

A geosynthetic of usually heavy mass per unit area provides mechanical protection to a geomembrane. This function, although relatively simple is a very large application area and one that is underrated due to the importance of protecting the vital fluid barrier (geomembrane). Nonwoven, needlepunched geotextiles with mass per unit area greater than 10 oz/yd^2 (350 g/m^2)are commonly used. It is interesting to note that this geotextile may also perform the transmission or planar drainage function as well (i.e. downstream layer of a geomembrane on a dam face). Geocomposites of layered geotextiles that are over 30 oz/yd^2 (1000 g/m^2)or geonet composites are also used as protection.

2.1.7 Surface stabilization function (IGS symbol E)

One of the fastest growing segments of the geosynthetics industry is erosion control. The myriad products (many are geocomposites of some type) all provide stabilization of the immediate surface soil to prevent soil particle migration and mass movement due to water flow. These products are increasingly being used in dams, especially in spillways and downstream slope protection and overtopping protection of smaller embankments and levees. This function can in fact combine filtration, separation, reinforcement and sometimes barrier during performance in erosive environments. Geocell's and geomats are examples of materials used in this important function.

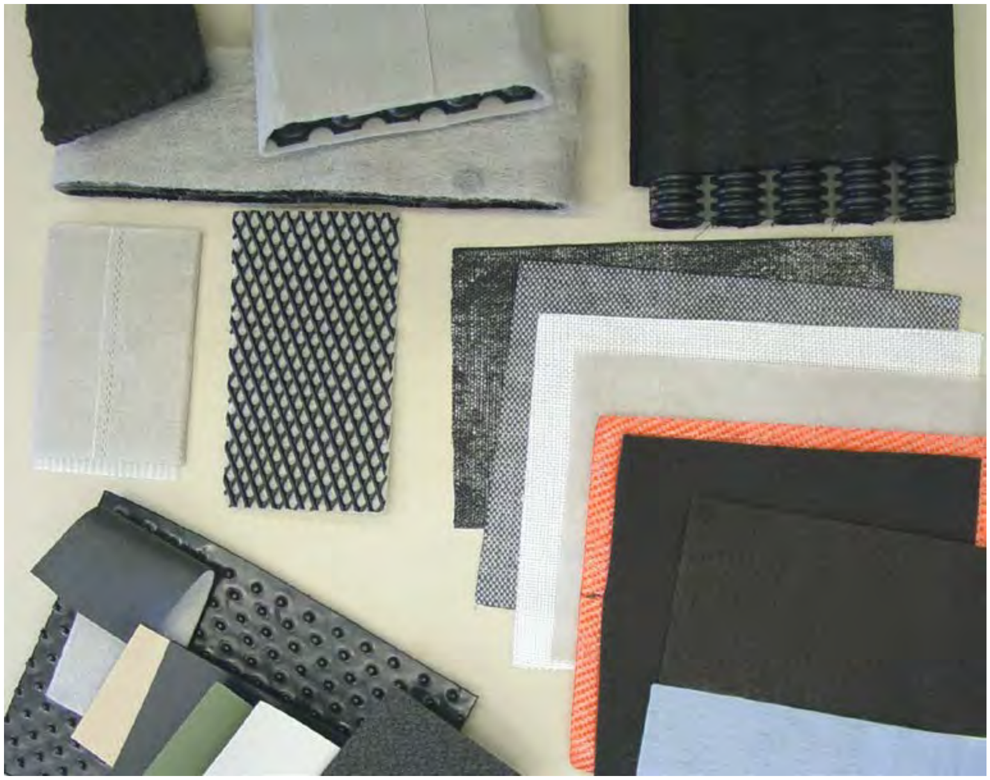


Figure 2.1.—Geosynthetic products are available in a wide range of chemical compositions, colors, and structures.

2.2 Geotextiles

Geotextiles are a "permeable geosynthetic comprised solely of textiles" (ASTM, 2005). Geotextiles perform a variety of geotechnical engineering functions and are used for a variety of both critical and noncritical applications in all aspects of Civil Engineering design on a large number of dams worldwide.

Geotextiles are a direct link to technical textiles or typical products of the textile industry. In fact the first geotextiles were textiles manufactured for purposes other than geotechnical applications. Woven textile use as a separator and filter date back to the 1950's in various shoreline erosion control applications and was originally pioneered by companies such as Carthage Mills. Barrett (1966) describes many applications using woven geotextiles in erosion control and as filter fabrics. Indeed, the term "filter fabric" is still in use today and actually shows up as a descriptive term in specifications.

The types of geotextiles that comply with the definition are the nonwoven, woven and knitted fabrics which again are typical fabrics of the textile industry today. Geotextiles, however, are manufactured in plants that are now devoted to the technical geotextile industry segment and thus are engineered for today's demanding applications in geotechnical engineering. Thus the term "geotextile" is not new but in fact describes the general functions of "fabrics" used to improve soils or soil conditions.

Geotextile polymers are predominantly polypropylene (PP) (95% at present), polyester (PET) and polyethylene (PE) with some geotextiles (nonwovens) using combinations of polymers. Nylon (polyamide) is used to a lesser extent.

Geotextile structures are comprised of the following:

2.2.1 Nonwoven geotextiles

Geotextiles formed with continuous or short fibers arranged in random directions and then bonded together into a planar structure (fig. 2.2) which can include the following:

- Nonwoven Mechanically Needlepunched
  - Continuous Filament Fiber
  - Staple Fiber (short fibers)

- Nonwoven Heat Set
  - Continuous Filament Fiber

2.2.2 Woven geotextiles

Geotextiles composed of two sets of parallel yarns or tapes systematically interlaced to form a planar structure (fig. 2.3) which can include the following:

- Multifilament woven

- Monofilament woven

- Slit Film woven

- Fibrillated woven

2.2.3 Knitted geotextiles

Geotextiles formed by interlocking a series of loops of one or more yarns to form a planar structure. Knitted geotextiles are a subset to woven geotextiles and are found mostly as filters on pipes as in two stage filter applications.

Multilayer Geotextiles are formed by bonding together several layers of fabrics which can be layers of nonwovens or layers of wovens and nonwovens to form a geotextile that could be a high strength filter geotextile or a high loft (thick) protection geotextile.

Geotextiles are the subject of this report and are discussed in more detail in Section 2.10.

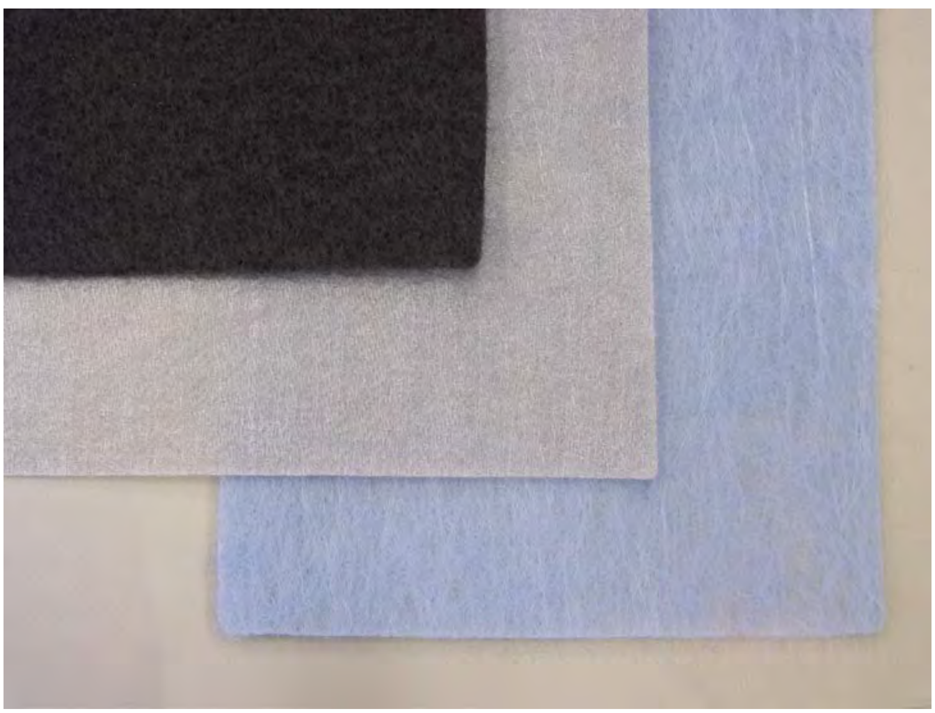


Figure 2.2.—Photograph showing examples of nonwoven geotextiles.

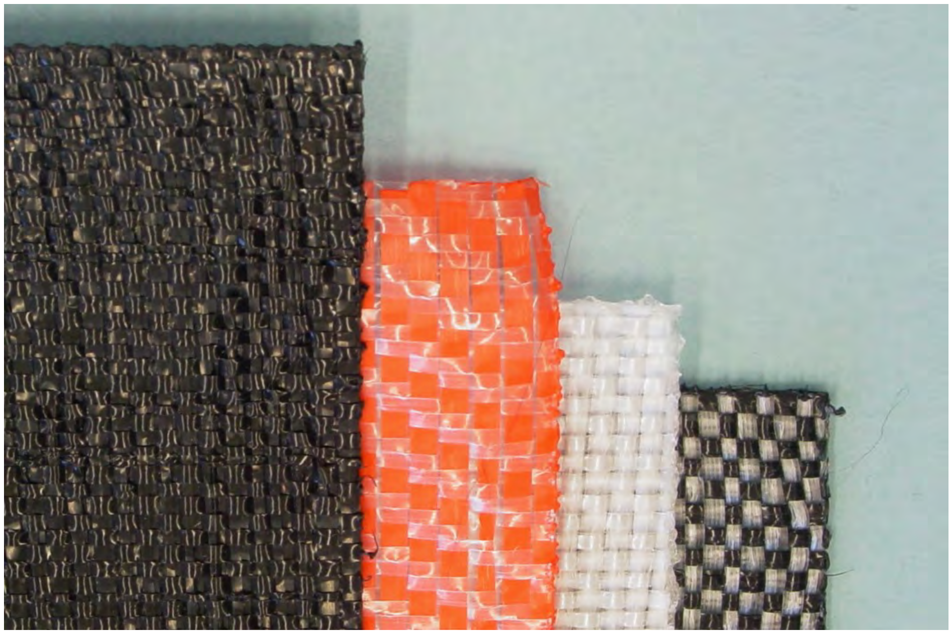


Figure 2.3.—Photograph showing examples of woven geotextiles.

2.3 Geomembranes

Geomembranes (figs. 2.4 and 2.5) by definition are "an essentially impermeable geosynthetic composed of one or more synthetic sheets" ASTM (2005). Thus, these materials are made up of a "membrane" which generally denotes something thin and flexible and which is used primarily for the purposes of waterproofing or liquid containment. Geomembranes were the first geosynthetic with applications (other than dams) dating back to the 1940's in canal and small reservoir containments. The earlier (now deprecated) terminology refers to Flexible Membrane Liners (FML's), pond liners, synthetic liners or simply plastic liners. In any event, the primary use was in waterproofing of a structure or containment of liquids. As nothing is impermeable, geomembranes are commonly referred to as "very low permeability" synthetic membranes. In comparison to a low permeability soil (10E-7 cm/s hydraulic conductivity), a geomembrane's calculated hydraulic conductivity will range from 10E-10 to 10E-14 cm/s. Geomembranes are manufactured in sheet form from synthetic polymers which range in thickness from less than 30 to 120 mils (1.0 mm to over 3.0 mm). Examples of polymers common to today's geomembranes are as follows:

- High Density Polyethylene (HDPE)
- Linear Low Density Polyethylene (LDPE)
- Polyvinyl Chloride (PVC)

- Ethylene-Propylene Diene Monomer (EPDM)
- Ethylene Interpolymer Allowy (EIA)
- Chlorosulfonated Polyethylene (CSPE)
- Flexible Polypropylene (fPP)

In addition to traditional polymeric geomembranes, there are also bituminous geomembranes that are manufactured in a plant by impregnating or coating a fabric with bitumen or a polymer/bitumen blend. These are referred to as Prefabricated Bituminous Geomembranes (PBGM).

All of the above have or are being used as a waterproofing element in dam construction which is the largest functional use of geosynthetics in dam construction and rehabilitation. As mentioned previously, the first use of a geosynthetic in dam construction was on the Contrada Sabetta Dam in Italy in 1959 and the use was as a waterproofing element on the upstream face which is still in operation today after over 45 years of service (Cazzuffi, 1987).

In addition to the base polymer for which the geomembrane is named, all geomembranes contain additives which perform myriad functions. The additives range from simple carbon black (for UV protection) to complicated antioxidant packages used to reduce the effects of oxidation on aging.

Figure 2.4.—Photograph showing examples of non-textured geomembranes.

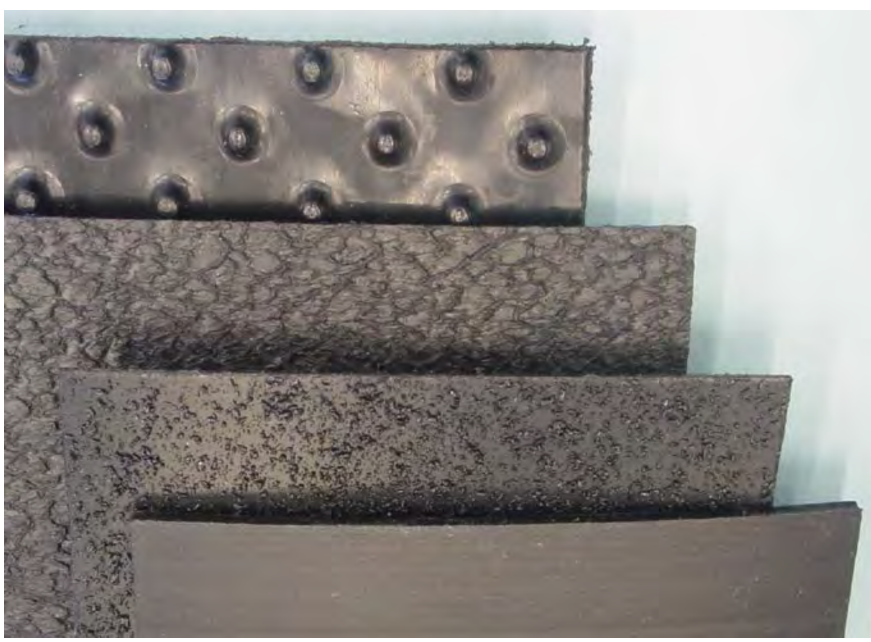


Figure 2.5.—Photograph showing varying degrees of texture in geomembranes.

Other additives are used for processing (processing aides) while some are fillers (inert particles such as clay) to decrease cost or improve production. One common example of an additive is plasticizers which provide the flexibility in PVC (commonly referred to as PVC-soft). Additives range in polymer compound proportion from less than 2% to over 40% depending on the base product. Most manufacturers will supply the basic compounding ingredients if requested.

Some geomembranes are reinforced with a fabric internal to the sheet which results in a three layer composite (two layers of polymer sheet with a middle layer of fabric or scrim) that is highly resistant to tearing, tensile stress and puncture. Geomembranes of base material such as CSPE (commonly referred to as Hypalon), EIA and PBGM are always reinforced whereas fPP, EPDM, and PVC are reinforced as an option for additional strength and dimensional stability depending on the application. Fabric reinforcement is commonly referred to as "scrim reinforcement" and is commonly a woven fabric of polyester or polypropylene. In addition to internal scrim or fabric reinforcement, polymer sheeting such as PVC are also reinforced with a layer of nonwoven geotextile thermally laminated to the sheet material (this is also referred to as a geocomposite and may have additional functional properties such as planar drainage). Polymer geomembranes that are reinforced are commonly referred to with an "R" in their abbreviations such as CSPE-R, PVC-R, EPDM-R, fPP-R.

In addition to geomembranes with scrim reinforcement, there are geomembranes with surface configurations that increase surface roughness (friction), provide an integral drain or provide protrusions for embedment in concrete or soil. These geomembranes are commonly manufactured with polyethylene polymers (HDPE, LLDPE) and are either produced by blown film extrusion or by extruded calendered profiles (structured geomembranes).

Manufacturing techniques generally consist of the following descriptive processes which are discussed in detail in Koerner (2005a):

- Blown Film Extrusion Process – HDPE, LLDPE, fPP in widths to 32.5 ft (10 m)
- Extruded Profile Calendared Process – HDPE, LLDPE in widths to 23 ft (7 m)
- Calendered Process – CSPE-R, fPP-R, PVC in widths to 10 ft (3 m)
- Spread Coating Process – EIA-R , PBGM

In addition to manufactured roll goods, all geomembranes produced from the calendared process in narrow widths (such as PVC and CSPE-R) are further fabricated in a fabrication plant into large panels. The geomembranes produced in wide rolls up to 32.5 feet (10 m) width such as HDPE are commonly transported directly to the construction site in roll sizes up to 15,000 ft^2 (1,400 m^2) for 1.0 mm thick sheet whereas the prefabricated panels produced from narrow roll goods must first be assembled, folded and rolled for transport to the construction site. Prefabricated panel sizes can be quite large dependent on weight and handling. Panel sizes are typically limited by weight (2,000 to 3,000 kg maximum) for shipping and handling, which equates to about 21,500 ft^2 (2,000 m^2) for a 40 mil (1.0 mm) thick sheet. Prefabricated panels can be designed specific for a site configuration and shape in order to minimize field seaming.

The site preparation, installation, field seaming and cover operations are the most critical for proper functioning of a geomembrane in waterproofing and containment applications. In this regard, the proper implementation of Construction Quality Control (CQC) and Construction Quality Assurance (CQA) is vitally important. The subjects of field seaming and CQC/CQA are abundantly covered in the literature (Koerner, 2005a), (Shukla and Yin, 2006).

2.4 Geogrids

Geogrids (fig. 2.6) have traditionally been one of the "geotextile related products" in that they have a coarser structure than conventional geotextiles. According to ASTM (2005), a geogrid is "a geosynthetic formed by a regular network of integrally connected elements with apertures greater than 6.35 mm to allow interlocking with surrounding soil, rock, earth and other surrounding materials to function primarily as reinforcement". Geogrids are polymeric materials that are a reinforcing grid-like structure sometimes associated with geotextiles (for filtration).

Polymers associated with geogrid manufacture are predominantly polyethylene (PE), polypropylene (PP) and polyethylene terephthalate (PET).

Figure 2.6.—Photograph showing examples of geogrids.

2.5 Geonets

Geonets (figs. 2.7 through 2.9) have also been called a "geotextile related product" in that they consist of coarse sets of parallel extruded strands or ribs that intersect at a constant angle (between 45 and 90 degrees) and are thermally bonded at the intersections. Geonets range in thickness from 5 to 9 mm. ASTM (2005) defines a geonet as "a geosynthetic consisting of integrally connected parallel sets of ribs overlying similar sets at various angles for planar drainage of liquids or gases." One, two or three sets of ribs create a network of channels which can convey fluids in their plane with minimal compression under load. Geonets are predominantly manufactured of HDPE. Geonets are also associated with geotextiles which are typically nonwoven and melt bonded to the geonet surface. Geotextiles associated with geonets are used as a filter and/or separator when interfacing with soils.

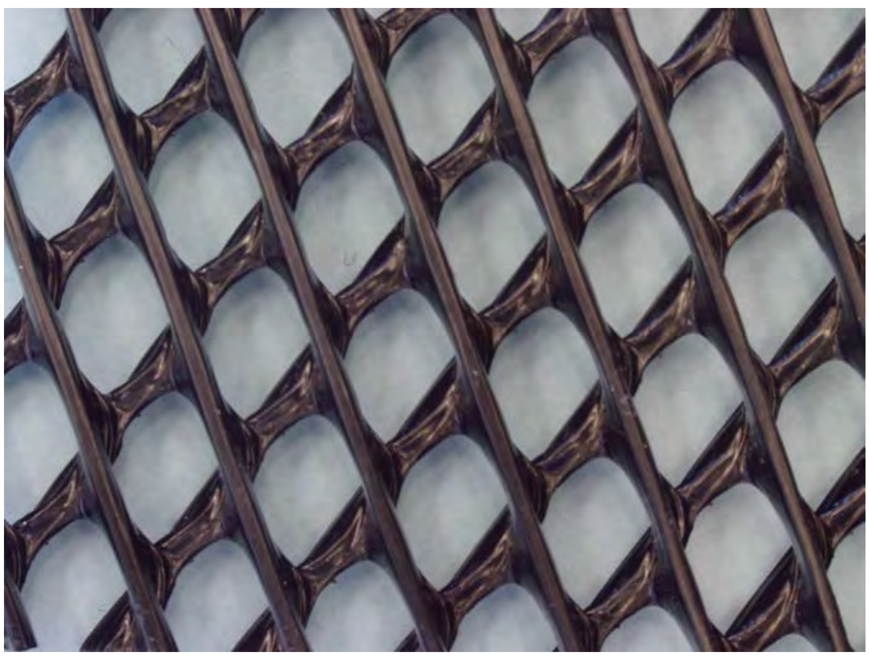


Figure 2.7.—Photograph of a bi-planar geonet. It is made from two layers of polymeric strands or ribs.

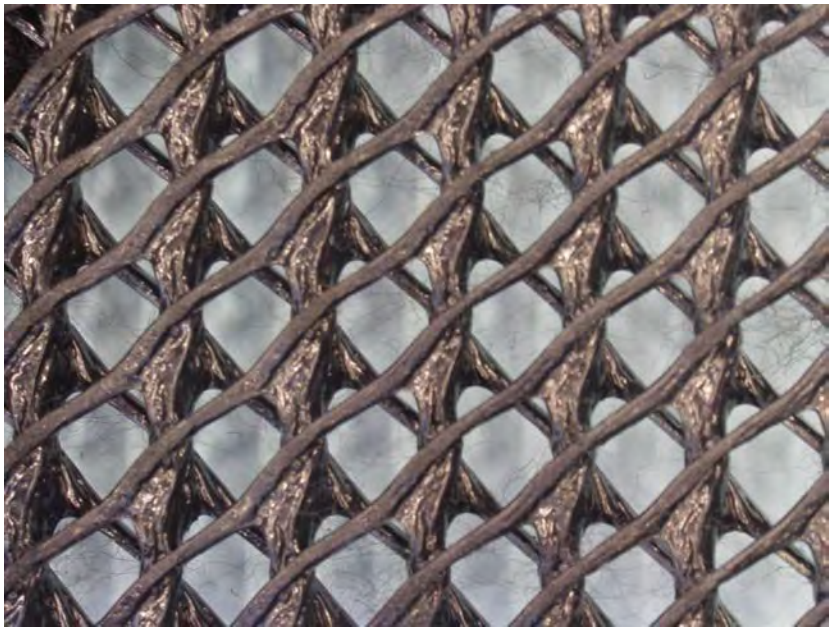


Figure 2.8.—Photograph of a tri-planar geonet. It is made by joining three layers of polymeric strands or ribs together at their intersections.

Figure 2.9.—Photograph of a single-sided bi-planar geocomposite geonet composite. It is made by bonding a geotextile to one side of a geonet.

2.6 Geocells

Geocells (fig. 2.10) are cellular confinement or "honeycomb" structures that are normally filled with soil or concrete to reinforce the soil or provide erosion resistant areas. Geocells are manufactured by joining polymeric strips at regular intervals. Strip widths are typically 3 to 8 inches (75 to 200 mm) and this width forms the depth of the three dimensional geocell when positioned and expanded or unfolded on site to form the honeycomb structure. The structure is anchored in place and filled with soil, gravel, or concrete depending on the application. Geocells are predominantly manufactured of HDPE strips ultrasonically bonded at discrete points in thicknesses of 40 to 48 mils (1 to 1.2 mm) although geotextile strips are also used.

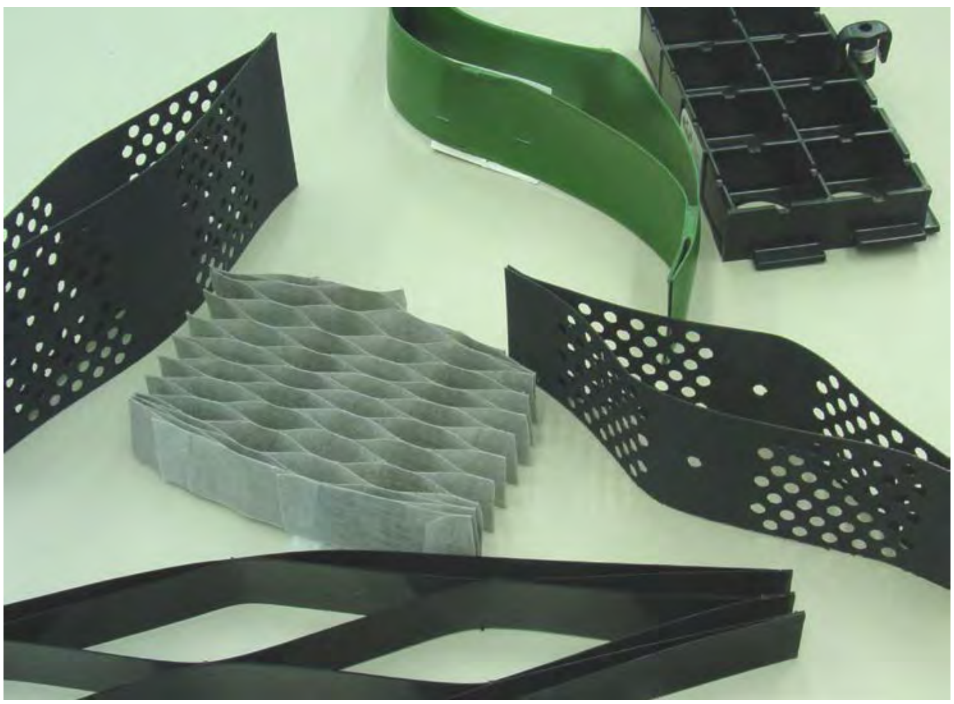


Figure 2.10.—Photograph showing examples of geocells.

2.7 Geomats

Geomats are essentially three dimensional drainage media that are thick, open and compressible. They are made by a variety of processes including coarse PE filaments that are bonded at their intersections and the mat may or may not be associated with a geotextile (top and/or bottom). Geomats are normally 0.4 to 0.8 inch (10 – 20 mm) in thickness and water flow rate in the plane of the mat is highly dependent on the normal loads and compressibility of the product. Opening sizes are usually on the order of 0.2 inch (5 mm).

2.8 Geocomposites

Geocomposites (figs. 2.11 through 2.19) are made by bonding together two or more layers of flexible synthetic materials that perform different functions. According to the ASTM (2005) definition, a geocomposite is "a product composed of two or more materials, at least one of which is a geosynthetic". There are a myriad of geocomposites, some of which have already been alluded to in the above discussions. The following are illustrative examples:

- Geomembrane/Geotextile Composite
- Geonet/Geotextile Composite
- Geogrid/Geotextile Composite
- Geomat/Geotextile Composite

An example of a specific drainage geocomposite would be a "wick drain" which is comprised of a 4 inch (100 mm) wide waffle like corrugated structure surrounded by a filter geotextile. Geocomposites are the fastest growing segment of geosynthetics when considering the number of products. Most geocomposites are associated with the erosion control industry and incorporate both synthetic mats and geotextiles with natural materials.

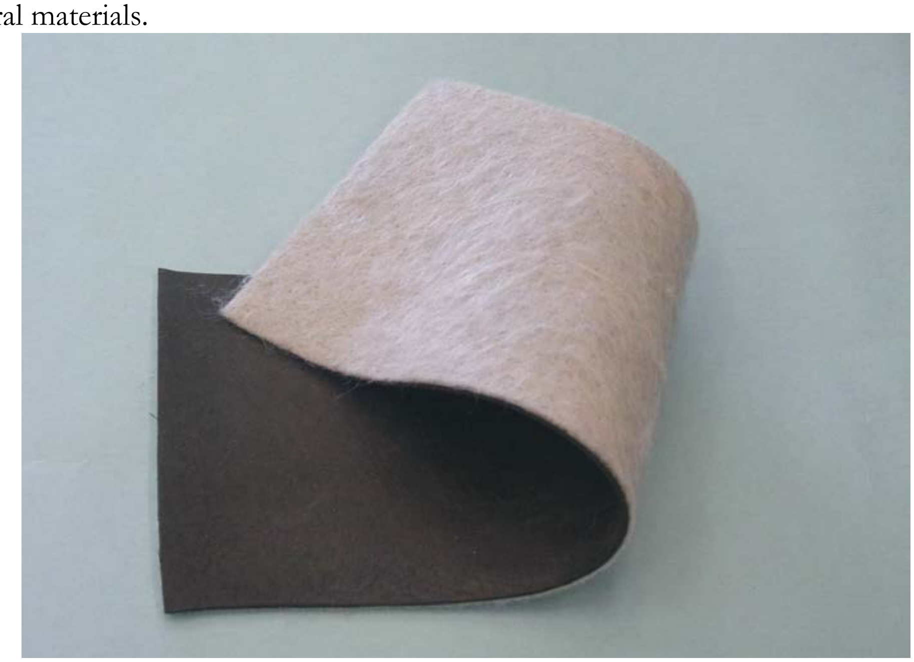


Figure 2.11.—Photograph of a single-sided geocomposite geomembrane. It is made by bonding a geotextile (grey colored layer) to one side of a geomembrane.

Figure 2.12.—A double-sided geocomposite geomembrane made by bonding geotextiles to both sides of a geomembrane (black colored core).

Figure 2.13.—Photograph of a geocomposite geonet drain made by bonding a geotextile to each side of a bi-planar geonet.

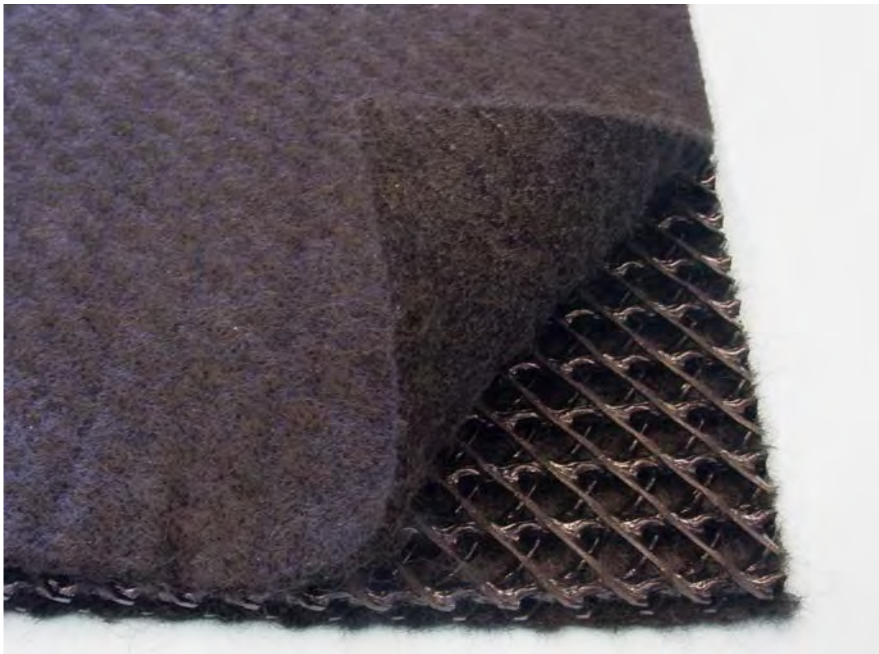


Figure 2.14.—Photograph of a geocomposite geonet drain made by bonding a geotextile to each side of a tri-planar geonet. One corner of the upper geotextile layer has been peeled back to show the underlying geonet core.

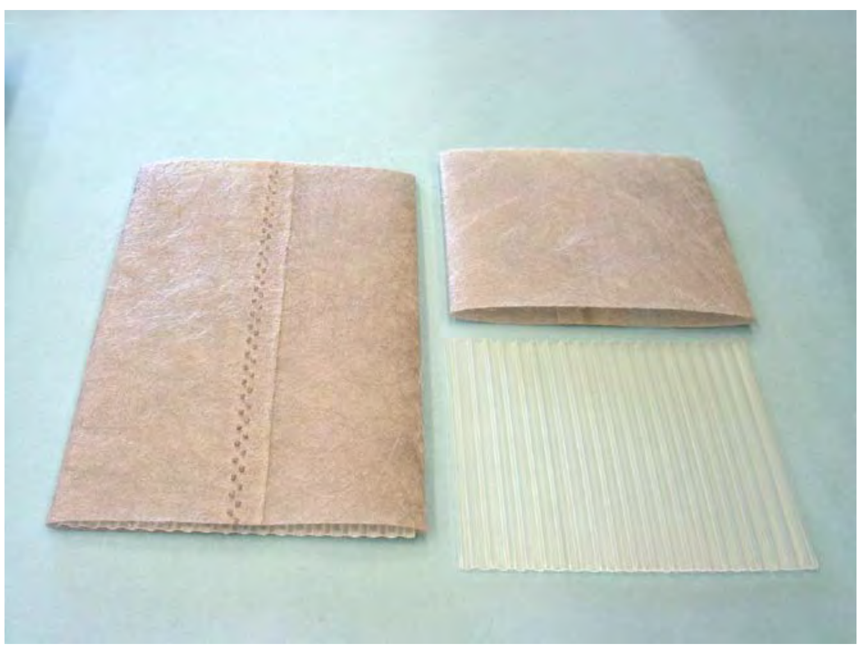


Figure 2.15.—Example of a 4-inch-wide wick drain composed of a polymeric corrugated core and outer geotextile . The core is shown in the lower right part of the photograph and the nonwoven geotextile is in the upper right. The assembled wick drain is shown in the left side of the photograph.

Figure 2.16.—Photograph of a geocomposite edge drain made by wrapping a geotextile tube around a vacuum-formed drainage core.

Figure 2.17.—Photograph of a geocomposite drain formed by enclosing a row of perforated geopipes inside a geotextile tube.

Figure 2.18.—Photograph of a geocomposite edge drain made by placing a perforated geosynthetic core inside a geotextile tube. The core functions as a flat-shaped pipe.

Figure 2.19.—Photograph showing a close-up view of a portion of the geocomposite drain shown in figure 2.18.

2.9 Geosynthetic clay liners

Geosynthetic Clay Liners (GCL's) are geocomposites that are used as a low permeability liquid barrier, usually in association with a geomembrane (i.e. composite liner system in landfills). The ASTM (2005) definition of a GCL is "a manufactured hydraulic barrier consisting of clay bonded to a layer or layers of geosynthetic materials". The layer of clay is usually a 0.2 to 0.4 inch (5 to 10 mm) thick layer of sodium bentonite that is encapsulated between two geotextiles or attached to a geomembrane by adhesive. If between two geotextiles, the resulting mat is usually stitched together by needlepunching. Once under normal load (usually a minimum of 3 ft. of soil) and hydrated, the GCL provides a low permeability barrier. GCL's are available in rolls up to 16 feet (4.9 m) in width and overlaps are "seamed" with granular bentonite to form a seal under load.

2.10 Geotextile materials, properties, and applications

The second largest volume use of geosynthetics used in dams is geotextiles which is the subject of this status report. Geotextiles are second only to geomembranes in dam construction considering all types of dams. Again, by definition, geotextiles are a "permeable geosynthetic comprised solely of textiles", ASTM (2005). Geotextiles perform a variety of geotechnical engineering functions including separation, filtration, drainage, reinforcement and protection (of geomembranes), all of which have been used in dam construction and rehabilitation. The first use of a geotextile in dam construction was in the Valcros Dam, France in 1970 where it was used functionally as a filter according to Giroud (1992, 2003). This geotextile has been performing its intended function and has shown little degradation since its installation over 25 years ago (Giroud, 1992). Since then, geotextiles have been used for a variety of functions and applications on a large number of dams worldwide with great success. The following will give a brief but necessary introduction to geotextiles – what are they, what are their properties and where are they used in dam construction and rehabilitation?

2.10.1 Geotextile polymers, structures and manufacturing methods

The textile industry has developed many textile fiber types and resulting fabric styles for numerous industrial and domestic applications. The geotextile industry, however, has devoted significant resources and know-how into development of specific end use products for geotechnical applications. To this end, much research has been accomplished in the study and application of polymer, fiber and fabric structure for specific use in long term geotechnical and civil structural applications.

2.10.2 Polymer types

According to Koerner (2005a), geotextile fibers are manufactured from the following basic polymer groups:

- Polypropylene (PP) 92% of geotextiles
- Polyester (PET) 5% of geotextiles
- Polyethylene (PE) 2% of geotextiles
- Polyamide (Nylon) 1% of geotextiles

The majority of nonwoven or woven geotextiles presently available for use in dam construction are manufactured of polypropylene fibers. Detailed information on the physical properties of individual polymers and the resulting fibers used in geotextile production can be found in Koerner (2005a), Van Zanten (1986), and Ingold and Miller (1988).

Polypropylene (PP) fiber is a semi-crystalline thermoplastic olefin produced by polymerizing propylene monomers in the presence of a catalyst. Two types of polypropylene are the homopolymers and the copolymers. The more rigid homopolymers are predominantly used in fiber production. Polypropylene homopolymers for geotextile production are specifically designed to meet both the stringent processing and final end-use strength and durability requirements. Polypropylene fiber is produced by melt spinning the molten polymer, followed by stretching to orient the fiber molecules. Special additives including antioxidant packages and thermal stabilizers and UV packages are used to protect against ageing. A life expectancy of a minimum of 200 years can be expected from properly stabilized and protected polypropylene geotextile fibers in buried applications (Van Zanten, 1986).

Polyester, generally known as polyethylene terephthalate (PET), is a manufactured fiber produced by polymerizing ethylene glycol with dimethyl terephthalate or terephthalic acid. Various additive packages are used to increase the speed of polymerization as well as antioxidants and thermal stabilizers to reduce degradation during production and ageing. Properly stabilized polyester in a covered environment will have a very long life expectancy. Polyester fibers have high strength and are resistant to shrinking and stretching (creep). Polyester fiber must be protected from aggressive alkaline environments.

Polyethylene (PE) fiber is made of 97-98% pure polyethylene resin usually in monofilament form. Ethylene is polymerized at high pressures and the resulting polymer is melt-spun and cold drawn. Polyethylene fibers are low in specific gravity, extremely low in moisture regain and have the same tensile strength wet or dry.

Nylon (Polyamide) fiber is a manufactured fiber in which the fiber-forming substance is any long-chain synthetic polyamide having recurring amide groups as an integral part of the polymer chain. The polymer material is melted and extruded through a spinneret while in the molten state to form fibers or fine filaments. The filaments are then drawn to orient the long molecules in the direction of the fiber axis. The drawing process gives the Nylon fiber its strength and elasticity.

2.10.3 Fiber and fabric types

The fiber types commonly used in geotextile manufacture are monofilament, multi-filament, staple and slit film. From the common fiber types, the basic fabric structures are manufactured and include the nonwoven and woven as well as knitted. Table 2 illustrates the basic geotextile fibers, structures and raw materials (after Adanur, 1995).

Table 2.2.—Geotextile Manufacturing Methods

	Fabric Structure	
	Nonwoven	Woven
Raw Polymer Material	PP, PET, PE	PP, PET, PE, Nylon
Fiber Type	Continuous Filament Staple Filament	Monofilament Multi-filament Slit Film tapes Fibrillated tapes
Bonding Process	Needlepunching Thermal Bonding	Weaving Knitting

Once the filament is formed or multifilament is made into a yarn, fabric structures are formed. As shown above, the two basic structures are the nonwoven and woven. The knit (which is a form of woven) structure is a very small percentage of the fabrics manufactured for the geotextile industry.

Nonwoven geotextiles (figs. 2.20 through 2.23) are manufactured in four basic steps:

1. Fiber spinning and preparation
2. Formation of the web structure by laydown of fibers
3. Bonding of the web fibers for stability of the structure
4. Post treatment for improvement of the structure

Nonwoven fiber types as discussed above are either continuous filament or staple filament. The continuous filament process is also referred to as the spun bonded process where fabric is formed by filaments that have been extruded, drawn and then laid in a random mass on a continuous moving belt. Staple filaments are short lengths of continuous fiber that are placed in a random orientation mass on a moving belt. Both processes for nonwoven geotextiles are then bonded or stabilized as a web by thermal (heat set or melt of fibers) or mechanical needlepunching. The needlepunching process mechanically interlocks fibers by driving a large needle loom with thousands of barbed needles down and up through the continuous or staple fiber web. The resulting entanglement stabilizes the web. Detailed descriptions of the processes can be found in The Needlepunch Handbook by Huntoon (1990).

Woven geotextiles (figs. 2.24 through 2.26) are made on conventional mechanical textile weaving machines into a variety of fabric weaves. The pattern of the weave is determined by the sequence in which the warp (long or machine direction) filaments or yarns are threaded into the weaving loom and encapsulate the weft (cross machine or short direction) yarns. The various types of weaves used in the production of woven geotextiles are relatively simple and cost effective and thus most woven geotextile fabric structures fall into the plain weave category. The woven final product is wound onto rolls directly off of the weaving loom. The fiber type or elements can be single monofilaments, multifilaments (i.e. low twist yarn), tape yarn or flat tapes (extruded and/or fibrillated or slit film). The resulting structures are typically 1 mm in thickness with a regular distribution of pore size or mesh openings. Detailed descriptions of the woven fabric manufacturing process can be found in the Handbook of Industrial Geotextiles by Adanur (1995).

The basic types of geotextiles formed by the above processes are as follows:

- Nonwoven continuous filament needlepunched
- Nonwoven continuous filament (spun bonded) heat set
- Nonwoven staple fiber needlepunched
- Monofilament woven
- Multifilament woven
- Monofilament on multifilament woven
- Slit film woven
- Fibrillated tape film woven

There are many variations on the above types such as monofilament on tape, slit tape on fibrillated tape, heat set, needlepunched, etc.

An important development with respect to geotextile filtration applications for embankment dams is the development of a two-layer geotextile (Giroud, Delamas, and Artieres, 1998), (Artieres and Tcherniavsky, 2003). By combining two different geotextile materials into a single fabric, the optimal properties of each geotextile can be combined. Such a combination could be a light weight geotextile selected for filtration, which alone would be vulnerable to installation damage, being combined with a heavy weight geotextile that is very strong but open to filtration and drainage. Such combinations have been made by joining two different woven geotextiles, two different nonwovens geotextiles, and it is also possible to join a woven and a nonwoven geotextile together to form a single material for placement. Even three layer or multilayer materials are possible to manufacture with a high degree of quality. An emerging advancement in geotextile filtration is the joining 2 or 3 layers of nonwoven geotextiles of different porometry, which when lightly needled together produces a graded filter.

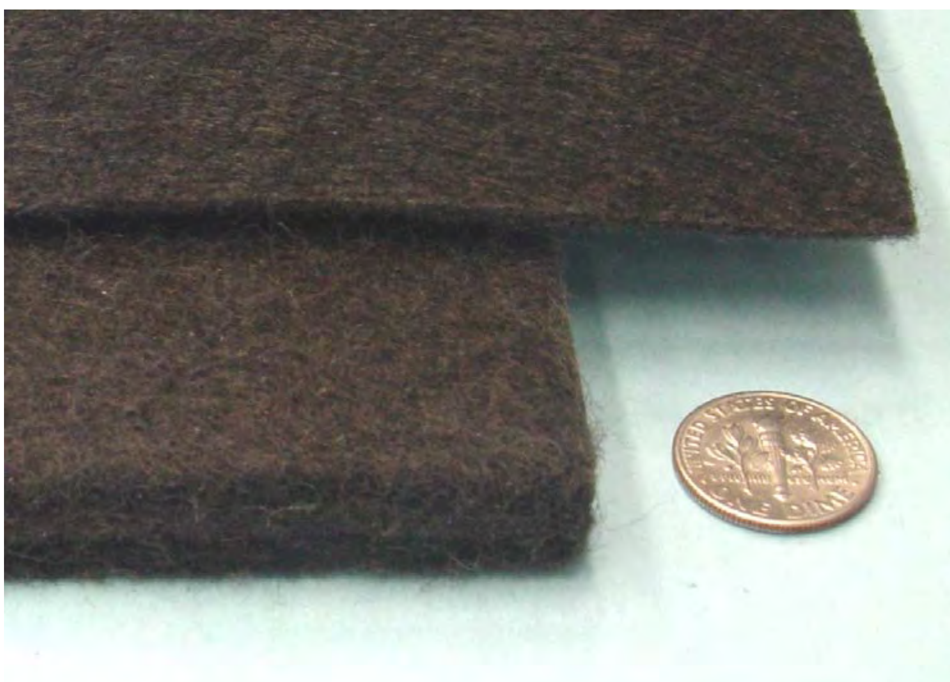


Figure 2.20.—Examples of nonwoven geotextiles showing variation in weight. At top a 4 oz/yd^2 geotextile, at lower left a 32 oz/yd^2 geotextile.

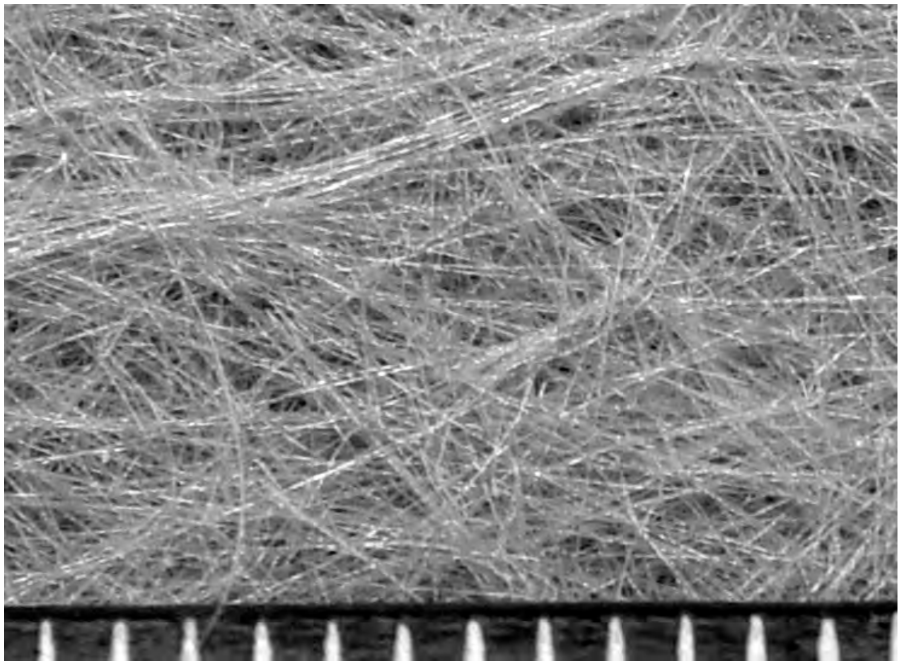


Figure 2.21.—Photomicrograph showing a nonwoven needle-punched continuous fiber geotextile, (1 mm scale).

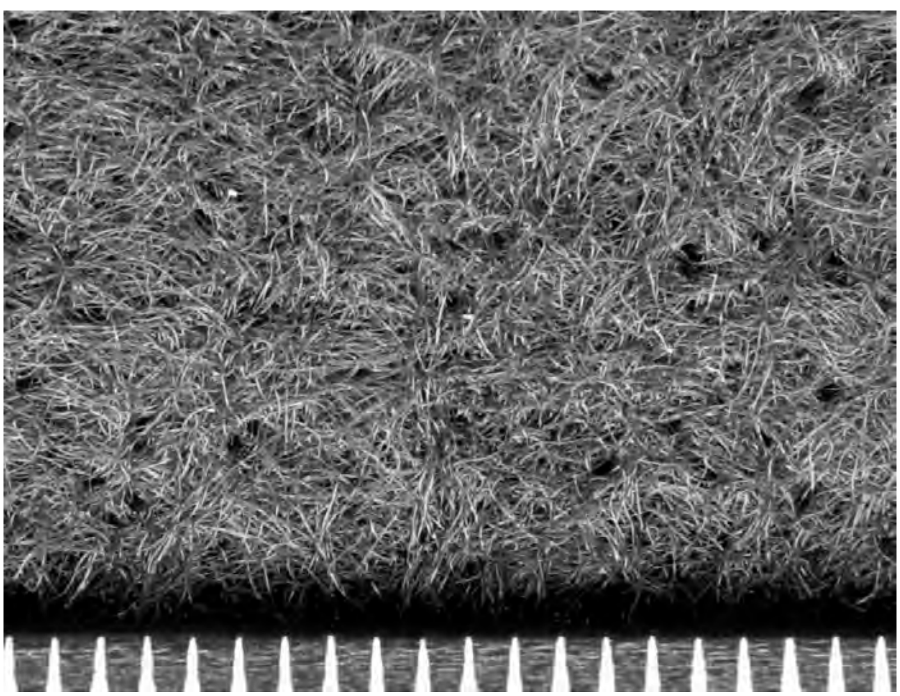


Figure 2.22.—Nonwoven needle-punched staple fiber geotextile, magnified view (1 mm scale). Note that the needle holes are visible in the photograph.

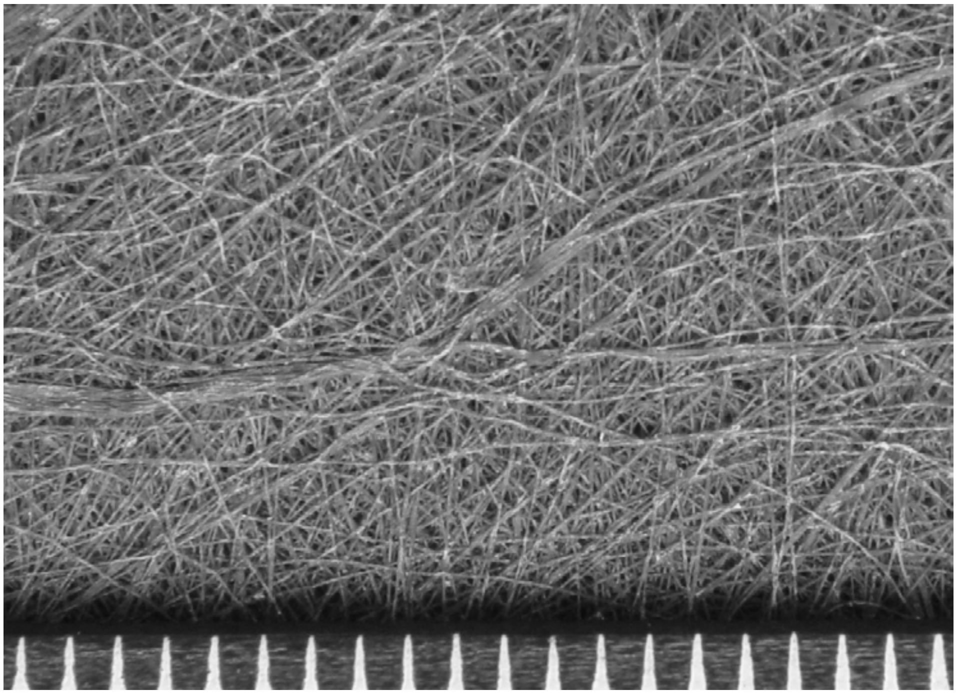


Figure 2.23.—Nonwoven heat-bonded continuous filament geotextile, magnified view (1 mm scale).

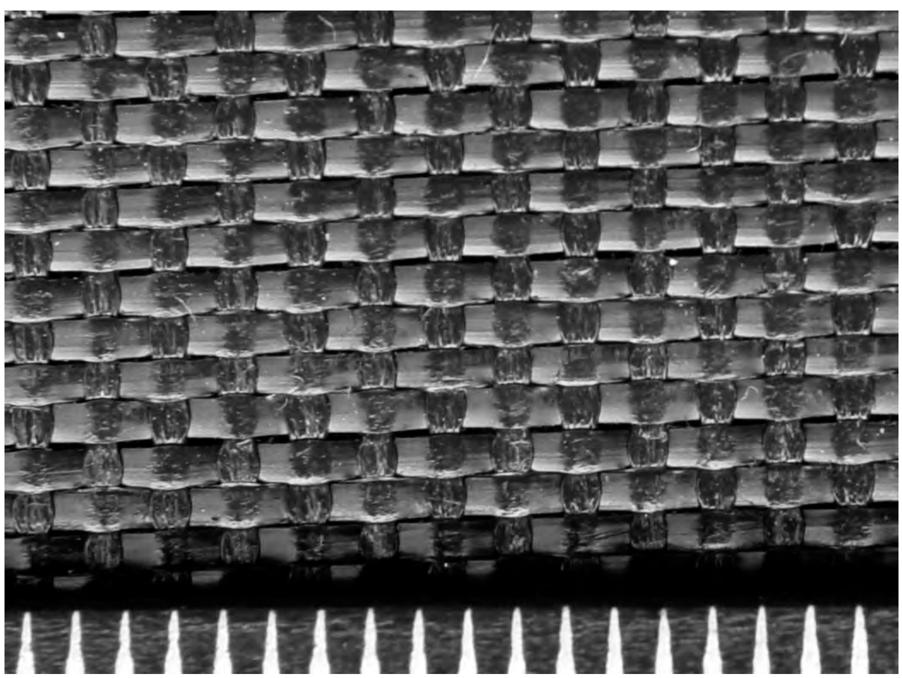


Figure 2.24.—Woven monofilament geotextile, magnified view (1 mm scale).

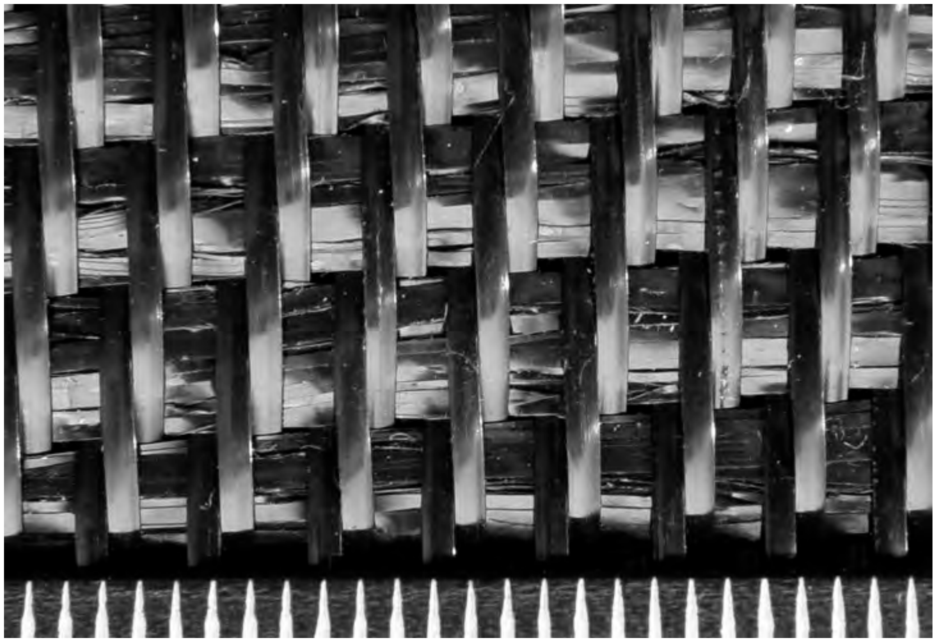


Figure 2.25.—Woven monofilament and slit film geotextile, magnified view (1 mm scale).

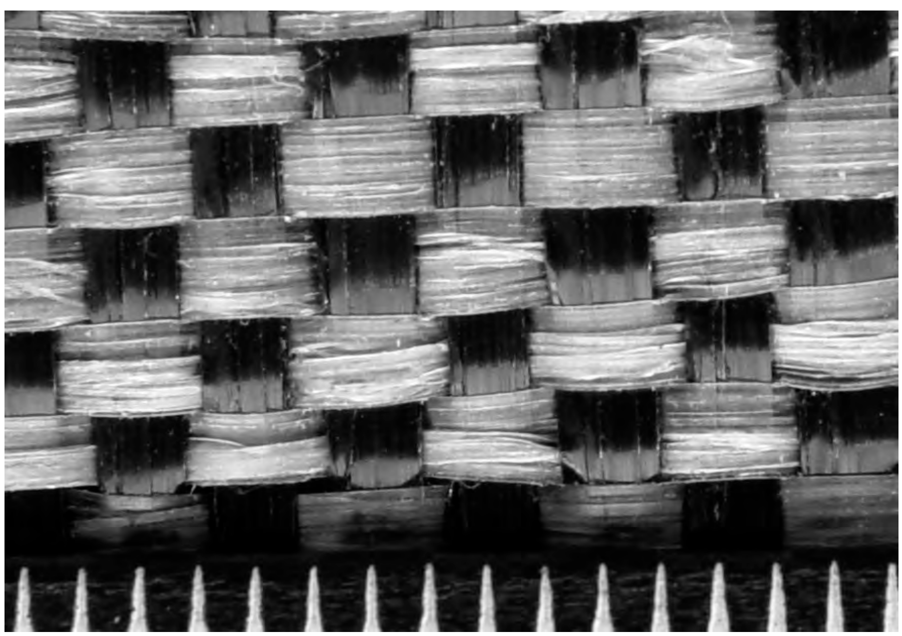


Figure 2.26.—Woven slit film geotextile, magnified view (1 mm scale).

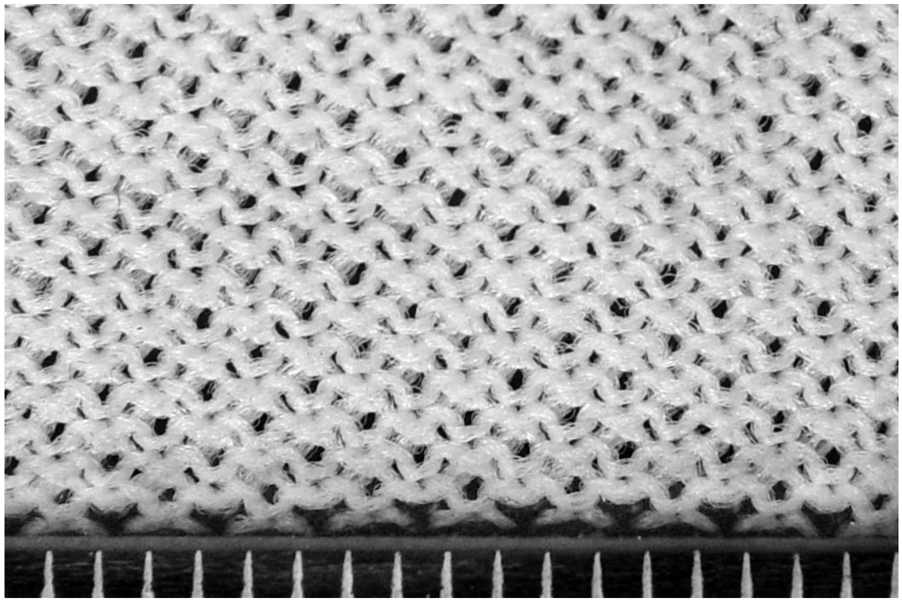


Figure 2.27.—Knitted multifilament geotextile, magnified view (1 mm scale).

2.11 Geotextile related products

Geotextile Related Products are generally geosynthetics that are either much thicker, coarser in structure or combined multilayers of the previously described geotextiles and other geosynthetics (also referred to as geocomposites). These types of products either utilize a geotextile or are composed of geotextiles and hence are related to the functional groups described in the introduction. Examples of geotextile related products are geomats with a geotextile attached for filtration, geonet composites which are geonets with a geotextile attached to one or both sides, geodrains which include a geotextile wrap or facing for filtration, woven/nonwoven geotextile composites, nonwoven/coarse nonwoven geotextile composites, geotextile/geomembrane composites and virtually all erosion control materials.

The most common geotextile related products in embankment dam construction are those which provide combinations of functions such as filtration and drainage, protection, hydraulic barrier and drainage and surface reinforcement with filtration. Examples are as follows:

<u>Filtration/Planar Drainage</u>. A geonet composite (geonet with nonwoven geotextile on both sides) or a geomat with geotextiles provides a toe drain drainage blanket function by filtering the embankment soils away from the internal planar drain to relieve pore water pressures.

Hydraulic Barrier/Planar Drainage. A geomembrane such as a thick PVC laminated to a thick nonwoven geotextile provides upstream waterproofing as well as planar drainage downstream of the waterproofing element in the event of a leak. The geotextile may also function as a protection layer depending on the dam facing materials that the composite is in contact with.

Surface Reinforcement/Filtration Function. An erosion control mat consisting of coarse upper facing structure with a bottom filter geotextile to prevent soil loss during heavy flow is used in emergency spillway applications or downstream embankment protection on Levees. The surface reinforcement could also be a geogrid with a nonwoven geotextile attached in which the geogrid is preventing surface soils from moving down slope during saturated conditions while the geotextile provides filtration and prevention of fine grain embankment soils from being extracted.

2.12 Geotextile properties and test methods

The geotextile manufacturing community and the geosynthetics industry in general are mature in that a completely unified set of standards exists, not only in the United States through the American Society for Testing and Materials International (ASTM), but worldwide through the International Organization for Standardization (ISO). In addition, there are many variations of individual country standards and collective groups such as the Central European Normalization (CEN) which effectively harmonizes standards within the European Union. The following section will present the most common ASTM methods only, and will be subdivided into five major categories, namely physical, mechanical, hydraulic, and endurance and degradation. Detailed descriptions of all of the following properties and test methods can be found in various ASTM procedures which are listed in full in Appendix C. Informative discussion and design examples on many can be found in Koerner (2005a).

2.12.1 Physical properties

Specific Gravity – (ASTM D792 or D1505) is the specific gravity of the fibers from which the geotextile is manufactured. Specific gravity is the ratio of the density of the geotextile to the density of distilled, de-aired water at 4°C. The two most common geotextile polymers are polyester (specific gravity ≈ 1.3) and polypropylene (specific gravity ≈ 0.9). Note that polypropylene has a specific gravity less than 1.0, meaning that it will float, which may be important for underwater installation.

Mass per Unit Area – (ASTM D5261) is the unit weight of the geotextile in grams per square meter (g/m2) or ounces per square yard (oz/yd2).

Thickness – (ASTM D5199) – is sometimes listed in specifications as more of a descriptive property than a design property.

Flexural Stiffness – (ASTM D1388) – can sometimes be used as a measure of the geotextile ability to provide a suitable working surface for installation over various types of subgrade soil conditions. Note that it is not the modulus of the material, as can be obtained in a tensile strength test.

2.12.2 Mechanical properties

Compressibility – (ASTM D6364) – is a measure of a geotextile thickness under various normal loads. This property can be important for transmissivity which decreases with decreasing thickness. Needle-punched nonwoven geotextiles are the most compressible.

Tensile Strength – (ASTM D751, D4632, and D4595) – is perhaps the single most important mechanical property of a geotextile. All geotextile applications rely on tensile strength either as the primary function (as in soil reinforcement) or as a secondary function (as in separation, filtration, drainage, or containment). During testing, load and deformation are measured to develop a stress-strain curve. Several different specimen sizes and configurations are commonly used. Strip tensile (ASTM D751) uses a 1- to 2-inch wide specimen. Grab tensile (ASTM D4632) grips a 1-inch section out of a 4-inch wide specimen. Wide width tensile (ASTM D4595) grips the entire width of an 8-inch wide specimen.

Seam Strength – (ASTM D4884) - Geotextile rolls are often joined together in the field by sewing or thermal welding. Seam strength is evaluated by testing a wide (10-inch) specimen cut across the seam and compared to the wide width strength of the parent geotextile material. Efficiencies of greater than 80% are not uncommon for nonwoven geotextiles.

Burst Strength – (ASTM D3786) - commonly used as an index test during manufacture QC, the burst test or "Mullen Burst" tests a small diameter area by rapid inflation until rupture. The test method is being phased out in preference to puncture type tests.

Tear Strength – (ASTM D4533, D751) - Geotextiles are often subject to tearing during installation. The most common tear test for geotextiles is the trapezoidal tear (ASTM D4533) which is initiated by a cut. However, the "tongue tear test" (ASTM D751) is still used primarily due to the higher values obtained.

Puncture – (ASTM D4833, D6241) - measures the geotextile puncture resistance from stones and debris under quasi-static conditions. For ASTM D 4833, an 8-mm steel rod punctures the geotextile which is clamped firmly to the end of a 45-mm-diameter steel cylinder. Although used as an index QC test, the small diameter rod gives much variability in lighter fabrics. ASTM D 6241 was developed based on a 50 mm diameter puncture probe (California Bearing Ratio (CBR) test probe) and is now commonly used also as a QC test method. Additionally, due to the large puncture probe size, there is a direct relationship between wide width (ASTM D 4895) tensile values and CBR puncture values.

Puncture – Hydrostatic Vessel (ASTM D5514) – a large scale performance test where geotextiles are used as cushions beneath geomembranes. Puncture resistance can be determined in 500-mm diameter hydrostatic pressure vessels using actual test soils or rock. The geotextile is placed between the test soil and the geomembrane to be protected. The test fluid (usually water) is then placed over the geomembrane and the test pressure is increased until the geomembrane ruptures.

Friction or Interface Shear – Large Scale Performance Direct Shear Tests (ASTM D5321) use a 12- x 12-inch soil box to measure the frictional properties between the geotextile and site-specific soil, or between the geotextile and another geosynthetic. As this is a true performance test, the method can model soil type, density, loading and anticipated strain rates.

Pullout Resistance – (ASTM D6706) - A large scale performance test for geotextiles used to provide anchorage for reinforcement applications. The geotextile is usually sandwiched with soil on either side. The pullout test greatly resembles the direct shear test and provides the user with a set of design values.

2.12.3 Hydraulic properties

Porosity – (ASTM D6767) is the ratio of the void volume to the total volume. Porosity is typically calculated from other geotextile properties as follows:

$$n = 1\text{-}m/\rho t$$

n = porosity (dimensionless)
m = mass per unit area (g/m^2)
ρ = rho = density (g/m^3)
t = thickness (m)

Pore size distribution can be derived using ASTM D6767 which tests pore size by capillary flow.

Percent Open Area (POA) – for woven monofilament geotextiles only, POA is the ratio of the geotextile open area (the open area between adjacent fibers or yarns) to the total geotextile area.

Apparent Opening Size (AOS) – (ASTM D4751) - uses a dry-sieving method with glass beads to find the US standard sieve size that approximates the largest openings in the geotextile (O_{95}). This test is also referred to as Equivalent Opening Size (EOS) but it should be noted that the AOS and EOS are reported in U.S. standard sieve size numbers where as the O_{95} is the corresponding sieve opening size in mm.

Permittivity – (ASTM D4491) - is a measure of the geotextiles ability to pass water perpendicularly through the geotextile. In filtration, the geotextile should ideally allow this perpendicular flow without impediment. Permittivity is equal to the geotextile cross-plane permeability (hydraulic conductivity) divided by the geotextile thickness.

$$P = k_n/t$$

P = permittivity (s^{-1})
k_n = permeability normal to the geotextile (m/s)
t = thickness of geotextile (m)

Permittivity under Load – (ASTM D5493) this test is the same concept as permittivity, however now the geotextile is tested under a normal load which is more of a performance test than an index test.

Transmissivity – (ASTM D4716) – as a performance test method, measures the flow of water within the plane of the geotextile under normal load. This time, the transmissivity is equal to the geotextile in-plane permeability (hydraulic conductivity) times the geotextile thickness.

$$\Theta = k_p\, t$$

Θ = Transmissivity (m^2/s)
k_p = permeability in the plane of the geotextile (m/s)
t = thickness of geotextile (m)

2.12.4 Endurance properties

Creep – (ASTM D5262) - this test measures elongation over time under constant load. Test specimen is similar to the wide-width tensile specimen (ASTM D4595). Specimens are loaded to some percentage of ultimate strength (typically 20%, 40% and 60%). Test duration is typically 1,000 to 10,000 hours. Since geotextile polymers are creep-sensitive, this property is important for soil reinforcement applications.

Abrasion – (ASTM D4886) – as an index test, the "Tabor Abrasion" is the most common. The geotextile specimen is placed on the test platform and abraded by steel serrated wheels for 1000 revolutions. Strip tensile specimens are then cut from the abraded geotextile and tested for tensile strength. Although used for comparative purposes, the simulation for field abrasion is questionable.

Clogging – Clogging of the geotextile with soil particles is one of the greatest concerns for use of geotextiles in critical applications involving filtration. Several clogging tests are available, but they are all difficult and time consuming to run. Available tests include the Gradient Ratio (ASTM D5101), and Hydraulic Conductivity Ratio (ASTM D5567). Difficulties include interpretation of results and biological clogging. Typical test duration is 1,000 hours (about 42 days). Test methods exist for biological clogging as well (ASTM D1987).

2.12.5 Degradation properties

Ultraviolet (UV) Degradation – Geotextiles degrade under UV light, especially the shorter wavelengths known as UV-B (315 to 280 nm). Therefore geotextile specifications typically require that the geotextile be shipped and stored in opaque UV resistant wrapping and be covered within 14 days of placement. The most widely used test devices for UV resistance are Xenon-Arc (ASTM D4355) and Fluorescent UV (ASTM D5208).

Temperature Degradation – High temperatures cause geotextiles to degrade more rapidly (time-temperature superposition). Low temperatures do not degrade the polymer but can cause geotextiles to stiffen and become brittle. Although ASTM D746 can be used to determine the brittleness temperature for a geotextile, geotextiles are rarely affected by temperatures in service under most climatic conditions. For shallow burial in extreme climatic conditions, temperature effects should be considered.

Oxidation Degradation – (ASTM D794) All types of polymers react with oxygen causing degradation. The polyolefins (i.e., polypropylene and polyethylene) are more susceptible to oxidation than other polymers.

Hydrolysis Degradation – Polyester resins are the most susceptible to hydrolysis, especially when immersed in liquids with high alkalinity.

Chemical Degradation – ASTM D543 describes chemical degradation testing, and includes a list of 50 standard reagents. Chemical degradation testing using site-specific chemicals (leachate) is covered under ASTM D5322 and D5496. Chemical degradation may be a factor in waste containment applications such as tailings dams, and industrial effluent storage facilities.

Radioactive Degradation – This type of degradation is only an issue for waste containment situations and is not considered problematic for embankment dams.

Biological Degradation – Micro-organisms (such as bacteria and fungi) do not readily degrade geotextiles, because the high molecular weights leave very few chain ends where biodegradation might begin.

Other Degradation – Other degradation processes might include ozone, rodent or termite attack. Synergistic attack (a combination of two or more degradation factors acting at the same time) is a complex issue, but has not been found to be a problem in most geotextile applications.

Aging – Specific test standards have not been developed to measure aging of geotextiles. However tests on exhumed samples generally show that geotextiles are still in good to excellent condition after decades of service.

2.13 Application of geotextiles as functional elements in embankment dams

In the Introduction, the functions of all geosynthetics in Dam Construction were briefly discussed. It should be noted that with the exception of the liquid barrier function, geotextiles are shown as a possible choice to fulfill all other functions. It is important from a designer's point of view to know what the functional application is and where it can be used relative to embankment dams in order to consider a geotextile for use in a particular function.

2.13.1 Filtration of soils particles

As discussed in the Introduction, a geotextile (nonwoven or woven) performs a filter function if it allows water to pass while controlling the soils migration through the geotextile. Sometimes the filtration application is a dual function (i.e. filtration and drainage).

- Filter between zones of protective stone and embankment soils or transition soils
- Internal chimney drain upstream filter
- Internal toe drain filter

- Internal downstream filter
- External toe drain filter

2.13.2 Separation of dissimilar materials

For a geotextile, the separation or interlayer function sometimes coincides with the filter function in that the geotextile separates a finer material from a coarser material to prevent mixing. This could occur on the upstream or downstream shell of an embankment dam when separating different materials, or between an embankment and its foundation soils.

2.13.3 Planar drainage

Geotextiles are usually associated with Geocomposites (i.e. geonet composite, geomats, etc) in planar transmission or drainage. However a major contribution in drainage for geotextiles alone is in the use of a very thick nonwoven directly downstream of a geomembrane used as the upstream face or upstream barrier under hard armor protection. Typical locations of drains are as follows:

- Upstream face drainage
- Internal chimney drain
- Horizontal layer drains
- Downstream geocomposite drain
- Horizontal blanket toe train

2.13.4 Reinforcement

Both woven and nonwoven (to a lesser extent) geotextiles can be used in the reinforcement functional application, although geogrids are preferred for economy and tensile strength depending on the application. This application is particularly suited for rehabilitation of embankment dams, especially in the raising of dams or in increasing the slope on an existing dam.

2.13.5 Protection

The primary application for the protection function is placement of a geotextile against one or both sides of a geomembrane designed as the hydraulic barrier. The geotextile protects the lining system from damage before, during, and after construction. This function is best served by a thick nonwoven needlepunched geotextile or geotextile composite (woven/nonwoven composite).

2.13.6 Prominent geotextile types used in embankment dams

Historical use by functional group (fig. 2.28):

- Filtration
  - Nonwoven needlepunched continuous filament (Polyester and Polypropylene)
  - Woven monofilament
- Drainage
  - Nonwoven needlepunched staple fiber (large mass/unit area)
  - Composite
- Separation
  - Woven Slit Film
  - Nonwoven needlepunched staple fiber and continuous fiber
- Reinforcement
  - Woven monofilament
  - Woven slit film
- Protection
  - Nonwoven needlepunched staple fiber and continuous filament
- Erosion Control
  - Nonwoven needlepunched stable fiber and continuous filament
  - Composite

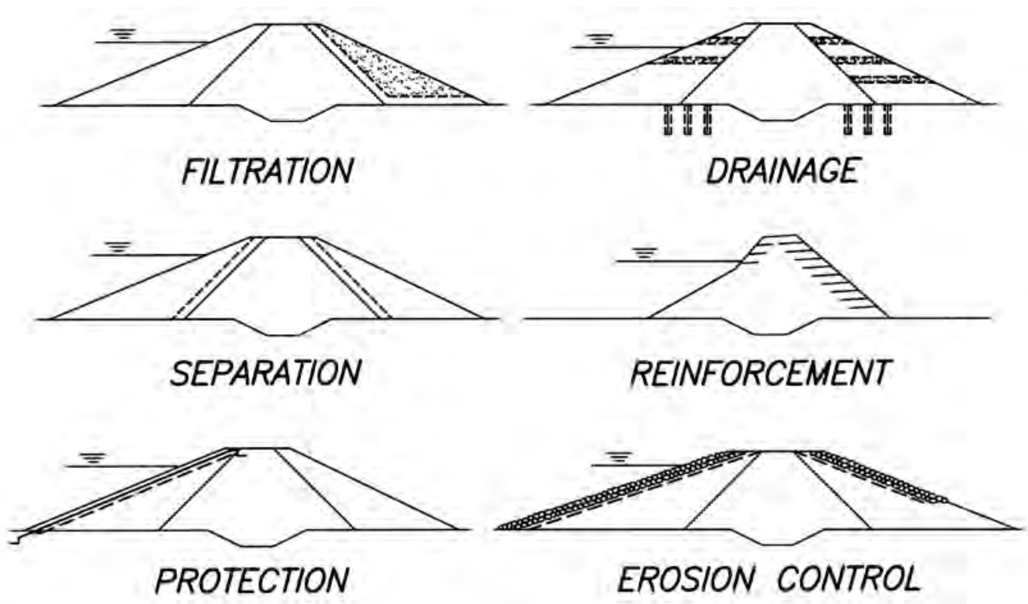


Figure 2.28.—Examples of some of the functions of geotextiles in dams.

2.14 Durability of geotextiles in embankment dams

The design engineers of embankment dams are traditionally very conservative in their design and the materials used in construction of the dam. To this end, geosynthetics and geotextiles in particular have not played a prominent role in most embankment dam design and rehabilitation. There are two primary reasons for this: Education and Longevity (Durability). Education is ongoing and the design of structures with geosynthetics is becoming routine and accepted with many educational institutions and texts available that are devoted to design practice (Koerner, 2005a). But what about the durability of geotextiles in structures such as embankment dams that should last well over 100 years?

Polymeric materials undergo a gradual deterioration in properties over time due to a variety of known ageing mechanisms resulting in molecular level bond breaking, cross-linking or simple extraction of components. The following mechanisms are fully described in detail in Van Zanten (1986) and Koerner (2005a):

- Ultraviolet degradation due to sunlight
- High temperature degradation
- Oxidation degradation

- Hydrolysis degradation
- Chemical degradation
- Radioactive degradation
- Biological degradation

It must be emphasized that geotextiles buried in embankment dams are protected from exposure to the elements, and from to many environmental degradation mechanisms including damaging effects of UV, high temperatures or even temperature fluctuation and accelerated oxidation due to exposure (thermo-oxidation and photo-oxidation). Hydrolysis degradation (chemical decomposition by addition of water) is associated with extremes of pH which are usually not a problem unless immediate contact with concrete is anticipated (alkaline environment) or the dam is a tailings dam or contaminated water containment dam that may be exposed to acidic impoundment solutions, and then this only affects PET geotextiles. Chemical and radioactive degradation are usually associated with waste containment applications and is not a consideration in buried soil environments such as internal to a dam. Biological degradation is also not generally associated with geotextiles other than by biological clogging which will occur in some soil environments (i.e. iron ochre) but which does not degrade the polymer.

The long-term performance of geosynthetics in dams has been demonstrated by over 45 years of historical use. Additionally, the manufacturing methods and polymers as well as polymer chemical stabilization technology (i.e. anti-oxidant packages) have advanced to the point that these materials will outlast traditional construction materials such as steel and concrete. Why is this possible?

- Proven historical use and case histories
- Improved polymeric materials
- Improved anti-ageing additives
- Low temperature buried environments
- No exposure to harmful thermo or photo-oxidation degradation
- No corrosion
- No spalling
- Proven design methods

One key point to remember is that geosynthetics, and geotextiles in particular, must be treated as any other construction material used in civil engineering in that their strengths and weaknesses must be recognized and be properly addressed in design and construction.

Chapter 3

Functions of Geotextiles in Embankment Dams

Geotextiles have been used in many applications as components in the design and construction of embankment dams. These products have been used more frequently in repair of existing dams where dam safety concerns mandate rapid construction. In the construction of new dams, particularly in the United States, geotextiles are usually a secondary or composite component in combination with natural materials. Geotextiles have been substituted for natural materials in dams by some practitioners when the availability or expense of natural aggregates makes them impractical.

Geotextiles have been considered for the following functions in various design applications associated with dams:

- Filtration
- Drainage Conveyance
- Separation
- Protection
- Reinforcement
- Surface Erosion Control

Geotextiles have been used more frequently as a separator function for drainage aggregates or riprap and far less frequently as traditional filter/drainage applications in dams. Another common application is in soil reinforcement or to improve the slope stability of an embankment.

3.1 Filtration and drainage

In a limited number of cases, geotextiles have been used in the filtration of seepage through and under embankment dams (fig. 3.1). These materials, when properly designed and constructed, can act as a filter, controlling the migration or the transport of soil particles by seepage (Holtz, Christopher, and Berg, 1997). However,

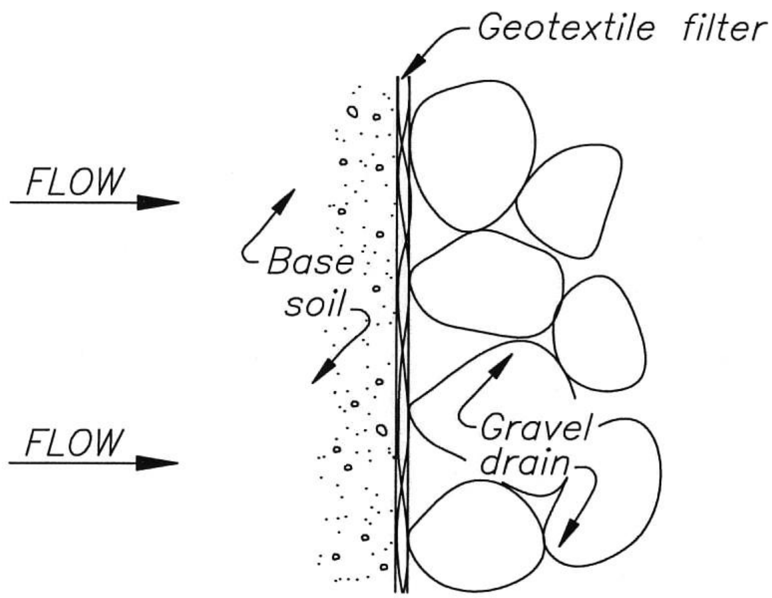


Figure 3.1.—Illustration showing geotextile filter placed between soil and aggregate drain).

many have questioned if a geotextile product can meet all of the requirements of a key component of a safe dam, thus they are not used for filtration and drainage by most dam designers.

Many dam designers do not recommend using geotextiles in critical filtration or drainage zones in a dam. A critical filter is defined as a filter that serves as the sole defense in protecting the embankment and foundation from internal erosion and piping failures. Chimney filters and filters associated with blanket and foundation trench drainage systems in dams are considered to be critical filters. The reasons given for precluding the use of geotextiles as critical filters and drains in dams are (ICOLD, 1986), (Talbot et al., 2001), (ASDSO, 2003), (Fell et al., 2005):

- The long term design performance of the geotextile may be affected negatively from chemical attack, prolonged immersion in water, oxidation, and ultraviolet exposure.

- Geotextile filters are susceptible to excessive clogging from the buildup of fines at the face of the geotextile.

- The growth of biological, fungal, or mineral matter buildup within the pore spaces of the geotextile may lead to excessive clogging and reduction of capacity to transmit flow.

- Design details at interfaces, junctions, connections, and boundaries are often a source of strain incompatibility and a starting point for failure to occur.

- These materials are easily damaged by construction equipment.

- Damage caused by placement and hauling of cover materials may not be detected.

- Geotextiles in near-surface applications are susceptible to damage from vegetation roots and burrowing animals.

Geotextiles in general are gaining wider acceptance in many applications in dams and some dam designers (Hollingworth and Druyts, 1982), (Biche, 1987), (Cazzuffi, 2000), (Legge, 2004), (Fell et al., 2005) contend that geotextiles may be used for non-critical or redundant filter applications. Others relegate the use of geotextile filters in locations in dams where they can be easily reached with construction equipment without affecting the safety of the dam such as the toe of the dam. Some recommend their use only outside the footprint of the dam collecting nuisance seepage from abutments and side channel springs or seeps. In some filtration applications, the use of a geotextile has advantages over graded granular filter material because of:

- Installation expediency and ease of construction.

- Reduced excavation and less wasted materials.

- Lower risk of the contamination and segregation of drainage aggregate during construction installation.

- The use of less or lower quality drainage aggregate.

- Processing costs

- Transportation costs

Although they may in some cases require more surface preparation, geotextiles can be easier to place or install than natural material, particularly for those applications that require multiple layers of aggregates. For example, Section 3.1.3 Foundation Trench Drain shows a trench drain system for an embankment located at the toe of a dam consisting of a trench lined with geotextile and filled with gravel. The alternative to this design is a two-stage granular filter with a gravel core inside a trench filled with filter sand. Placing two zones of granular filter requires more construction effort than the single zone of gravel which is possible with the geotextile-lined trench.

Despite the practice by some engineers (List, 1982), (Degoutte, 1987), (Giroud, 1987), (Wilson, 1992), (Artieres and Tcherniavsky, 2003) who have used geotextiles in critical dam filtration and drainage applications in overseas projects, the vast majority of dam designers do not allow the use of geotextiles as a critical filter or drain element within a dam. Such use is not consistent with accepted engineering practice in the United States.

3.1.1 Toe drain systems

Geotextiles have been used in a number of applications as the filtering element or in conjunction with conventional graded granular filters in drainage applications near the toe of dams. Filtering capacity is necessary to prevent soil from migrating into high capacity drainage aggregate such as gravel, rock, or other geosynthetic materials.

Drains that incorporate geotextiles can also be placed in the toe of the embankment for improved slope stability or simply located to control nuisance seepage that can sustain a wet toe or abutment of a dam and/or downstream wet area. Figure 3.2 shows an example of how to construct a toe drain in a small embankment dam. It should be noted that the use of a geotextile as the sole filter in this manner rather than using a natural filter is not consistent with accepted engineering practice in the United States. The geotextile in this design is both inaccessible for replacement and critical to safety. As configured, it would require evacuation of most of the reservoir and excavation of almost 1/3 of the embankment to facilitate replacement of the geotextile. Also, it would not be possible to provide a redundant natural filter if the

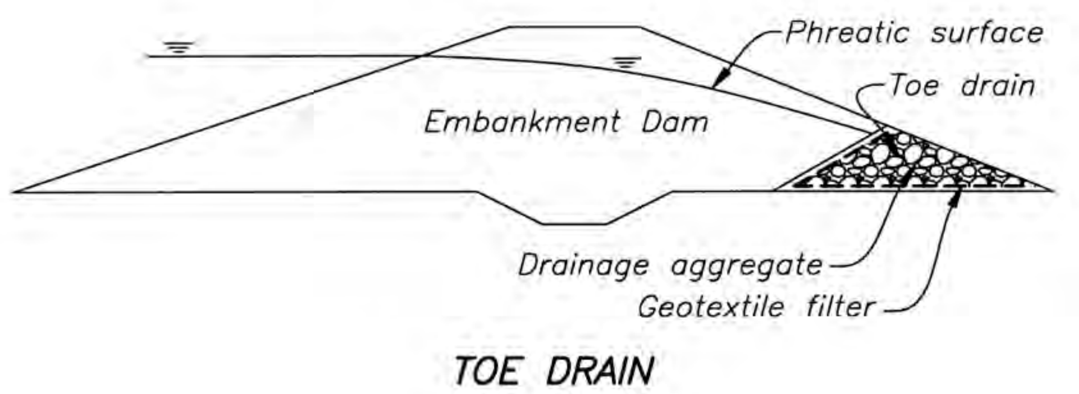


Figure 3.2.—Illustration of a geotextile filter used in construction of a rock toe drain. The geotextile filter in this configuration is considered a critical element and is not consistent with accepted practice by most dam engineers.

geotextile were to experience excessive clogging. Seepage would not reach the drain. The seepage would likely exit above the drain on the down stream slope thus subjecting the dam to potential failure due to piping and downstream slope instability.

Geotextiles should be compared to graded granular filter material to determine which product should be used in a particular design, because both have advantages and disadvantages. An example of this comparison is as follows:

Table 3.1.—Comparison of geotextile filter with a granular filter for non-critical applications in embankment dams.

	Geotextile Filter	Granular Filter
Ease of Construction	Relatively simple and fast, Reduced trench excavation Lower risk of contamination of drainage aggregate. Requires preparation of a suitable subgrade and cover material.	Special processing and handling required to minimize fines content and prevent segregation. May require use of forms if a multiple filter configuration is used
Cost	Low to moderate	Moderate to high
Ability to transmit large quantities of seepage	Good with a large gravel or rock core	May require multiple filter zones if large gravel is necessary to carry large seepage rates
Ease of Quality Control	Requires visual inspection only. Intensive inspection of all aspects of cover placement is essential. Test section may be required to be excavated to ensure covering does not damage geotextile.	Requires close inspection and verification of gradation of fine filter. Transport and placement technique must avoid segregation and generation of fines. No risk of construction damage.

3.1.2 Internal chimney and horizontal blanket drains

Geotextiles have been used in a limited number of applications as the filtering element or in conjunction with conventional graded granular filters in drainage applications within dams (figs. 3.3 through 3.5). Drainage capacity is necessary to lower the phreatic surface in dams for improved slope stability of the embankment or simply located to control nuisance seepage that can sustain a wet toe or abutment of a dam and/or downstream wet area. Filters protect the upstream soil from being eroded into the drain.

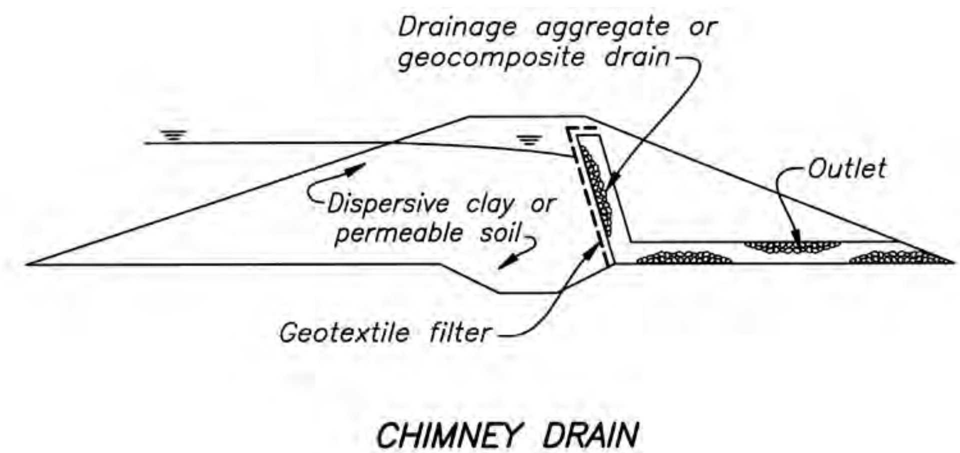


Figure 3.3.—Illustration of a chimney filter and drain incorporating a geotextile filter. This configuration is not consistent with accepted practice by most dam engineers.

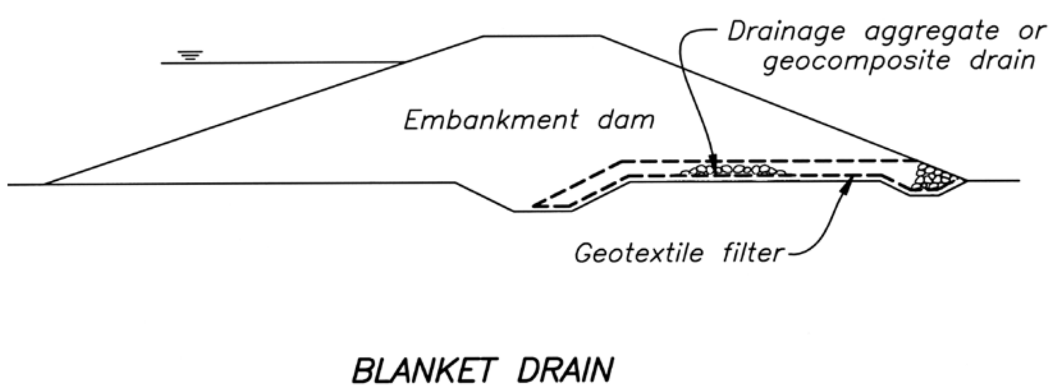


Figure 3.4.—Illustration of a blanket drain incorporating a geotextile filter. This configuration is not considered as accepted practice by most dam engineers.

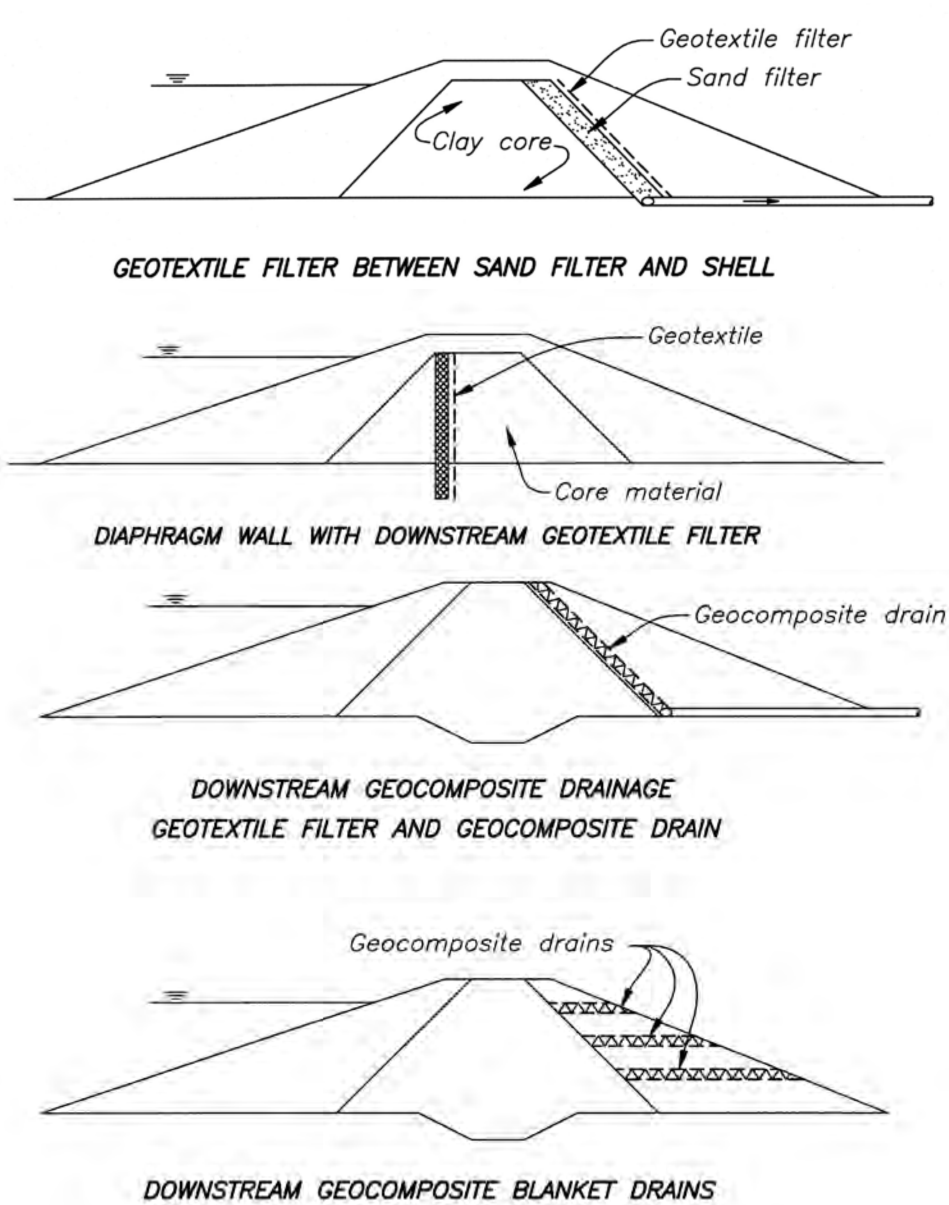


Figure 3.5.—Additional examples of geotextiles used in filtration and drainage. Only the configuration at the top with the sand filter and redundant geotextile to filter the core may be consistent with accepted engineering practice. It would be consistent with accepted engineering practice if the sand filter is compatible with the down stream shell. If the geotextile were needed to prevent piping of the sand filter into the downstream shell, then the geotextile is acting as a critical design element, not as a redundant feature to protect the core; therefore, it would not be consistent with accepted engineering practice.

3.1.3 Foundation trench drain

Drains with geotextile filters have also been placed at depth in trenches near the toe or downstream of a centerline cutoff trench of a dam to collect excessive foundation seepage for the purpose of reducing potential excessive uplift pressures within or under a dam (fig. 3 6).

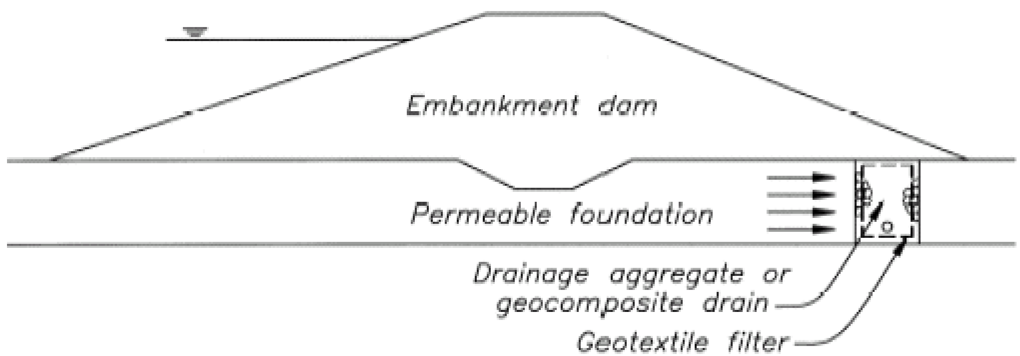


Figure 3.6.—Illustration of a foundation trench drain incorporating a geotextile filter. This configuration is not considered as accepted practice by most dam engineers.

3.2 Transverse embankment cracking protection zone

Geotextiles have been used in dams as a crack stopper or for the purpose of controlling internal erosion through relatively small transverse cracks that can develop in embankment dams from desiccation or from differential foundation movements (fig. 3.7). This design application is not a drainage function, because the geotextile is intended as a cutoff curtain more than as a drainage element. This application has been used primarily on single purpose flood control dams in the arid west region of the country with dry pools. The geotextile functions by collecting soil particles on the face of the geotextile until a filter cake forms eventually sealing the crack or cracks while allowing a small amount of water to pass.

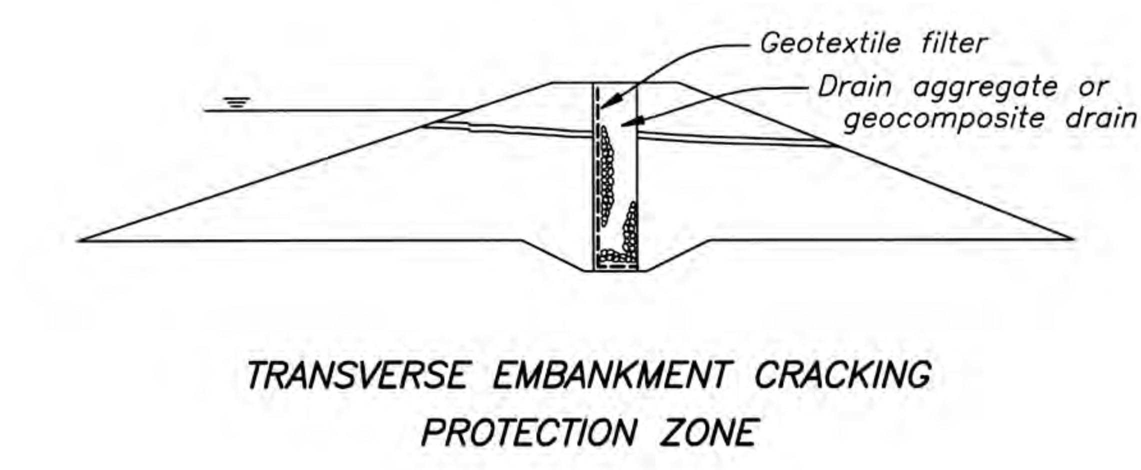


Figure 3.7.—Illustration of a geotextile filter providing crack protection. This configuration is not considered as accepted practice by most dam engineers.

Geotextiles have often been used in these zones as an element in a composite system used to treat larger cracks. To accomplish this, a geotextile is placed on the downstream face of a composite filter system composed of natural materials such as sand or gravel (fig. 3.8). The geotextile helps protect the natural materials from moving into the downstream cracks where gravity or gradients would transport these materials into the cracks.

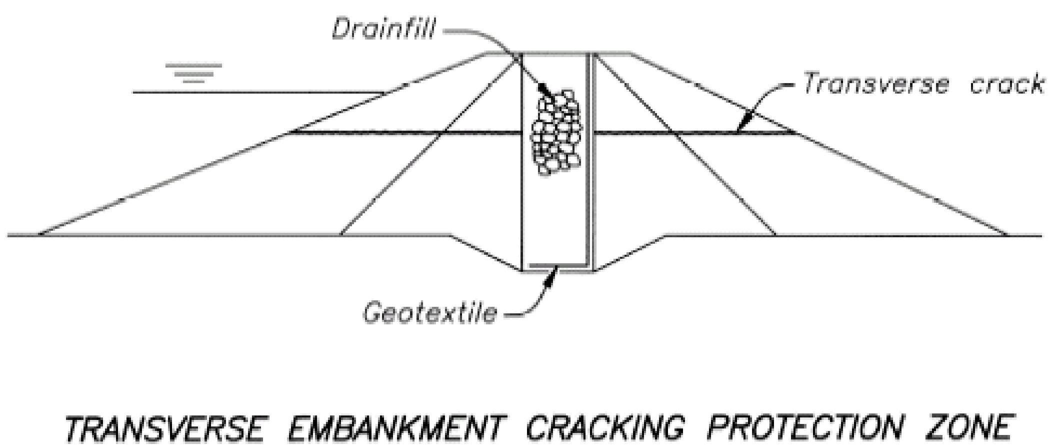


Figure 3.8.—Illustration of a geotextile filter providing crack protection on the downstream side of a chimney filter. This configuration is not considered as accepted practice by most dam engineers.

3.3 Separation and protection functions

Geotextiles have been used most commonly in dams as a separator of natural materials to prevent the contamination of adjacent zones in an embankment (fig. 3.9). A related function is protection. Just as a separation layer prevents one soil layer from intruding and mixing with another layer, in protection the geotextile prevents a soil or gravel layer from intruding and damaging the material to be protected such as a geomembrane.

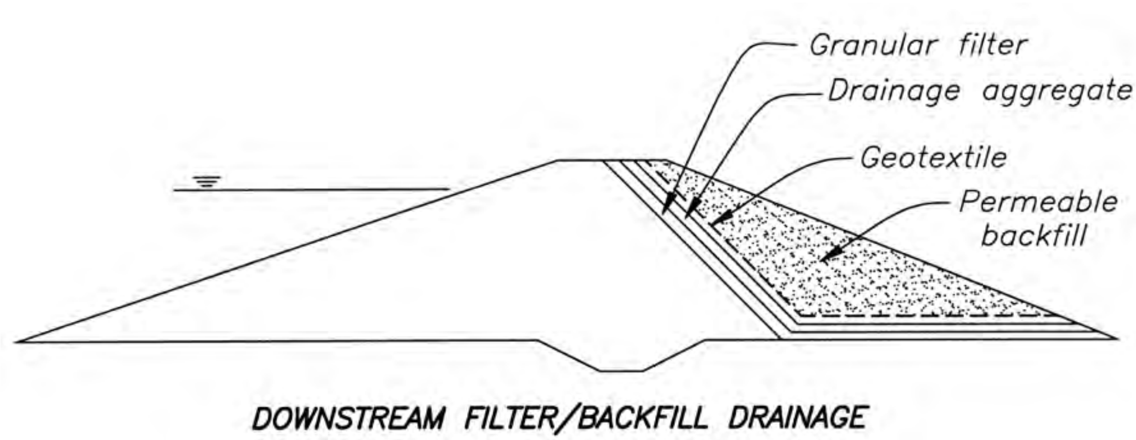


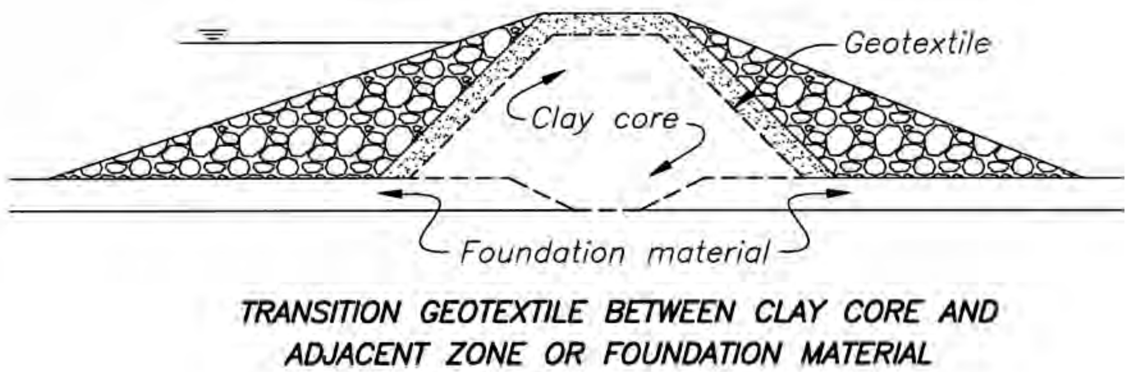
Figure 3.9.—Illustration showing geotextile filter/separator being used to separate a downstream drainage zone from the overlying backfill. This configuration is considered to be an acceptable engineering practice by most dam engineers.

3.3.1 Material transition zone

Geotextiles have been placed within embankment dams to separate earthfill material zones (fig 3.10). An example would be placing a geotextile between a filter/drainage zone and a downstream earthfill zone. Geotextiles used for this application can potentially save material and placement costs by ensuring a definite and consistent boundary of clean uncontaminated material in the drainage aggregate layer.

3.3.2 Soil cement and roller compacted concrete

Geotextiles have been placed between the soil cement mix and soils to act as a separator to prevent the mixing and to maintain the desired design thickness. A similar use of geotextiles has been made when placing roller compacted concrete against a soil surface.



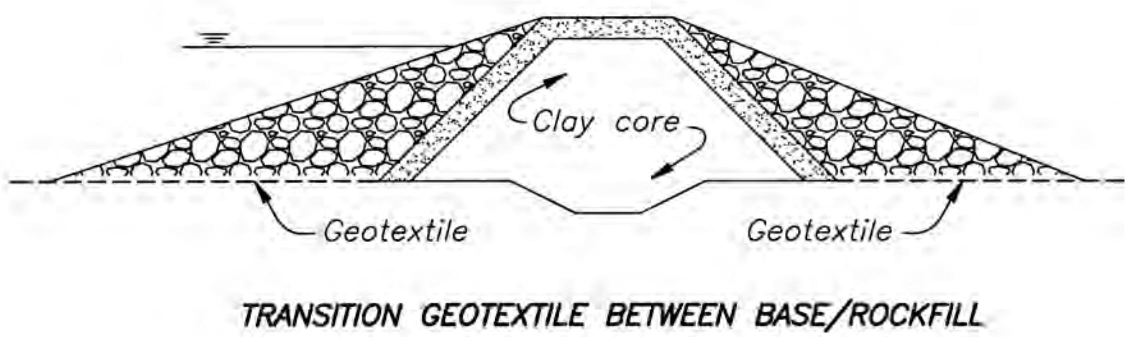


Figure 3.10.—Additional examples of geotextiles used as transition zone separators. These configurations are not considered to be consistent with accepted practice by most dam engineers.

3.3.3 Protection of geomembranes

Geotextiles have been placed against surfaces of geomembranes as a protection layer to prevent damage to the geomembrane from foundation discontinuities and the damage that can occur during soil placement and other construction operations. The geotextile will help prevent rocks and other unidentified material in the soil backfill from damaging the geomembrane by providing additional tensile strength to the system and by providing a cushioning layer.

3.4 Soil reinforcement

High modulus geotextiles have been utilized to provide a tensile strength component to a soil mass when placed under or within an embankment or foundation. This tensile reinforcement can reduce stress and strains within the soil mass or embankment enabling the embankment to resist large differential settlements and lateral spreading or slope movements. The use of reinforcement in embankment construction may allow for:

- An increase in the design factor of safety.
- An increase in the height of the embankment dam.
- A reduction in embankment earthfill quantities during construction

3.4.1 Soft soil foundations

Geotextiles have been used to support embankments placed over soft or weak foundation soils (fig. 3.11). Embankments constructed on relatively deep soft, saturated silt, clay or organic soils have a tendency to spread laterally because of horizontal earth pressures acting within the embankment. These earth pressures cause horizontal shear stresses at the base of the compacted embankment which cannot be fully resisted by the weak or low shear resistance foundation soils. Embankment stability may be compromised with potential for failure.

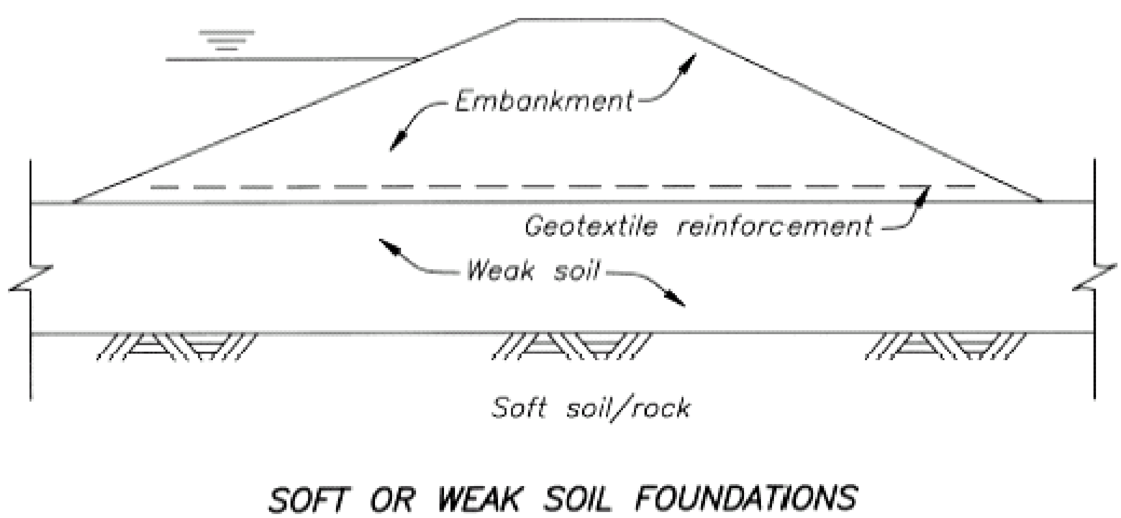


Figure 3.11.—Illustration showing a geotextile being used to support an embankment placed upon a weak soil foundation.

3.4.2 Locally weak or voided foundations

Geotextiles have been used to assist in supporting embankments placed over locally weak soil zones or voided foundations (fig. 3.12). These zones or voids may be caused by sinkholes, old stream beds, soluble bedrock such as gypsum, or pockets of silt, clay or organic soils. The role of the geotextile in this application is to bridge over the weak zones or voids, and provide tensile reinforcement in all directions. Although this practice has been used in South Africa to span over underground mine workings, it can not be considered good practice. Foundation voids are a potential seepage pathway that could result in internal erosion of the dam or its foundation material.

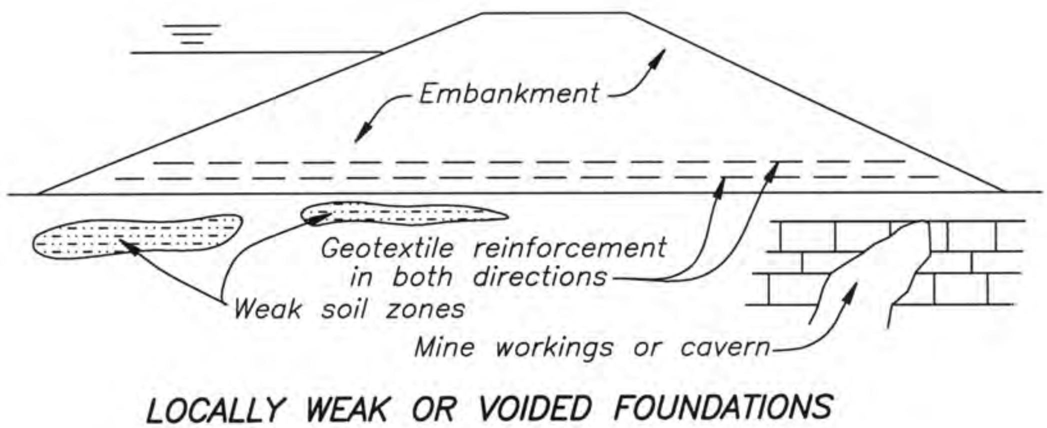


Figure 3.12.—Illustration of a geotextile being used to support an embankment placed over weak areas and foundation voids. These configurations are not considered to be consistent with accepted practice by most dam engineers.

3.4.3 Slurry cutoff walls

Geotextiles have been used to support embankments placed over designed features in the foundation that have a significantly higher consolidation potential compared to the surrounding in-situ soils. An example of this is a soil/bentonite or another type of slurry cutoff wall. The role of the geotextile in this application is to span the top of the wall and reduce the embankment loading on the weak slurry zones. The geotextile reduces consolidation of the slurry material to prevent a void or potential seepage path from developing through the cutoff.

3.4.4 Reinforced slopes

Geotextiles can be used to improve the stability of the embankment slopes by adding tensile reinforcement (fig. 3.13). This allows the slopes to be constructed at a steeper angle and can be important where expanding the dam footprint is not an option (Engemoen, 1993).

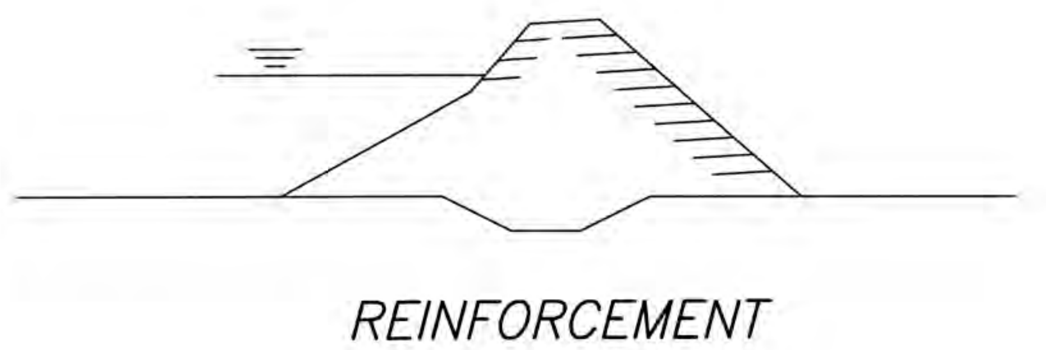


Figure 3.13.—Illustration of an embankment whose slopes have been steepened by incorporating geotextile layers into the soil as slope reinforcement.

3.5 Surface stabilization

Geotextiles have been effectively used with armor systems for wave erosion and scour protection associated with dams.

3.5.1 Rock riprap or manufactured concrete block

Geotextiles have been successfully used as bedding when placed on the upstream slope of dams to prevent fines from migrating through the armor system (fig. 3.14). Similarly geotextiles have been used as a bedding with armor protection for stilling basins, plunge pools and outlet works channels.

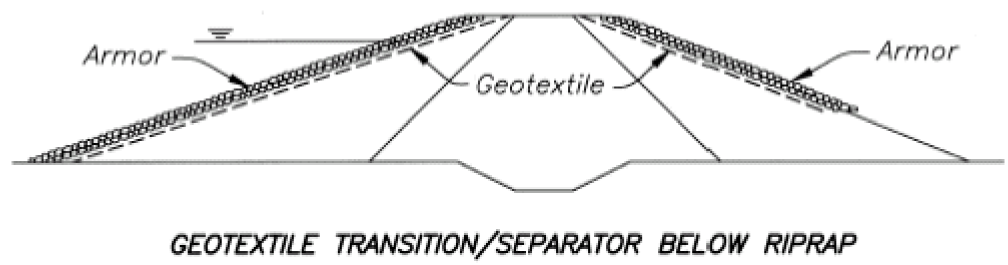


Figure 3.14.—Illustration of geotextiles being used for filtration/separation beneath riprap erosion control revetments.

3.5.2 Permanent surface erosion control

Geotextiles have been used on dams as surface runoff conveyance systems. They have been used in conjunction with armor to control erosion in channel gutters placed on berms and groin areas on embankments.

3.5.3 Temporary erosion control

Geotextiles have been used as temporary erosion protection to minimize erosion and sediment transport during dam construction. To accomplish this geotextiles have been used as silt fences instead of hay bales to remove suspended particles from sediment laden runoff water. Geotextiles have been used as a silt curtain placed within a stream or lake to retain suspended particles and allow sedimentation to occur.

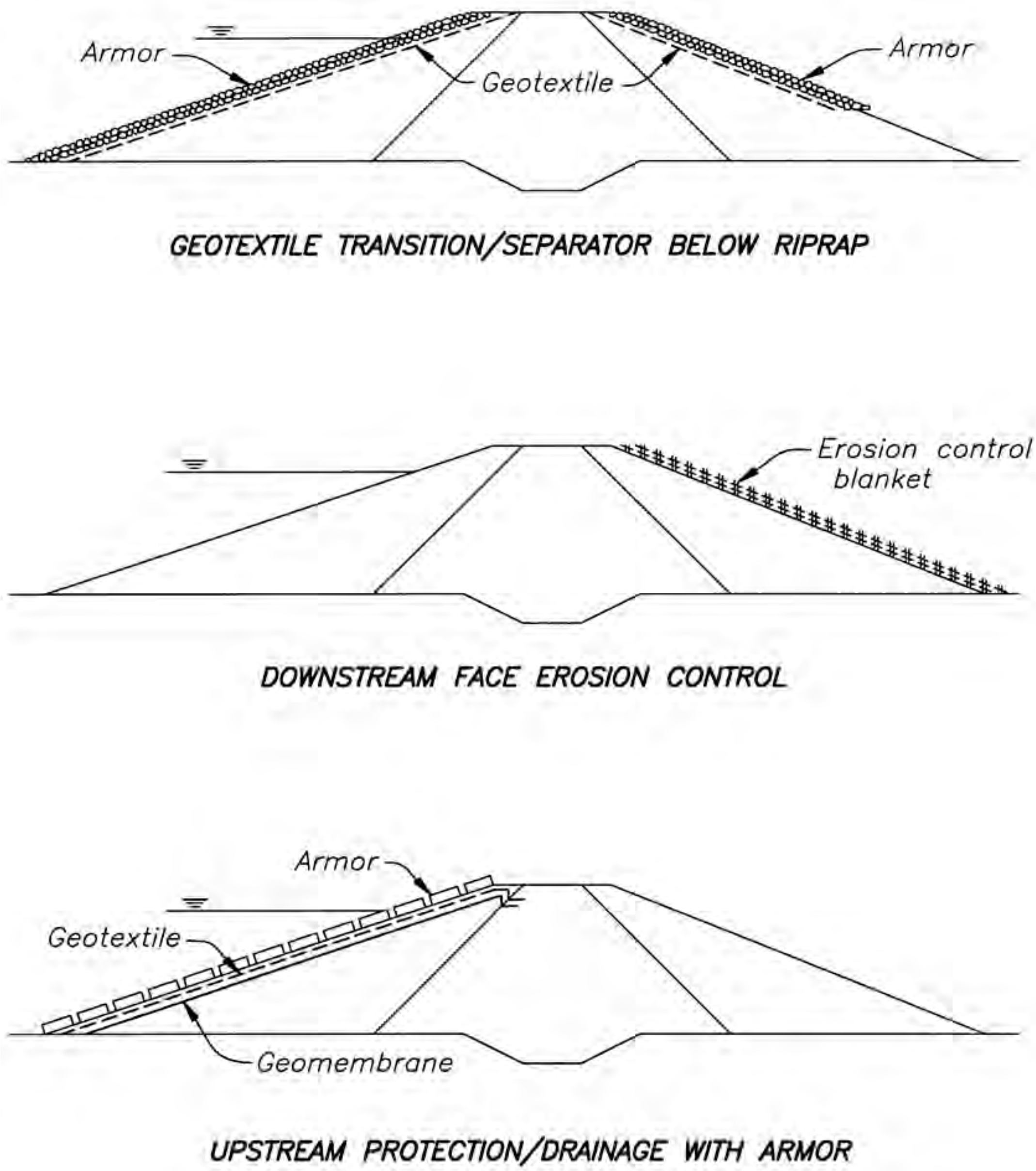


Figure 3.15.—Additional examples of geotextiles used in protection, separation, and erosion control in embankment dams.

Chapter 4

Potential Performance Issues Associated with Geotextiles

The significant economic and technical advantages of geotextiles cannot be realized if performance is compromised. Performance issues with geotextile products fall into three common categories: (1) Limitations that can be accommodated by design, conservative assumption of material properties, use of safety factors; (2) Harsh environments that may be recognized and avoided; and (3) Inherently high-risk applications which should be avoided or undertaken with caution and full understanding of the risks.

Under the first category, design assumptions can be conservatively made for geotextile properties and for loading conditions. Material properties of geotextiles are generally well established since they are manufactured materials. Uncertainties may include ultraviolet degradation, installation damage, and design methods for using geotextile products. These concerns are normally addressed in design conservatism and construction quality control. These common performance issues are relevant to all applications of geotextiles in civil engineering and construction. These issues require attention to detail, but do not preclude use of geotextiles for classes of applications, such as in dams.

Harsh environments have contributed to documented failures of geotextiles. However, these conditions can usually be recognized through site investigation and experience gained from past performance problems. Environmental degradation includes the effects of ultraviolet light, high temperatures, hydrolysis, chemicals, radioactive materials, and biological organisms. Degradation of the polymers used in geotextiles has been shown to be inconsequential for typical soils. Difficult applications may also contribute to geotextile failures. Filtration in dispersive soils and filtration in flow reversal are applications that can cause clogging. These issues require increased attention to detail, and in some cases high-risk environments can be avoided by early recognition. But these concerns do not generally preclude the use of geotextiles in embankment dams.

The last category involves inherently high-risk applications. Perhaps the highest concern is use of geotextile filters for drainage in portions of a dam that are not readily accessible for removal and replacement. Failure of an internal feature of a large dam is not only very expensive to repair; it could jeopardize the safety of the dam. Designers are cautioned to evaluate the consequences of failure during the design process and decide if the risks are worth taking.

There are numerous factors that can lead to performance problems with geotextile installations. The performance problems are related to one of the following general mechanisms:

- Excessive clogging or piping
- Stress induced distortion
- Environmental degradation
- Slope instability
- Rupture

The performance problems can be caused by improper design, poor installation, post installation damage, or degradation.

4.1 Excessive clogging or piping

Clogging occurs when particles fill the void space of a geotextile and reduce its hydraulic conductivity. A reduction in permeability and permittivity occurs in proportion to the amount of void space that becomes clogged with foreign material. The clogging can be caused by filling the voids with soil, with biological microorganisms and their byproducts, or with inorganic chemical precipitates. Some degree of clogging always occurs with a geotextile. If a large amount of the pores within the geotextile become clogged, the geotextile is likely to fail to adequately perform its intended filtration and drainage functions. Such a material which can no longer effectively perform its intended filtration and drainage function is described as being excessively clogged. Excessive clogging can not be allowed to occur.

A related problem, referred to as "blinding" occurs when fine-sized particles accumulate on the surface of the geotextile. The problem of blinding often originates where a geotextile is not placed in direct contact with the soil to be filtered. The void spaces between the soil and the geotextile become filled with fine particles having a lower permeability than the base soil or the geotextile. Blinding can be considered a form of clogging where the blockage is at the surface of the geotextile rather than within it. Many authors in the field of geotextiles make no distinction between clogging and blinding and use the term clogging to imply either mechanism.

Excessive clogging of a drainage system could raise groundwater levels to dangerous levels in a dam. An embankment slope failure could result leading to an uncontrolled loss of the reservoir.

Piping of soil through a geotextile occurs when large amounts of soil pass freely through the openings. If a significant amount of soil is lost it can lead to clogging of down stream drains or can cause internal erosion of the embankment. Piping of the embankment materials could lead to formation of a breach and cause an uncontrolled loss of the reservoir. This problem can occur if the geotextile is specified with too large of openings, if the geotextile properties change in response to stress, or if the geotextile is damaged and can not act as a protective filter. The concepts of clogging and piping are shown in Figure 4.1.

There are several situations where geotextiles are not recommended as filters for base soils (Koerner, 2005a):

- Narrowly graded soils such as loess, rock flower, or crusher fines – It is difficult to build up a filter cake of various soil particle gradations on or in the geotextile when the base soil is made of particles of a fairly uniform size

- Dispersive clays – These non-cohesive particles tend to break down into fine particles that are easily transported through a geotextile.

- Gap graded cohesionless soils – It may be difficult to build a filter cake unless the finer fraction shows a range of particle sizes.

- Turbid water – Such as water that is affected by dredging operations.

- Microorganism laden water – Water from agricultural runoff can be problematic.

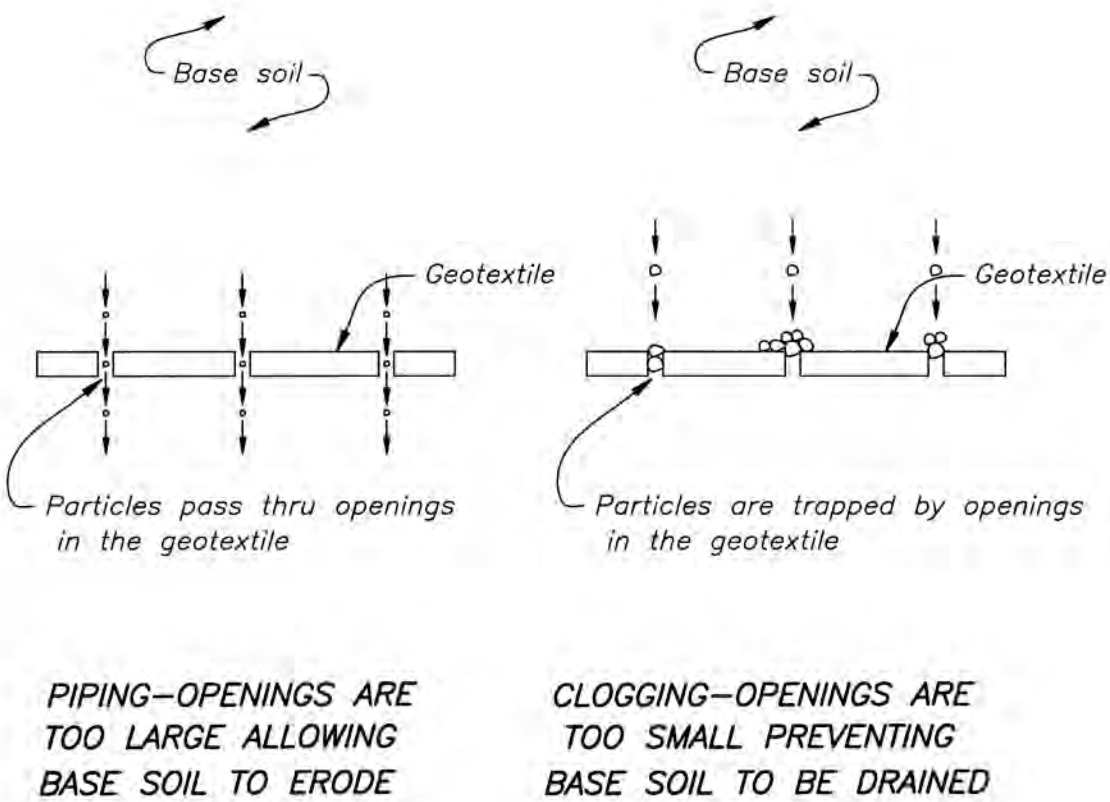


Figure 4.1.—Illustration showing the concepts of soil piping and clogging a geotextile.

4.1.1 Particulate clogging

When a geotextile is placed into service in a soil, soil particles embed themselves on and within the geotextile. The seepage of water will transport additional soil particles to the geotextile. Depending upon the size of the particle and the size of the voids in the geotextile, the particle will either be:

- Stopped at the geotextile surface if the particle is larger than the geotextile voids.
- Enter the geotextile and become trapped within if there is a void space along the flow pathway that is smaller than the particle.

- Pass through the geotextile if the voids along the flow pathway are larger than the particle.

The above discussion applies to non-cohesive sand- and silt-size particles. For smaller clay-sized particles, surface effects resulting in cohesion have an influence upon particle movement and accumulation. Cohesive soils tend to be eroded as groups of particles held together by cohesive forces. This allows use of a filter opening size in the geotextile that is larger than the individual soil particles to be filtered (Berendsen and Smith, 1996), (Giroud, 1997). This filter criteria applies to cohesive soils with a PI>5 (Luettich, Giroud, and Bachus, 1992).

4.1.2 Biological clogging

Biological clogging occurs when microorganisms and or their byproducts fill the void spaces in a geotextile. The resulting substances causing the clogging are often referred to as "biofilms" or "bioslimes" and are typically composed of a mixture of living and dead organisms and mineral precipitates. Microorganisms require nutrients as an energy source for metabolism and thrive where the nutrients are available in conjunction with a growth substrate. The growth substrate is a material having a large surface area that the organisms can attach onto. Excessive biological clogging is not limited to geotextiles. Gravel drains, sand filters, slotted well screens, and geotextiles are all examples of substrates which have a large amount of surface area and have been know to be affected by biofilm deposition.

Biological clogging can occur in both aerobic and anaerobic environments. Microbiology is an area of active research into natural geochemical processes and their effects upon man-made structures and systems. There are many types of water chemistries and microorganism combinations that can lead to this type of biological activity. Experience has shown that processes involving either iron oxidation or sulfate reduction can be problematic at dams.

The formation of "ochre biofilm," a yellowish-brown substance containing iron oxides and organic matter, is the most prevalent cause of excessive biological clogging in embankment dam drainage systems and it also is known to affect geotextile filters. When seepage water containing dissolved iron reaches an oxygen rich environment such as a filter or drain pipe the ochre deposits are observed to form. The mechanism involves oxidation of the iron from Fe^{+2} to Fe^{+3} and subsequent precipitation of Fe_2O_3. This mechanism can occur naturally through inorganic processes but at a very slow rate. Research has shown that microorganisms are able to greatly accelerate this geochemical process (Mendonca, et al., 2003). It has been speculated that it may be possible to limit the ochre clogging problem (Mendonca, et al., 2006) by constructing drains so they remain submerged. At the Ergo tailings dam in South Africa, a p trap is used to vary the drain conditions from aerobic to anaerobic on a regular basis to control biological clogging (Legge, 2004).

An example of an anaerobic biological clogging mechanism involves acidic waters containing iron and sulfate. In this case sulfate reducing bacteria can act in an oxygen depleted environment to form brown to black-colored bioslimes composed of organic matter mixed with iron sulfides. It has bee problematic for geotextiles installed in some tailings dams, although it is believed that sand filters would experience similar problems with clogging (Scheurenberg, 1982). This phenomena is the subject of considerable investigation and research in the mining industry. Attempts to use sulfate reducing bacteria to remove acid and metals from contaminated mine drainage has been hampered by bioslimes clogging of flow paths in water treatment and drainage systems.

4.1.3 Chemical clogging

Chemical clogging involves the precipitation of minerals into the void spaces of a geotextile without the influence of a biological microorganism. Water can dissolve and hold minerals in solution. Precipitates form as a result in a reduction in a waters mineral solubility. This solubility reduction can arise from several causes. It is principally affected by changes in water temperature, pH, or salinity. Change in water pH is the most significant cause for formation of large amounts of mineral precipitates.

Water pH may change by mixing of two different water sources, chemical reaction with minerals in soils, changes in oxidation state, or by dissolving or releasing dissolved gas such as carbon dioxide.

The problem of mineral precipitation typically arises in geotextiles where there is highly alkaline groundwater flowing through the material. Calcium, sodium, or magnesium precipitates may form depending upon the water chemistry.

4.1.4 Inability to support the seepage discharge face

An objection to the use of geotextiles as filters in embankment dams is a propensity for excessive clogging based upon the difference in how a geotextile filter works as compared to a granular filter (Talbot et al., 2001). The theory is that unlike a granular filter which places pressure against the base soil it is filtering, a geotextile can not do this. When a geotextile is placed between a base soil and a gravel surface, seepage forces will move the geotextile away from the base soil and into the voids of the adjacent gravel drain as shown in Figure 4.2. This results in formation of voids between the base soil and the geotextile surface. Seepage forces remove fine particles from the base soil and they fill the voids creating a low permeability zone thus blinding the filter.

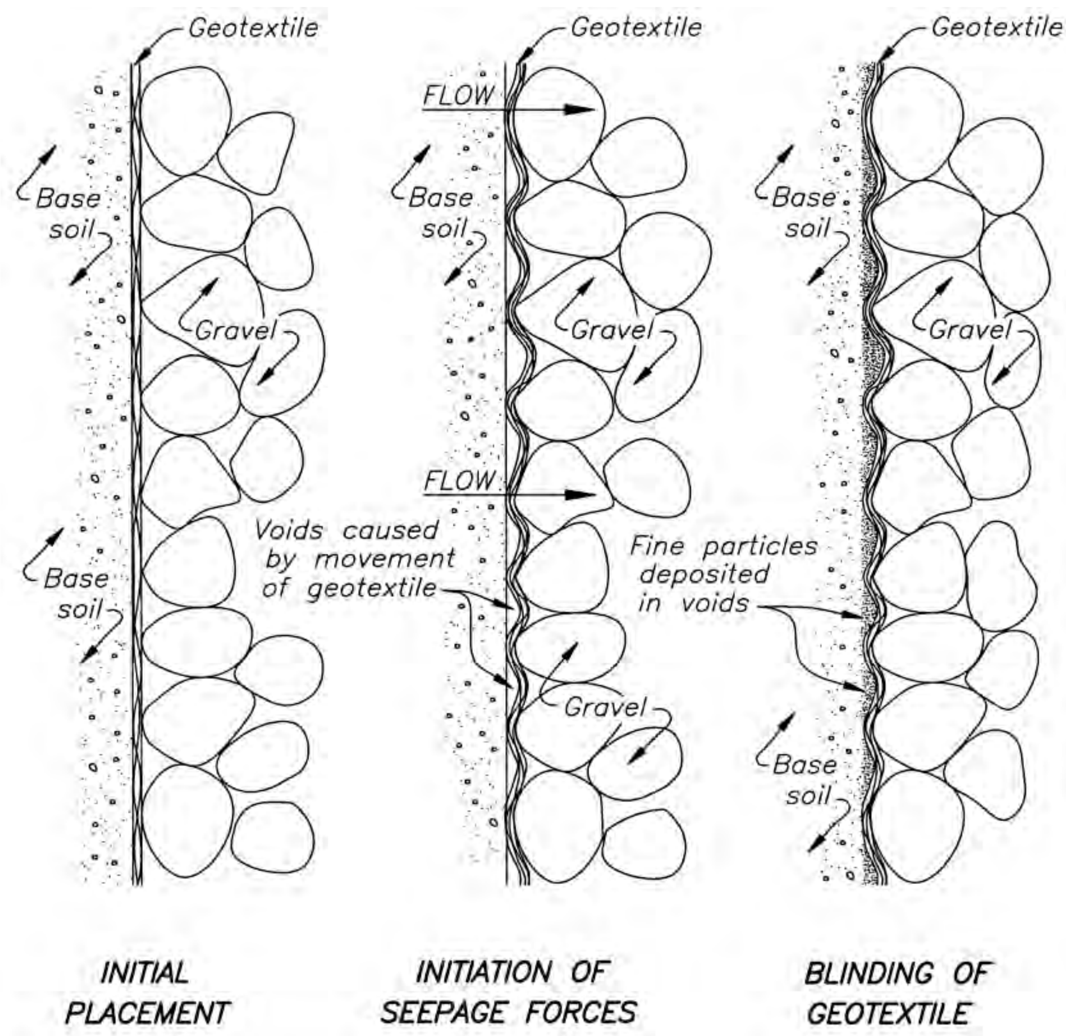


Figure 4.2.—Illustration showing the progressive steps leading to blinding of a geotextile which is a type of clogging that can be caused by using drainage aggregate which is too large in size.

The problem of blinding can also occur if there are open voids in the base soil, or if the base soil surface is irregular and thus prevents good contact with the geotextile from being established and maintained. This problem has been observed for geotextile placements against vertical or steeply inclined slopes. Two precautions are needed to eliminate the tendency towards blinding:

- Use fine gravel (around 1-inch maximum size) rather than a coarse rock for the drainage layer. By limiting the size of the gravel placed in contact with the geotextile, the geotextile will be held tightly against the base soil Giroud, (1997).

- Ensure the base soil surface is smooth and regular and place a flexible geotextile in close contact with the base soil with a minimum of wrinkles.

Regarding the maximum gravel size to use against the geotextile, published recommendations vary from 0.75 inches (Giroud, 1997), to 1.5 inches (Van Zyl and Robertson, 1980).

4.2 Stress induced distortion

Distortion, or a change in dimensions, results from the application of stress to a geotextile. Selection of a geotextile for a particular design may not be valid if it is based upon material properties exhibited in an unstressed state. The dimensions of the geotextile fibers change in response to the loading conditions imposed by their environment. The fibers may become flatter and wider, or they may become thinner and elongate. Considering that geotextiles have varying structural arrangements of the fibers, the responses of these materials to applied stresses can be varied and complex. These dimensional changes can affect the properties of the geotextile. Of most significance to the design engineer are changes to the physical dimensions, size of openings, permeability, and transmissivity of the geotextile material. These changes are of major concern to the filtration and drainage functions of a geotextile.

The stress-induced reduction of geotextile performance in drainage applications has been recognized in both laboratory investigations and in field installations. This issue has been the cause of numerous problems in the municipal solid waste landfill industry and it also raises significant concerns regarding deep burial of geotextiles within dams. The formula proposed by Giroud (1996) has been shown to give reasonable results when compared to laboratory investigations (Palmeira and Gardoni, 2002). Laboratory filtration tests under conditions simulating maximum burial depths can be performed (Palmeira and Fannin, 1998), (Palmeira and Gardoni, 2000). One problem is that these test procedures have not been standardized.

4.2.1 Change in apparent opening size (AOS)

The apparent opening size of a geotextile can be altered by the loading conditions. Tensile forces have been shown to have a significant effect upon the apparent opening size of a geotextile. Knitted and woven geotextiles are more sensitive to the effects of tensile forces than needle-punched nonwoven geotextiles. The relative changes are large enough that the filtration and permeability properties of the geotextile could be significantly changed and result in poor performance.

A study of two woven geotextiles was performed to evaluate the effects of tensile forces upon opening size (Fourie and Addis, 1999). The study showed that the application of tensile forces of about 10% of the tensile strength of the materials could either increase or decrease the filtration opening size. One geotextile exhibited a 28% reduction of the filtration opening size while the other geotextile showed an 11 % increase in the size of the openings.

In another study the openings in a knitted geotextile were found to double in size when stressed and allowed to deform (Fourie and Blight, 1996). Such a large change could lead to failure of a geotextile filter to retain soil particles (piping) if it were selected based upon the average opening size in a low-stress and un-deformed condition.

Compressive forces cause nonwoven geotextiles to become thinner, denser, less porous and less permeable. The changes in opening size can reduce flow rates across the geotextile and may lead to excessive clogging.

4.2.2 Change in transmissivity

Under heavy loading, a nonwoven geotextile will compress making it thinner and denser. As the fibers move to fill the void space, the transmissivity is reduced. If flow in the plane of the geotextile is an important function, the effects of compression must be evaluated. In some cases the compression may reduce the geotextile transmissivity to unacceptable values. This change in material properties can be evaluated by standard laboratory test methods such as ASTM D4716 (Test Method for Hydraulic Transmissivity under Constant Head Conditions).

A similar problem has been encountered in the application of geocomposite geonet drains. Compressive forces cause the geotextile to move into the open flow space formed by the geonet thereby reducing the flow carrying capacity of the drain. Tri-planar geonet drains are more resistant to intrusion and maintain higher flow rates under compression than bi-planar geonet drains.

4.2.3 Change in dimensions due to creep

Under constant loading a geosynthetic material will tend to elongate over time. This is called creep. This elongation can alter the material properties in filtration and drainage and can lead to objectionable amounts of deformation where the material is placed in tension. Geotextile materials are tested under various stress conditions for periods up to 10,000 hours to evaluate creep. Creep is material specific and affected by level of stress and temperature. Reduction factors are used in design to limit the expected amount of strain in a geotextile in order to account for the long-term creep that will take place. Calculation procedures for determining stress levels in a geotextile are provided by (Koerner, 2005a).

4.3 Environmental degradation

The service life of geotextiles can be dramatically reduced by environmental degradation. Environmental factors leading to such degradation include prolonged exposure to ultraviolet light, high temperatures, oxidation, hydrolysis, chemical degradation, radioactive degradation, and biological degradation (Koerner, 2005a).

Ultraviolet light is problematic where geotextiles are left exposed without covering. High temperatures may be a problem during construction or in certain special applications. Most buried applications protect geotextiles from high temperatures and from oxidation. Shallow burial of only a few feet will not protect a geotextile from oxidation. Shallow burial applications should be expected to have shortened life spans due to oxidation of the geotextile.

Hydrolysis is rarely a problem unless the geotextile is exposed to fluids with low or high pH, and then this is polymer specific. One study (Grubb et al., 2001) of polyester and polypropylene geotextiles used in the disposal of gold mine tailings demonstrated that highly alkaline wastes in the residual products of a cyanide beneficiation process cut average retained strengths by more than 40% at 360 days of exposure.

Chemical degradation is polymer specific; for example, diesel fuel is known to degrade polypropylene and polyethylene geotextiles. Contact with radioactive soil or gas in not normally anticipated for water retention embankments and is principally as issue in industrial and waste containment settings. Geotextiles manufactured from modern polymers are not degraded by biological organisms.

4.4 Installation damage

Geotextiles, geomembranes, and other geosynthetic materials are susceptible to installation damage. Contamination, degradation, abrasion, puncture, and tearing of geotextiles during the construction process is likely to occur unless a strict regimen of quality assurance and quality control is followed from the beginning to the end of construction process. The issue is so significant that Chapter 6 of this report details construction methods.

4.4.1 Improper storage and handling

Damage to geosynthetic materials can occur anywhere in their journey from the factory to the completed installation. Typical damage resulting from poor loading, shipping, and offloading procedures are tears and punctures caused by tie down restraints, shifting of loads during transport, improper removal of restraints, and abrasion from dragging materials.

Contamination can originate from storage on bare ground, accidental spills of chemicals, and storage and transport in dusty environments. Particulate contamination can reduce filtration and drainage performance due to clogging. Chemical contamination may degrade the polymer compounds resulting in severe loss of strength.

The problem of degradation by ultraviolet light can originate from extended outside storage of geosynthetics without protective covers. Since geosynthetics are shipped with a protective outer wrapper, the problem of light exposure typically originates when the protective wrapper is damaged or when rolls of goods have been unwrapped and then delays in installation are encountered.

Onsite transport activities also can damage geosynthetics. Common problems are improper lifting of rolls off of a pallet. Methods such as using an excavator bucket or a forklift to lift the rolls creates a stress concentration that can stretch or tear the geotextile. In some cases forklifts have been observed to impale the roll resulting in severe puncture damage. During transfer to the deployment area, care is required that the product does not strike any other objects which could abrade, puncture, or tear the geosynthetic material.

4.4.2 Deployment

Damage during deployment often results from improper handling. While rolled goods can safely be unrolled by hand labor, it must be done in a manner so that the material is not dragged across the ground surface. Dragging the geotextile can abrade it, disrupt angular stones in the subgrade leading to puncturing, or cause stretching or tearing by pulling on the material in an effort to make it slide across the ground surface. Oversize stones in the subgrade can cause punctures.

Intimate contact of the geotextile with the surrounding is required, especially for functions such as filtration and drainage. Deployment methods must limit or eliminate the formation of wrinkles. Repositioning must be performed in a manner to avoid stretching the geotextile. Stakes and pins should not be allowed as temporary anchors because they will needlessly puncture the geotextile. Sandbags, smooth-surfaced weights, or small piles of gravel are preferred means of temporarily securing a geotextile during deployment.

4.4.3 Covering and equipment operation

Placing cover soil onto a geotextile is also a potential source of damage. A minimum of 1.5 feet of cover is usually required in order to allow light traffic over a geotextile. Low ground pressure bulldozers are specified for use in covering the geotextile without damage. On slopes it is recommended to push cover uphill rather than in a downhill direction. The minimum cover layer will not protect the geotextile from sudden braking, sharp turns, or heavy hauling by construction equipment. Haul roads should have thicker cover (around 5 feet) but this still may completely protect the geotextile from sudden braking and sharp turns by a scraper or large truck.

Some installations call for placing riprap directly onto a geotextile. Although damage can be minimized by limiting the drop height, larger riprap (about 3 ft. diameter) should not be placed directly onto a geotextile. Determining what size of riprap is too large to place directly on a geotextile is site specific and depends upon the nature of the subgrade, the strength of the geotextile, hardness and angularity of the rock, and the method of placement. Test placements can be used to determine if installation procedures are viable. Where damage is indicated, a protective layer of sand and/or gravel should be placed between the geotextile and the riprap.

4.5 Post installation movement

Geotextiles must be designed to consider movement after installation. Foundation failure, slope instability, and embankment cracking may rupture a geotextile. In the first two cases problems with design or construction are the likely cause. Damage from embankment cracking is perceived as a problem where geotextile filters are thought to have a disadvantage in comparison to natural filters, especially in seismic events.

4.5.1 Foundation instability

Foundation instability and movement, if excessive, will cause a geotextile to rupture. Geotextiles are often placed upon weak foundations to act in tension to prevent excessive settlement. They must be properly designed to prevent failures such as those shown in Figure 4.3. A more problematic issue is the use of a geotextile to span over a locally weak or voided space such as is found in karst terrain or associated with underground mine openings. Differential settlement can result in large elongations of the geotextiles or geogrids resulting in failure. Geotextiles should not be used to span over foundations with significant voids.

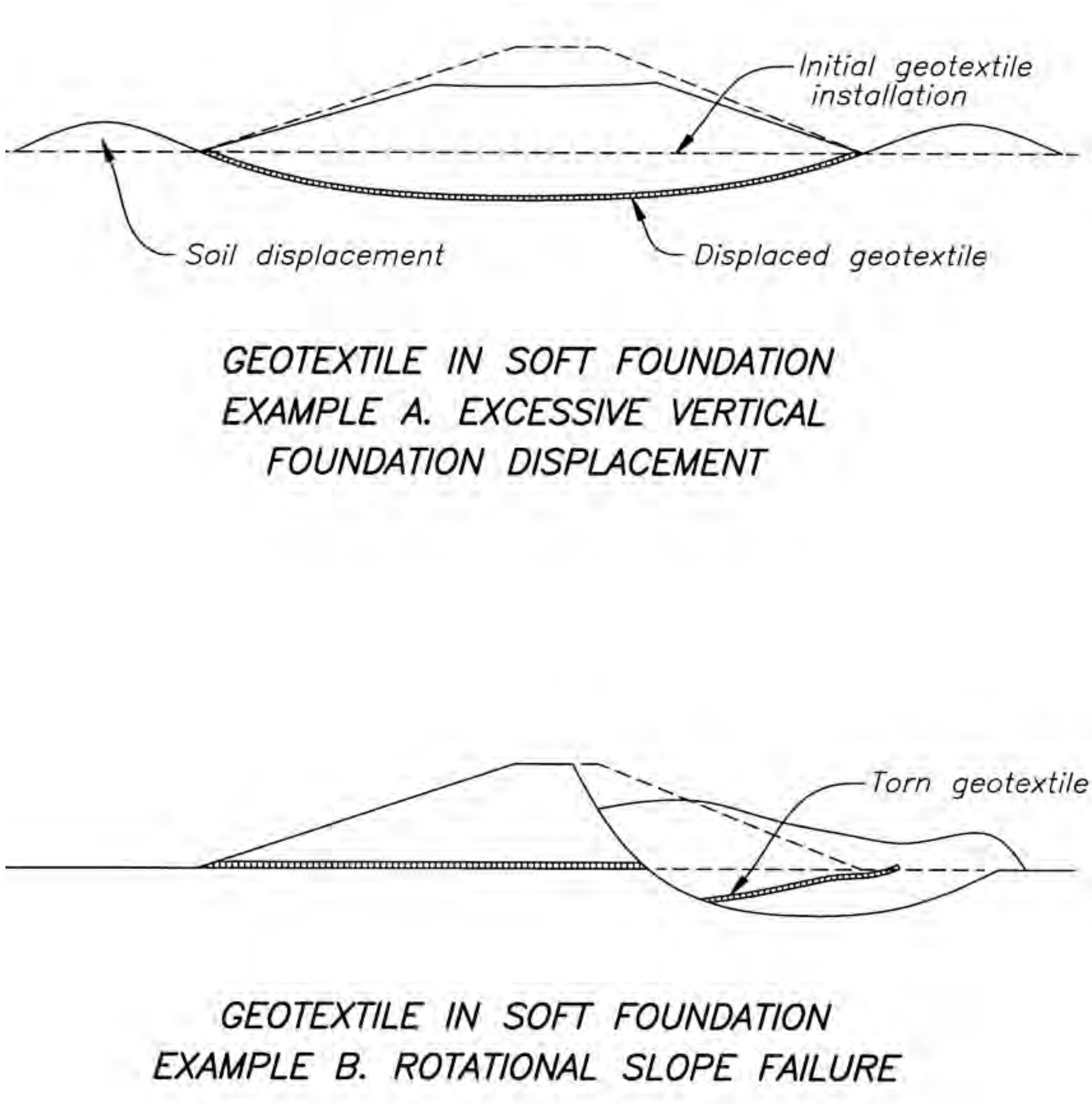


Figure 4.3.—Illustration showing examples of geotextile failures in soft foundations.

4.5.2 Slope instability

The incorporation of one or more geosynthetic materials into a soil mass creates a potential failure plane. Movement along the interface between a soil and a geosynthetic material or between two geosynthetic materials must be properly evaluated during design. Failures have resulted where the interface frictional strength has not been properly determined or where the build up of soil pore water pressure has occurred. This problem has occurred in numerous instances in the solid waste industry (Koerner, 2005a).

There is a tendency for engineers, who are not experienced in geosynthetic design, to try to utilize published values for interface friction strength as a design basis for slopes incorporating geosynthetic materials. While use of published values can often be used to approximate soil slope stability, it is a dangerous approach for final geosynthetic design. The actual soil to geosynthetic frictional strength can vary considerably from published values and must be determined in the laboratory.

It is recommended that large scale shear testing (ASTM D5321) be performed with the site specific soils and samples of the actual geosynthetic materials that are proposed for use. Where the construction soils are not available ahead of time, the required testing program can be included as part of the construction performance specifications so that the design assumptions can be confirmed early on and prior to building the entire project.

Large scale shear testing must include all of the layers to be placed under and over a geosynthetic and must model the loading and soils compaction characteristics. A geotextile placed against a geomembrane is often found to form the weakest interface surface in a layered geosynthetic and soil slope configuration. Textured geomembranes help increase the interface friction and resulting factor of safety against sliding failures.

Another area of concern is the buildup of pore water pressures on top of a geomembrane or behind a geotextile. In the first case, consider a geomembrane placed near the upstream slope of a dam to act as an impermeable barrier to contain the reservoir and prevent excessive seepage through the embankment. The geomembrane is typically covered by soil and riprap to protect it from the elements. As the reservoir is drawn down by operation of its outlet works pore pressures can build up at the geomembrane surface and potentially cause a slope failure. To guard against this type of problem a drainage layer is usually placed immediately above the geomembrane. The drainage layer is typically a geotextile or a geonet geocomposite.

Another problem with pore pressure can occur where a geotextile is used underneath riprap. The soil under the geotextile must be able to dewater through the geotextile to dissipate pore pressure as the reservoir is drawn down or under significant wave action. If the geotextile has too small an opening size or becomes excessively clogged, it may not adequately transmit the water and a slope failure can occur. Some designers prefer using a woven monofilament geotextile for placement under riprap because of the ability of woven material to rapidly drain when impacted by large waves (Christopher and Valero, 1998).

4.5.3 Stress induced tearing

A major objection to the use of geotextiles as filters in embankment dams is the potential for tearing of the geotextile from movements in the dam (Talbot et al., 2001). There are several means by which the impervious core of an embankment dam can crack including differential settlement, seismic activity, and desiccation. The theory is that a geotextile is compressed by high soil pressures which will inhibit its movement. If the embankment cracks in a direction that is perpendicular to the plane of the geotextile, the geotextile may tear because it will undergo stretching over a short distance.

In order to investigate this issue of geotextile tearing in response to embankment cracking the following calculations were made:

Failure Criteria for embedded fabric, with interface friction top and bottom:

$$P = \frac{T_{ult}}{FS} = 2L\sigma \tan\delta = 2L(K_a\gamma h)\tan\delta \qquad (1)$$

Where:
P = Pullout force (lbs)
T_{ult} = Ultimate Tensile Strength (lbs)
FS = Factor of Safety
L = Effective Embedment Length (feet)
σ = stress normal to plane of geotextile (psf)
δ = Interface friction angle between soil and geotextile
Ka = Earth Pressure Coefficient
γ = Unit Weight of Overburden (pcf)
h = depth (feet)

Elasticity of the fabric, where there is an effective embedment on both sides of the crack center:

$$e_{ult} = \frac{c}{2L} \qquad (2)$$

Where:
e_{ult} = Ultimate strain (at T_{ult}) (%)
c = crack aperture (feet)

Combining (1) and (2),

$$c = \frac{T_{ult} * e_{ult}}{K_a \gamma h \tan(\delta) FS} \qquad (3)$$

The resulting formula was graphed showing rupture limits for varying crack widths and burial depths and is shown in Figure 4.4:

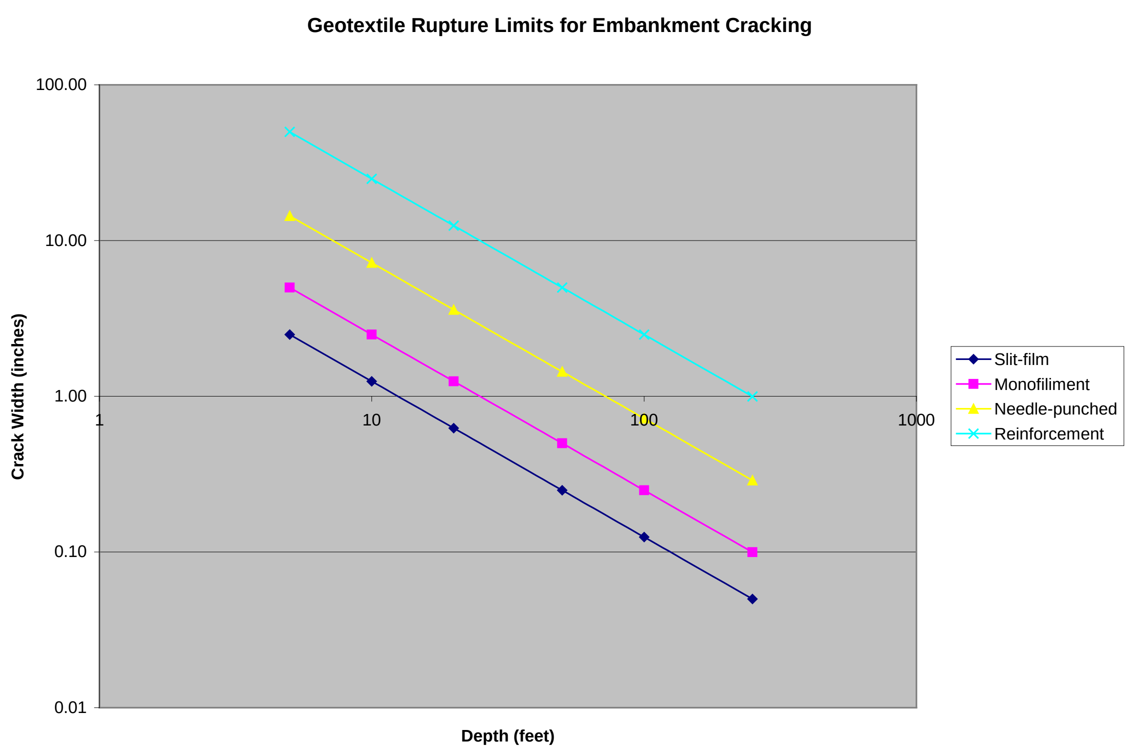


Figure 4.4.—Geotextile rupture limits due to cracking at various burial depths. Typical values were used for geotextile strengths.

4.6 Intrusion

Besides damage during construction, intrusion and rupture of geosynthetics can be caused by vegetation and by animals. Root penetration of embankments can open up seepage pathways and can lead to clogging of drains. Animals such as muskrats and beavers are notorious for digging into embankment dams and damaging the installation.

4.6.1 Intrusion by vegetation

Roots from vegetation can penetrate geotextiles and geomembranes. Geosynthetic drains may become clogged by roots. There is a proprietary product available which consists of a geotextile bonded to porous beads containing a herbicide (fig. 4.5). The longevity of the herbicide is not known and its use in dams has not been reported.

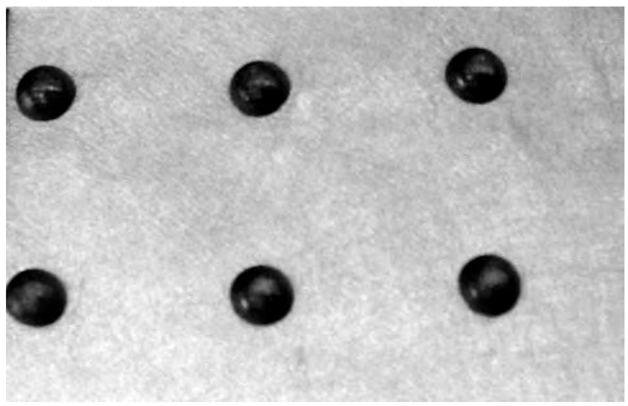


Figure 4.5.—Photograph of a geotextile with a herbicide delivery system designed to stop root penetration.

4.6.2 Intrusion by burrowing animals

Intrusion by burrowing animals is a problem in dams regardless of geosynthetic materials being used or not. Being relatively thin, geotextiles are easily penetrated by burrowing animals. Placing wire mesh screens over drain outfalls is a necessity to exclude burrowing rodents from drainage systems. Observation and reporting of burrow openings is important to identify a need for corrective action to limit damage to a dam.

Chapter 5

Current Status of Design Procedures

5.1 Risk and redundancy

A rational design method for geotextile applications in embankment dams should involve as a minimum the following steps:

- Assess the downstream hazard in the event of a dam failure.
- Identify the minimum design life and performance level expected of the dam.
- Select the materials, embankment cross-section and construction control to achieve the desired level of safety and serviceability for the dam.
- Assign a Design Classification for the proposed geotextile application.
- Perform preliminary economic analyses to evaluate whether cost savings strongly favor a design employing geotextiles over more conventional dam building materials.
- Perform the design analysis and select geotextiles meeting the design criteria.
- Conduct failure mode analyses to predict the likely impact on the integrity of the dam for realistic variances in the performance of geotextiles.
- Revise the design to achieve the desired level of performance.

Chapter 4 outlined in a qualitative sense the principal mechanisms that degrade the properties of geotextiles in service. So given their manifold limitations how does the engineering profession advance the use of geotextiles in the field of dam construction? It is important to understand the concepts of risk and redundancy as they relate to geotextile use in an embankment. The placement of a geotextile (inaccessible or accessible location) and the redundancy of the geotextile function (geotextile alone performs needed function or another conventional redundant system is also present) are important considerations with respect to evaluating the risk of failure associated with a particular design configuration and to determining the level of effort that should be applied to the design task. Table 5.1 presents a classification of the access, redundancy, and critical nature of the function of a proposed geotextile installation in order to facilitate the design engineers' understanding of the implications of geotextile use:

Table 5.1.—Classification of geotextiles in embankments by access and redundancy.

Design Classification	Access and Redundancy	Critical or Non Critical *
A-critical or A-noncritical	Geotextile performs a function in internal locations in an embankment with limited or no access, once installed. There is no redundant natural design element present.	Likely to be a critical design element.
B-critical or B-noncritical	Geotextile performs a function in internal locations in an embankment with limited or no access, once installed. There is a redundant natural design element present.	Unlikely to be a critical design element.
C-critical or C-noncritical	Geotextile is installed in locations where it can be accessed without excessive cost and effort. There is no redundant natural design element present.	May or may not be a critical design element.
D-critical or D-noncritical	Geotextile is installed in locations where it can be accessed without excessive cost and effort. There is a redundant natural design element present.	Unlikely to be a critical design element.

* Is Failure of the dam possible given poor performance of the geotextile? Each dam is unique and therefore evaluation of the critical nature of the application must be evaluated on a case by case basis.

It should be remembered that current policy is that geotextiles should not be used in locations that are critical to the safety of the dam. Expanding the use of geotextiles in dam construction will require that engineers take the initiative in incorporating them in their designs and be open to contractors' proposals to use them as practical substitutes for conventional building materials. Obviously, simply expanding the square footage of installed geotextiles is not the goal here. Engineers will have to document that the applications are consistent with defensible engineering practice. As with any evolving technology the engineer must expressly state the performance criteria the geotextile should meet. Further, the engineer has to document that geotextile limitations have been addressed with regard to their ability to perform their intended function. Finally, as with all designs, engineers have to concede that problems can develop. To the extent practicable, the design should consider potential failure modes and provide measures to guard against such failures should the geotextile or any other feature of the dam perform below design requirements.

Specifically, that documentation needs to expressly state and document where appropriate:

- The function that a geotextile is to perform; the reader is referred to Chapter 3 where the subject is discussed at length.

- The timeframe over which it needs to perform satisfactorily,

- The mechanisms that degrade the ability of the geotextile to perform as planned,

- The consequences of the geotextile performing at levels short of the design capacity, and

- Provision of complimentary design features as necessary to achieve the desired level of reliability.

Finally, where practicable, one should provide means to monitor the performance of the dam to provide data that infers how features are performing, i.e. trust but verify.

The concept of reduction factors has been developed as a means of ensuring that a geotextile will perform as expected (Koerner, 2005b). Rather than the conventional method of applying a factor of safety, the laboratory test values are identified as ultimate values which are reduced to an allowable level (of stress, etc.) that can be safely applied to the material in service. The reduction factors decrease the ultimate geotextile property value to a safe level. Because of uncertainties in design, the factors are conservative and can result in allowable values that are up to 16 times less than the ultimate value determined by laboratory testing (Koerner, 2005c). This issue is discussed further in Section 5.5.3.

5.1.1 Geotextile service life

While it would be desirable to have geotextiles last indefinitely, they have a finite life as do other man-made materials used in embankment dams such as concrete, plastic pipes and metal. Field data is available for geotextiles placed in 1970 in Valcros Dam (France) as a filter wrap on drains and as an underlayment for riprap. Mechanical and hydraulic testing of exhumed samples of the non-woven geotextiles showed losses from the original properties "were generally nominal with maximum reductions (perhaps installation-related) being 30%" (Koerner, 2005c). A thirty percent reduction in material properties in the matter of a decade of any feature of a dam's design would likely be a "show stopper" for its continued use, let alone the expanded use of such a material.

To clarify the questions arising from the 30 percent reduction in physical properties, the authors contacted Dr. Giroud, one of the principal designers of Valcros Dam. Dr. Giroud (Giroud, 2005) stated that "*the reduction in properties was observed the first time tests were made, i.e. 6 years after construction. Reduction in tensile strength was 10 to 20%. Tests were done for the second time 22 years after construction. No reduction was observed between year 6 and year 22. This is why mechanical damage during construction was assumed.*"

In response to the question whether ultra-violet exposure was a significant factor in the degradation of the geotextile, Dr. Giroud responded as follows: "*We were aware of the potential for UV degradation, but the geotextile was made of polyester and had a high resistance to UV light. Furthermore, construction was quick. Therefore, I do not think that UV degradation played a role.*" Dr. Giroud felt the degradation typified the "*ordinary type of construction damage. We could perhaps have taken more precautions, but I do not think there was poor construction practice. I think that the amount of construction damage that took place at Valcros dam probably occurs in many projects.*" The foregoing comment is sobering. It emphasizes the need for a rigorous quality control/quality assurance program to minimize such damage. Even with such a program, liberal factors of safety in the design phase are a must for those geotextile properties germane to the satisfactory performance of the material in the application at hand.

Given the uncertainty associated with the aging of geotextiles, the practitioner should identify an anticipated design life for the geotextile at which point some further action will be required to assess the condition of the material. One should have details, plans and a cost estimate for removal and replacement of the geotextile in the design documentation. The owner can then make a decision whether the cost savings and a more timely reduction in risk posture warrant the use of geotextiles given their finite but unknown service life. At present, when the engineer dismisses the use of geotextiles outright for durability concerns, that individual is making that decision for the owner.

5.1.2 Consequences of poor geotextile performance

If an internal feature of a dam does not perform as expected, it is not automatically repaired. Installations that are deeper than 20 feet are generally not easily accessible for removal and replacement. Instead, it may become a risk that may be accepted. Options to remedy the situation are balanced with cost, and are prioritized with other O&M work. Installation of geotextile products should be evaluated with respect to potential consequences should they fail to perform as expected.

Event trees are used as a tool for risk analysis. Possible results from geotextile failure are:

- Excessive clogging of a filter – increased embankment groundwater levels, uncontrolled seepage, reduced embankment stability, slope failure, and breach of embankment.

- Tearing of geotextile filter – loss of filtration, internal erosion, piping, excessive clogging of drainage system, sinkhole formation, and breach of embankment.

Given poor performance or failure of a geotextile, failure of the dam is not a certainty. The consequences must be evaluated on a case by case basis as part of the risk analysis.

The primary function of a geotextile to perform deep within an embankment is as a filter, most likely at the contact between the core and the chimney drain. Here, the fabric is expected to prevent the piping of fines from the core while maintaining a minimum permeability higher than that of the core. During placing and subsequent service the fabric can be expected to experience some clogging. If clogging of the fabric reduces the hydraulic capacity of the geotextile below that of the core, the phreatic surface in the core would rise and increase uplift pressures under portions of the downstream shell. This scenario raises stability concerns. Consequently, one needs to assess how likely is it that clogging would reduce the geotextile fabric's permeability below that of the core. Research in the characterization of the pore size distribution of fabrics has shed light on the matter. A fabric's pore size distribution determined from the bubble point method (Bhatia & Smith, 1994) has helped elucidate the relationship between the particle sizes that have clogged the fabric and the permeability of the affected fabric. The predictive permeability relationship developed from that research (Fischer, Holtz, & Christopher, 1996) showed a material reduction in permeability requires a significant degree of clogging. The relationship predicted that if the smallest 20% of pore constriction area were to clog there would only be a 5% reduction in the fabric's permeability. Should the smaller half of pore area be clogged, this would only reduce the fabric permeability by 17%. This suggests that clogging has to be excessive to blind off the geotextile fabric.

5.1.3 Providing the necessary complementary functions

A catastrophic failure normally requires a number of adverse events and/or conditions to prevail. If one or more of those events or conditions is absent or its impact mitigated, the progression to failure can be interrupted and failure likely averted. Thus, one design approach is to intercede and block/mitigate the development of a necessary step/condition in the progression to failure.

Consider the case of addressing the possible adverse impacts to downstream slope stability and/or piping concerns associated with excessive exit gradients near the downstream toe. One could start with the presumption that the geotextile filters for the chimney and blanket drains have somehow completely clogged. A steady state seepage analysis could be run to predict the resulting uplift and exit gradients acting on critical sections of the dam. Based on that assessment the designer could provide strategically located oversized drains to relieve excess pore pressures that would otherwise extend further beneath the downstream portion of the dam. Alternatively, the downstream section could be redesigned with a flatter slope or toe berm. The flatter slope improves slope stability by lessening driving forces while the toe berm lengthens the seepage path and thereby reduces the exit gradients driving internal erosion. An inverted filter near the exit area offers another approach to allow relatively high exit gradients to be dissipated with adequate factors of safety preventing a piping or "quick condition" developing in the toe area.

Geotextiles typically come in 12.5 to 15.5 foot widths. Thus, most applications require multiple panels of geotextiles laid next to each other to provide the necessary coverage. Past practice has been to simply overlap the panels by a minimum of 6 inches with greater overlapping provided based on a number of factors including where relatively large settlements are anticipated. More rigorous measures are appropriate where a geotextile is to be used in Design Class A through C. The designer has to be proactive in minimizing the likelihood of gaps opening between geotextile panels where tensile forces or differential movements act to pull them apart. This is best addressed by sewing or fusing the panels together to develop a tensile strength on the order of the geotextile itself. Note that the designer should have a sense of how long the stitched seam has to resist tensile stresses. It is likely that field seams need only survive the process of installation and initial settlement. Thereafter, the confining stresses of the encapsulating soil "pin" the geotextiles in place and largely eliminate changes that would tend to increase tension between individual panels.

The friction angle at the interface of the geotextile and the abutting soil may be less than that were the fabric to be absent and there was direct soil-to-soil contact. The designer should be aware of this potential weakened slip plane. Normally, the fabric is situated deep enough within the embankment section that a kinematically plausible slip surface has a suitably high factor of safety against a slope failure. On the rare occasion that the fabric compromises slope stability below accepted norms, the designer has a number of options. A different geotextile type with better frictional properties may be specified, the geometry of the chimney drain/fabric feature may be changed, or the downstream slope could be flattened or buttressed to improve stability.

Oversized, angular gravels and larger particles that bear directly against the geotextile pose a puncture or tearing hazard to the fabric. Attention should be paid to providing at least a narrow select zone immediately abutting the geotextile that is free of particles capable of damaging the fabric. Alternatively, there are hybrid geotextiles where a heavier fabric can be bonded to a lighter fabric selected for its filtering ability. The heavier fabrics afford a higher degree of protection against puncturing which is lacking in the geotextile selected for its filtering ability.

As previously noted the dam designer proposing to use a geotextile in a role falling within Design Classification A or B faces considerable uncertainty as to their design life and performance. It is incumbent on the designer to provide two criteria regarding their continued use.

> One criterion would be a stated service life after which the geotextile's integrity is to be demonstrated. Initially, this estimate would reflect the present limited ability to project design life. That projection is based on the degree of degradation resulting from accelerated aging tests of coupons of the material subject to elevated temperatures while submerged in a suitable permeant. This should be augmented over time by the periodic exhumation and testing of samples of the geotextile from the structure. In time, case histories should provide a database to improve both the foregoing predictions of a suitable service life for geotextiles under broad categories of service conditions.
>
> The other criterion would be some form of secondary performance measure(s) that if not met requires action. This would establish a threshold of adverse change in behavior which generally correlates with embankment performance. This would include such things as piezometric heads and drain behavior that show a disturbing trend in the quantity of seepage and/or its character, most notably the presence of soil fines in the seepage.

Finally, proponents of geotextiles have to acknowledge that there are situations where it is inappropriate to rely solely on geotextiles. Consider a situation with seismic induced cracking concerns. Since in new construction or retrofitting, all threats to the integrity of the dam would be addressed, it is presumed that the seismic stability of the embankment section is acceptable. Therefore, the potential for seismic induced transverse cracking (perpendicular to the long axis of the dam) is the primary threat to embankment stability. The principal area where such cracking would be of concern is in the immediate vicinity of any interface between the earthen portion of the dam and any significant concrete structures, and at the abutments. It is possible that the geotextile would be displaced away from its contact with such rigid structural elements. The geotextile lacks a self-healing capacity to fill in such a crack and stabilize the situation. Thus, additional measures are necessary to bring a survivability capability to the solution. So, a prudent design likely would rely on a geotextile to achieve the filter function over the majority of the dam length; additional localized measures would be applied in the immediate vicinity of the interface (for example embedding the geotextile in or against a layer of sand at the interface area. A similar argument could be made regarding embankment cracking induced by abrupt changes in foundation geometry. Geotextiles in such areas could be augmented in the immediate area of concern with conventional granular filter material which is a proven means of addressing such problems. In both instances the designer is taking advantage of geotextiles to reduce to a minimum those areas where more expensive conventional measures are perceived to be necessary at this stage of evolving practice.

5.1.4 Quantitative characterization of performance criteria

The foregoing discussion set the stage for identifying the relevant performance criteria to consider in using geotextiles in roles falling within the varying Design Categories in the embankment section. The discussion has been largely qualitative in nature. Once the decision is made to use geotextiles, it is necessary to quantify the properties that the geotextile must possess to provide the desired serviceability. It should be noted that the following information is not intended to serve as a design manual. Readers should go to the cited works for design procedures.

5.2 Filter Design

A large variety of geotextiles including nonwoven needle-punched, nonwoven heat-bonded, woven (usually monofilament) and knitted geotextiles have been successfully used for filtration in embankment dams. Each type of geotextile has its place in filtration applications. Although nonwoven geotextiles are most commonly employed as filters, they are not automatically the best choice for a given application. The key filtration properties of geotextiles with respect to their commercial availability are presented in Table 5.2:

Table 5.2.—Range of material properties for geotextiles commonly used for filtration.

Geotextile Type	Apparent Opening Size (O_{95}) ASTM D 4751 (mm)	Permittivity ASTM D 4491 sec^{-1}	Comments
Woven	common range: 0.212 to 0.85 can be as low as 0.05 (Ramesy and Narejo, 2005)	common range: 0.05 to 1.5 can range from 0.01 to 4.0 (Ramesy and Narejo, 2005)	They do not transmit flow in the plane of the geotextile, they are stiffer than nonwovens making direct soil contact more difficult to achieve and have lower interface friction strength than nonwovens. If heat-bonded (calendared) the fibers are fused together at the weave intersections providing excellent dimensional stability (maintains AOS). Percent open area (POA), is an important design property regarding permeability.
Nonwoven Needlepunched	common range: 0.15 to 0.5 can be as low as 0.074 (Hwang and Others, 1998)	common range: 0.7 to 2.5 can be as low as 0.5 (Ramesy and Narejo, 2005) and as high as 4.5 (Hwang and Others, 1998)	Flexible, conforms well to soil surfaces and has higher interface friction than woven or heat-bonded geotextiles. Provides higher flow rates than heat bonded geotextiles and can transmit flow in the plane of the geotextile. The AOS and permeability decrease due to increasing depth of burial which can lead to clogging if not evaluated during design. Thicker fabrics have greater strength but may be more prone to clogging.
Nonwoven Heat Bonded	0.1 to 0.3	0.2 to 0.8	These geotextiles are thin and stiffer than needlepunched nonwovens, may be hydrophobic and require a driving head for significant flow to occur.

			The fibers are heat fused which results in excellent dimensional stability in retaining their AOS. Wick drains utilize this type of geotextile to filter and dewater fine clay and silt.
Knitted	0.6		The principal application is as a polyester "sock" wrapping around a corrugated perforated drainage pipe. Tensile stress causes large changes in opening size, This geotextile filter is typically used in shallow burial situations with a sand backfill.

Similar to the design of granular filters (Kleiner, 2005), geotextile filter design has matured over several decades to incorporate lessons learned from research and experiences with poor performance (Christopher and Fischer, 1991), (Giroud, 2005). Past problems with clogging largely stem from a poor understanding of geotextile filtration behavior and inadequate design criteria.

In filtration, liquid flows across the plane of the geotextile while soil is retained. Similar to the design of a granular filter, the design of a geotextile filter requires balancing opposing criteria. The filter openings must be small enough to prevent loss of significant amounts of the base soil (meet particle retention criteria) and the openings must be large enough to effectively transmit seepage flows without blinding or clogging (meet permeability and clogging criteria).

The proper design of a geotextile filter involves the identification of a fabric which is able to facilitate the establishment of a soil "filter cake" or "bridging network" against the geotextile (Watson and John, 1999), (Aydilek, 2006). The filter cake is a transition zone formed by modification of the base soil being protected by the filter. Upon initiation of flow, the particles in the soil that are adjacent to the geotextile are mobilized. The smallest sized particles are removed and pass through the geotextile, the medium and larger sized particles are retained in and on the geotextile. A granular filter cake is built up and it acts to retain the remaining layers of base soil. In this ideal condition, neither excessive piping nor excessive blinding/clogging occurs. Since a variety of particle sizes are required for the filter cake to form, geotextiles may have difficulty in forming an effective filter for some soils. Highly dispersive clays, gap-graded and broadly-graded cohesionless soils have a tendency towards blinding and clogging rather than forming a filter cake. Such soils can often be filtered by a geotextile but design requires careful selection and laboratory testing may be necessary.

Current filter design is a multi-step process (Luettich, Giroud, and Bachus, 1992) which involves:

- Definition of the filtration and drainage requirements
- Definition of the soil boundary conditions
- Determination of the soil retention requirements
- Determination of the geotextile permeability requirements
- Determine the anti-clogging requirements
- Determine the strength and durability requirements
- Select a geotextile filter
- When warranted, verify performance by conducting laboratory tests with site soils

Important filter design parameters are defined as follows:

C_c	soil coefficient of curvature = $(d_{30})^2/(d_{60} \times d_{10})$
C_u	soil coefficient of uniformity = d_{60}/d_{10}
C'_u	soil linear coefficient of uniformity = $\sqrt{(d'_{100}/d'_0)}$
d_x	soil particle size where x is the percent of soil particles smaller than the stated size
d'_x	soil particle size where x percent is smaller obtained from a straight-line approximation of the soil particle size distribution
I_d	soil relative density
i_s	soil hydraulic gradient
k_s	soil hydraulic conductivity
PI	soil Plasticity Index
O_x	geotextile opening size where x percent of openings are smaller than the stated size
k_g	geotextile hydraulic conductivity (permeability)
ψ_g	geotextile permittivity
t_g	geotextile thickness
POA	woven geotextile percent open area

5.2.1 Filter and drainage requirements

The filter and drainage requirements are defined by the intended function and placement of the geotextile within the dam. The geometry of the filter and type of drainage system must be identified. Will the associated drain be a gravel layer, a gravel layer with a pipe, or will the filter also serve as the drain (such as a thick nonwoven geotextile or a geonet geocomposite drain)?

5.2.2 Soil boundary conditions

The gradation, plasticity, hydraulic conductivity, density, and coefficient of uniformity of the base soil to be filtered must be determined. The confining pressures acting on the geotextile must be determined. Is the soil a dispersive clay, or a gap-graded or broadly graded (internally unstable) noncohesive soil? Such soils are prone to internal erosion and only a small range of geotextile products may work as effective filters for these soils. Narrowly-graded internally stable base soils, and plastic clays are more easily filtered by geotextiles and there may be a wider range of geotextiles that can filter these types of base soils. The hydraulic conditions anticipated in the soil must also be determined, including the seepage pathways and anticipated gradients, flow quantities, and nature of the flow. Are steady, varying, or reversing flow conditions expected?

5.2.3 Particle retention criteria

Current design methods in the most popular design textbook (Koerner, 2005a) are based upon the method and flow chart presented by (Luettich, Giroud, and Bachus, 1992) and should be used for geotextile filter design. This work along with the recommendations of (Giroud, 2003) will provide a rational design method. The literature contains a large array of retention criteria for geotextile filters and has been reviewed by several authors (Christopher and Fischer, 1991), (Watson and John, 1999), (Legge, 2004). Many of the criteria are shown in Table5.3 Some of the early criteria did not consider the internal stability of the base soil, these out of date criteria should be discarded.

Table 5.3.—Summary of Particle Retention Criteria for Geotextile Design

Retention Criteria	Reference	Comments
For woven geotextiles and base soil with ≤ 50% passing the no 200 sieve: $O_{95}/d_{85} \leq 1$ For woven geotextiles and cohesive base soils: $O_{95} \leq 0.2$ mm	(Calhoun, 1972)	In a filtration study of a silty sand this criteria did not provide proper filtration (Aydilek, 2006).
For woven geotextiles: $O_{90}/d_{90} \leq 1$ For nonwovens: $O_{90}/d_{90} \leq 1.8$	(Ogink, 1975)	

For nonwovens & base soil $C_u = 1.5$: $O_{15}/d_{85} \le 1$ For nonwovens & base soil $C_u = 4$: $O_{15}/d_{15} \le 1$	(Sweetland, 1977)	
For wovens and thin nonwovens dependant upon C_u: $O_{90}/d_{50} \le 2.5\text{-}4.5$ For thick nonwovens, dependant upon C_u: $O_{90}/d_{50} \le 4.5\text{-}7.5$	(Schober and Teindl, 1979)	For silt and sand soils.
For dense soil with C'_u between 1 and 3: $O_{95} < 2C'_u\, d_{50}$ For dense soil with $C'_u > 3$: $O_{95} < 18\, d_{50}/C'_u$	(Giroud, 1982)	The criteria varies based on the linear coefficient of uniformity of the soil and on the density (loose, medium, and dense) of the soil to be filtered. Factors of safety should not be applied to these. (Watson and John, 1999) suggest that the dense criteria specifies openings too large for C_u between 2 and 3.2 and openings too small for C_u above 7.7
For soils that are internally stable i.e. (d_{85}/d_{50}, d_{50}/d_{35}, $d_{35}/d_{15} < 5$): $O_{95}/d_{85} < 2$	(Tan and others, 1982)	
$O_{95}/d_{85} < 2\text{-}3$	(Carroll, 1983)	In a filtration study of a silty sand this criteria did not provide proper filtration (Aydilek, 2006).
For steady flow: $O_{95}/d_{85} \le 1\text{-}2$ For dynamic & cyclic flow or if soil can move under fabric: $O_{95}/d_{15} \le 1$ or $O_{50}/d_{50} \le 0.5$	(Christopher and Holtz, 1985)	This criteria may lead to internal erosion for broadly graded soils with a high C_u.
$O_{90}/d_{85} \le 1.2\text{-}1.8$ $O_{50}/d_{50} \le 10\text{-}12$	(Chen and Chen, 1986)	Based on tests for vertical wick drains filtering fine-grained soils.

For soil with d_{50} > 0.074 mm (200 sieve): $0.297 \le O_{95} \le d_{85}$ (wovens) $0.297 \le O_{95} \le 1.8d_{85}$ (nonwovens) For soil with $d_{50} \le 0.074$ mm opening size varies with C_u: $C_u \le 2$: $O_{95} \le d_{85}$ $2 \le C_u \le 4$: $O_{95} \le 0.5C_u d_{85}$ $4 \le C_u \le 8$: $O_{95} \le 8C_u/d_{85}$ $C_u > 8$: $O_{95} \le d_{85}$	(John, 1987)	
$O_{50}/d_{85} \le 0.8$ $O_{50}/d_{15} \le 1.8\text{-}7.0$ $O_{50}/d_{50} \le 0.8\text{-}2.0$	(Fisher, Christopher, and Holtz, 1990)	Dependant upon Cu and geotextile pore size distribution.
$O_{90}/d_{85} \le 2\text{-}3$ $O_{50}/d_{50} \le 18\text{-}24$	(Bergado and others, 1992)	Based on tests run for vertical wick drains filtering fine-grained soils.
For soil with d_{20} < 0.002 mm: O_{95} < 0.21 mm For soil d_{20} > 0.002 mm, $C'_u > 3$: $O_{95} < 18\, d_{50}/C'_u$ For soil d_{20} > 0.002 mm , $C'_u < 3$: $O_{95} < 2C'_u\, d_{50}$	(Luettich, Giroud, and Bachus, 1992)	For steady flow, utilizes a flow chart for determining opening size. Criteria are given in the chart for loose, medium, and dense soils, only the dense criteria are shown here. For dispersive clays, a sand layer is to be placed between the base soil and the geotextile.
For $C'_u = 1$: O_{90}/d_{90} = 1 to 4.2 For $C'_u = 2$: O_{90}/d_{90} = 0.55 to 2.4 For $C'_u = 3$: O_{90}/d_{90} = 0.5 to 2.35 For $C'_u = 4$: O_{90}/d_{90} = 0.5 to 2.3 For $C'_u = 8$: O_{90}/d_{90} = 0.5 to 2.25	(Watson and John, 1999)	Uses a graph of opening size versus the base soil C_u. Gives upper and lower bounds for acceptable opening size range. Values shown here are taken from the graph.
For woven geotextiles: $O_{90} \le d_{90}$ For non-woven geotextiles: $O_{95} \le 1.8\, d_{90}$	Dutch practice as reported in (Legge, 2004)	
For broadly graded dense soil $C_u > 4$: $4d_{15} \le O_f \le 1.25d_{85}$ For broadly graded loose soil $C_u > 4$: $4d_{15} \le O_f \le d_{85}$ Uniformly graded dense soil $C_u \le 4$: $O_f \le d_{85}$ Uniformly graded loose soil $C_u \le 4$: $O_f \le 0.8d_{85}$	French practice as reported in (Legge, 2004)	Criteria varies with the base soil's C_u, density, & hydraulic gradient For i_s between 5 to 20 reduce geotextile size by 20%; for i_s greater than 20 or reversing flow conditions reduce geotextile size by 40%. The O_f values are the geotextile opening size as measured by the French AFNOR 38017 test.

$O_{40}/d_{15} > 1$ for geotextile POA < 8 $O_{40}/d_{35} > 1$ for geotextile POA > 8	(Aydilek, 2006)	Applies only to woven geotextiles filtering a silty sand. The designer should consider reducing the opening size since the criteria does not include a factor of safety.

The application of large factors of safety to opening size for retention is not a good practice because this may reduce the opening size of the specified geotextile to the point that it tends to clog. Most of the criteria are conservative and should be used as is or with only a small reduction to the specified opening size. The lower bounds of the allowable opening size will be determined by the permeability and non-clogging requirements. For important applications, filtration testing such as the gradient ratio test (ASTM D5101) will confirm geotextile filter soil retention performance.

5.2.4 Permeability criteria

The seepage flows must pass from the base soil through the filter and into the drain without restriction if excess pore pressure is to be avoided. This condition can be met if the downstream components receiving seepage flows (filter cake, geotextile, and drain) are equal to or more permeable than the base soil.

Design involves first determining the soil hydraulic conductivity (permeability) by laboratory testing such as ASTM D 5084. For less critical applications the soil hydraulic conductivity can be estimated based upon soil gradation d_{10} size, see Luettich and others (1992). The soil hydraulic gradient is then determined for the particular application. The minimum allowable geotextile permeability is then determined (Giroud, 1988):

$$k_g > i_s \, k_s$$

The permeability of candidate geotextiles can be obtained using the following formula:

$$k_g = \psi_g \, t_g$$

where:

k_g geotextile hydraulic conductivity normal to the plane (permeability)
ψ_g geotextile permittivity, provided by manufacturers or from testing (ASTM D 4491)
t_g geotextile thickness

The permeability of the specified geotextile is then checked against that of the minimum allowable value to determine the factor of safety provided. This should be a high value (10 or more). In the method proposed by the Geosynthetic Institute (Koerner, 2005b) the minimum allowable permittivity is calculated and then various reduction factors are applied to determine the allowable permittivity for the geotextile.

Other authors ignore the hydraulic gradient in the calculation (Christopher and Fischer, 1991), 1993), (Loudiere, et al., 1983) and use the following relationship:

$$k_g = 10 \text{ to } 100\ k_s$$

French practice for dams recommends the higher value of 100 (Degoutte and Fry, 2002). The requirement can be achieved with a geotextile filter if it is not too thick. For designs that do not include laboratory testing of the geotextile and soil filter combination, or where clogging may occur, a factor of 100 or more should be used.

5.2.5 Non-clogging criteria

In addition to meeting the permeability requirement, non-clogging criteria ensures that the geotextile is sufficiently open and that accumulation of particles and chemical and biological precipitates will not reduce the permeability to the point where the geotextile/filter cake becomes less permeable than the base soil. The designer should seek to provide as permeable and porous of a geotextile as possible while maintaining retention criteria. This will allow for a substantial reduction in the installed geotextile filter permeability due to compression, partial clogging, and other factors and yet maintain an overall installation that is more permeable than the base soil.

The following recommendations are made (Luettich, Giroud, and Bachus, 1992):

- Use the largest opening size that satisfies the retention criteria.
- For nonwoven geotextiles, use the largest porosity available, but not less than 30%.
- For woven geotextiles, use the largest percent open area (POA) but not less than 4%.

Where non-clogging is essential, laboratory performance testing is recommended. Tests include hydraulic conductivity ratio, gradient ratio, and biological clogging testing.

5.2.6 Strength and durability requirements

The geotextile must be able to survive the construction process and the post-installation stresses without significant damage. Durability relates to the environmental conditions the geotextile will be exposed to. It must resist degradation from ultraviolet light (UV), oxidation, and chemical exposure. Once buried, geotextiles exposure to UV and oxidation are of minor concern. These subjects are discussed in section 5.5.1 of this report.

Providing a geotextile with the proper strength to survive the construction process is a major concern. Strength requirements have been published for geotextiles based upon the severity of the application after (AASHTO, 1996), and as reported in (Luettich and others, 1992) as shown in Table 5.4 on the following page. Conventional geotextile design in the United States has been to specify these values which are derived largely from road construction. For some dam applications, such as design classifications A and B where the geotextile is not accessible for repair after installation, this simplistic approach may not be appropriate. The designer should instead evaluate the stresses expected to result from deep burial considering what type of material will be in contact with the geotextile. Procedures for calculations are found in (Giroud, 1984) which are based upon load and rock size, and a method for laboratory testing has been developed for the mining industry to evaluate geomembranes under very deep loads and is presented by Lupo and Morrison (2005). In cases of thin cover layers, and operation of heavy equipment, dynamic loads from construction activities may also need to be considered.

As previously mentioned, a new trend in geotextile filter design for dams is to combine two geotextile layers such as joining a nonwoven needlepunched selected for filtration to either a thick nonwoven or a heavy but open woven geotextile selected for its strength and resistance to installation damage. Such layered systems evolved out of the work of French researchers (Artieres and Tcherniavsky, 2003) and led to the development of a dam filtering geotextile known as "Bidim F."

A non-woven geotextile is made up of a random arrangement of geotextile fibers. The overlapping fibers form void spaces of varying sizes. While conventional filter design looks only at a characteristic opening size such as O_{95}, a soil particle passing through a nonwoven geotextile will encounter voids of various sizes, the smaller voids are constrictions that may trap and retain the soil particle. Just as a geotextile has a range of opening sizes, it also has a range of pathways with differing minimum constrictions, as a geotextile of the same material is made thicker (for increased strength) the variation in these minimum constriction sizes will narrow (all flow pathways will tend to have similar sized small constrictions) and this can lead to unwanted behavior such as clogging (Giroud, 1997). It was found that restricting the number of constrictions to between 25 and 40 will minimize the risk of clogging.

Table 5.4.—Strength Requirements for geotextiles (AASHTO, 1996)

Application	Contact Stress	Grab Strength pounds	Elonga-tion %	Sewn Seam Strength pounds	Puncture Strength pounds	Burst Strength pounds	Trapezoid Tear pounds
Subsurface Drainage	High Stress - angular drainage media, heavy compaction, high confining stress	180	-	160	80	290	50
Subsurface Drainage	Low Stress – rounded drainage media, light compaction, low confining stress	80	-	70	25	130	25
Armored Erosion Control	Direct stone placement	200	15	180	80	320	50
Armored Erosion Control	Sand cushion, low drop height	90	15	80	40	140	30

This realization led to the development of a two-layer geotextile for dam filtration (Giroud, Delmas, and Artieres, 1998), (Artieres and Tcherniavsky, 2003). One can select the optimum nonwoven geotextile for a filtration application, but this is often a light weight geotextile that may be at risk to installation damage. By bonding a second geotextile to the filter fabric, the strength can be increased. The second fabric is one that is selected for strength but has a very open and permeable structure so it has little effect upon the filter performance of the two-layer geotextile combination.

The initial French two-layer geotextile was made by needlepunching to bond a thin nonwoven filtering geotextile to a thick nonwoven geotextile. At present it is not only possible to bond two or more nonwoven geotextiles together, it is also possible to bond two woven geotextiles together, or a nonwoven can be bonded to a woven geotextile. Such multi-layer systems provide an advancement in filtration capacity (Jeon and Mlynarek, 2004) and continue to be an important area of geotextile filtration research (Kutay and Aydilek, 2005). Even three layer and multi-layer products are possible to manufacture. It is possible to manufacture a graded geotextile filter, also called “depth filtration,” with enhanced filtration and survivability characteristics.

5.2.7 Performance testing

In overseas practice, laboratory performance testing procedures have become the norm for embankment dam filter design. Performance testing has the advantage of being able to integrate many complex issues regarding geotextile-soil interaction during filtration thus overcoming many of the uncertainties in the design procedure. Uncertainties in filtration performance include:

- The actual size distribution of the openings in the geotextile are different than the single AOS value reported by the manufacturer (Aydilek, et al., 2005).
- Soil particles embedded in the geotextile reduce porosity and permeability.
- Compression caused by burial reduces opening size, porosity, and permeability (Legge, 2004).
- Variations in seepage gradients and flow rates in the base soil affect filter behavior.
- Variations in soil gradation, compaction, and particle shape affect filter behavior.

5.3 Design for drainage

Drainage implies that water will be transported in the plane of the geotextile or geocomposite material. In contrast, filtration considers flow perpendicular to the plane of the geotextile. Normally, the geotextile must be designed to perform properly as a filter if it is also intended to function as a drain. Calculation procedures are presented in (Koerner, 2005a) and other standard geotextile design references.

5.3.1 Permeability

In order to function as an effective drain the geotextile or geocomposite must remain permeable and not clog. The design requirements for retention and permeability also apply to drains.

5.3.2 Transmissivity

The added dimension of drainage design is that it must have adequate flow capacity. Flow in the plane of the geotextile is governed by the following formula:

$q = k_p iA$

$q = ki(W\ t)$

where:

q = flow rate in the plane of the geotextile
k = hydraulic conductivity along the plane of the geotextile
i = hydraulic gradient
W = width of the geotextile
t = thickness of the geotextile

5.3.3 Compression considerations

Where depth of burial is significant, the effects of compression should be evaluated. This is best performed using laboratory testing.

5.4 Design for separation layers and cushions

Typical applications in embankments are as a separation/filter layer underneath revetments, or as a protective cushion placed against a waterproofing geomembrane on the upstream embankment slope. These applications of geotextiles are fairly widespread and more accepted in dam engineering practice than their use as internal filters. Proper design can be complicated if dynamic flow or frequent flow reversal is expected such as in revetments on large reservoirs that experience large wave heights. Such revetments must be rapidly draining and not subject to excessive clogging if stability is to be maintained. A through design includes evaluation of filtration, permeability, drainage, and strength requirements including slope stability considerations. Failures have occurred where the installation has not been able to maintain adequate permeability and drainage characteristics which are essential for maintaining slope stability (Abromeit, 2002).

5.4.1 Filter criteria

Filter design criteria as discussed under Section 5.2 applies to many separation functions. For a an upstream geomembrane waterproofing and revetments installed for erosion control, such as riprap or cellular concrete mattresses, the geotextile installation may experience dynamic flow conditions with frequent flow reversal. This situation places additional demand upon the geotextile/soil system to avoid clogging. Clogging of the geotextile results in elevated pore water pressures and is likely to result in slope failure (Fluet and Luettich, 1993), (Abromeit, 2002). Filter criteria are different than for steady flow conditions because more emphasis must be placed upon maintaining permeability than upon soil retention criteria (Luettich, Giroud, and Bachus, 1992). Procedures for evaluating the flow requirements have been developed (Luettich and Fluet, 1993), (Crum, 1995). In addition, testing of the selected geotextile with the site soils is recommended for dynamic flow conditions (Fannin and Pishe, 2001).

5.4.2 Direct placement of riprap on geotextiles

Some embankment designs call for riprap placement directly on the geotextile to form the upstream erosion control revetment. This places an additional demand upon the geotextile flow capacity. The surfaces of the riprap in contact with the geotextile block the seepage flows. All of the seepage must flow between the spaces between the riprap pieces. This will require use of a geotextile with a high percent open area (for woven geotextiles) or a high porosity (for nonwoven geotextiles). This aspect of the permeability requirement should be verified during design. If enough permeability can not be provided to drain the underlying soil, then an intervening granular soil layer will be required between the riprap and the geotextile. The soil layer will allow the entire geotextile surface area to pass seepage flows from the underlying embankment soil to the granular soil layer.

5.4.3 Strength and durability considerations

The geotextile must resist puncture and tearing from the stresses imposed by installation and covering, and must have a high enough interface frictional strength to provide adequate slope stability.

Geotextiles placed on steep soil slopes or against smooth geomembrane liners may create weak interface surfaces prone to slope instability. These failures are usually traced back to the designer using published interface friction values rather than having the proper tests run. When geotextiles or other geosynthetic materials are to be placed upon sloping surfaces, laboratory testing to determine the actual interface friction is a necessity. The geosynthetic materials should be tested with the actual materials that are planned to be placed in contact with them and the materials should be saturated. For geomembranes, additional strength can be obtained by using a textured membrane rather than a smooth one.

5.5 Material Selection

Regarding polymer composition, geotextiles are made from polypropylene, polyethylene, polyester (PET), and polyamide (nylon); however; polypropylene dominates the geotextile manufacturing industry with approximately a 92% share of the marketplace (Koerner, 2005a).

For most filtration applications a nonwoven needle-punched polypropylene geotextile is a likely choice. Woven monofilament polypropylene geotextiles are often used underneath riprap for erosion protection revetments because of their ability to rapidly dissipate pore pressures, but nonwovens have also provided good service if properly selected with large enough openings to avoid clogging. Woven slit-film geotextiles are not to be used where filtration is an important function for the geotextile, woven monofilament geotextiles perform better.

Socks wrapped around perforated drainage pipes are normally supplied as knitted polyester with an opening size of 0.6 mm (#30 sieve). Heat-bonded nonwovens can also be obtained as pipe wrappings, but there may be some lead time on orders. It is not recommended to place a geotextile-wrapped pipe into a soil fill or trench unless the soil is sand. When fine-grained soils are used against the geotextile wrapped pipe, the geotextile is likely to clog. The more appropriate design is to embed the perforated pipe in gravel and wrap the outside of the gravel surface with a geotextile. A much larger surface area of geotextile is provided which reduces the likelihood that the geotextile would clog.

Heat bonded nonwovens geotextiles are used for wick drains and other applications where there are fine-grained soils to be filtered at depth. Most heat-bonded nonwovens geotextiles will repel water under low-head conditions and therefore they may not be the best choice for shallow burial depth, low head installations such as a toe drain. Nonwoven needlepunched geotextiles are not water repellant and therefore are a better choice for low-head installations.

Both needle-punched nonwovens and woven geotextiles are used in reinforcement applications. Wovens often provide greater strength than nonwovens for a given geotextile weight. Geogrids provide even greater levels of reinforcement, but, they are not able to provide filtration and drainage functions, so geotextiles also remain as a reinforcement element in some situations.

In order to provide a long service life, geotextile polymer material selection needs to consider the nature of the physical and chemical environment of the proposed installation. Some environmental factors can lead to rapid degradation of the polymer and must be avoided. The chemistry of the soils and of the water that will be in contact with the geotextile should be evaluated for possible adverse conditions. Where chemical exposure is possible, consultation with geotextile manufacturers is essential. In cases of significant chemical exposure, materials testing with the anticipated fluids/leachates should be considered to properly evaluate long-term geotextile performance.

5.5.1 Environmental degradation considerations

Microbial growth associated with geotextiles raises two concerns: consumption of the carbon fraction of the polymers and clogging of the fabric as the microbes fill the openings in the geotextile. Studies (Kossendey, Gartung, & Schmidt, 1996) of the interaction of microbes with geotextiles permeated with landfill leachates have not found that the polymers were consumed by either aerobic or anaerobic bacteria. The polymers did provide a site for microbial growth to occur and there was a commensurate reduction in permeability. Sands exposed to leachates suffered the same fate. Relatively speaking, the overall decrease in permeability was greater in the sands than in the geotextile. The principal controlling factor in the process was the availability of nutrients in the permeating fluid, in this case the leachate. In the typical dam application one would expect that the seepage reaching the chimney drain at depth would be largely devoid of nutrients and thus, a poor feed for bacterial growth. Given that sands are likewise susceptible and microbial clogging has not been a problem, the lack of nutrients in the seepage minimizes the microbial threat to geotextiles deeply embedded within dams.

Exposure to ultraviolet light and oxidation will also degrade these materials. On a positive note a number of mechanisms that degrade the performance of geotextiles, i.e. exposure to sunlight and oxidation, are eliminated and greatly reduced respectively by deeper burial. The threat of vandalism is eliminated. Burrowing animal concerns are lessened as the deeper buried segments of the geotextile are further removed from the habitat an animal operates in normally.
Burial minimizes this risk.

The expected service life of a geotextile is dependant upon its resistance to degradation. For buried applications, a service life of over 100 years is anticipated. Most research has been conducted upon geomembranes where service life predictions in the range of 90 to 500 years have been forecast (Koerner, 2005c). Table 5.5 presents the susceptibility of geotextiles to environmental conditions:

Table 5.5.—Potential Degradation of Geotextile Polymers By Environmental Factors

Factor	Polypropylene	Polyethylene	Polyester	Polyamide
Ultraviolet Light	Susceptible	Susceptible	Less Susceptible	Susceptible
Oxidation	Susceptible	Susceptible	Less Susceptible	Less Susceptible
Hydrolytic Degradation	Not affected	Not affected	Degraded by low pH and high pH liquids	Degraded by low pH liquids
Elevated Temperatures	Expands and softens, melts at 165 °C	Most susceptible, expands and softens at 80 °C, melts at 125 °C	More resistant to thermal changes melts at 260 °C	Most resistant to thermal changes, melts at 280 °C
Fuels and Organic Solvents	Susceptible	Susceptible	Resistant	Resistant
Biological Decay	Not affected	Not affected	Not affected	Not affected
Animal Intrusion	Susceptible	Susceptible	Susceptible	Susceptible

5.5.2 Other performance considerations

Where a geotextile is intended to transmit seepage or gases in the plane of the fabric, the design needs to consider the adverse impact on performance resulting from a reduction in the amount of "available" voids. "Available" here refers to the ability of a void to pass liquids or gases. Obviously, soil clogging reduces the available area to pass fluids and thus restricts overall hydraulic capacity of the fabric. In the case of gas venting, wetting of the geotextile reduces the fabric's ability to transmit gases (Bouazza, 2004). As already noted, stressing the geotextile reduces its ability to transmit both gases and fluids. The design normally accounts for this behavior by applying suitable reduction factors.

5.5.3 Reduction factors

The concept of reduction factors was previously mentioned under permittivity The basic approach taken to characterize the design capacity involves reducing the ultimate measured capacity cited for the material by various reduction factors, i.e.

$$\text{Property}_{\text{allowable}} = \text{Property}_{\text{ultimate}} \left(\frac{1}{RF_A \cdot RF_B \cdot RF_C} \right)$$

where $RF_{\text{subscript}}$ refers to the any of appropriate reduction factors compromising the ultimate capacity of the geotextile.

The following is a list of the typical reduction factors (RF) employed (Koerner & Koerner, 2005) in analyses that likely would apply to geotextiles used in embankment dam construction in filtration and drainage roles.

RF_{ID} = reduction factor to account for installation damage,

RF_{CR} = reduction factor to account for creep effects such as reduced void space,

RF_{BC} = reduction factor to account for biological clogging,

RF_{SM} = reduction factor for seams, if appropriate,

RF_{SCB} = reduction factor for soil clogging and blinding,

RF_{CC} = reduction factor to account for chemical clogging, and

RF_{IN} = reduction factor to account for abutting materials intruding into void space.

The following table is an amalgam of the recommended Geosynthetics Institute reduction factor values for geosynthetics presented in a number of tables in Koerner and Koerner, (2005). The table reflects the judgment of functions which approximately correspond to tasks that geotextiles are expected to provide in an embankment dam application. The decision matrix used by the Geosynthetic Institute follows. It provides one rationale to select from the recommended range.

Table 5.6.—Recommended drainage and filtering reduction factors

APPLICATIONS	RANGE OF REDUCTION FACTORS					
	RF_{IN}	RF_{CR} [1]	RF_{CC} [2]	RF_{SCB} [3]	RF_{BC} [4]	RF_{ID}
Drainage Blankets	1.3 to 1.5	1.2 to 1.4	1.0 to 1.2	2.0 to 4.0	1.0 to 1.2	-
Underdrain Filters	1.0 to 1.2	1.0 to 1.5	1.2 to 1.5	2.0 to 10	2.0 to 4.0	-
Pressure Drainage	1.0 to 1.2	2.0 to 3.0	1.1 to 1.3	2.0 to 3.0	1.1 to 1.3	-
Gravity Drainage	1.0 to 1.2	2.0 to 3.0	1.2 to 1.5	2.0 to 3.0	1.2 to 1.5	-

[1] Creep of geotextiles is a product-specific issue. The magnitude of the applied load is a major factor.
[2] Values can be higher particularly for high alkalinity or high turbidity groundwater
[3] If riprap or concrete blocks cover the surface of the geotextile, use the upper values or include an additional reduction factor, i.e. RF_{ID}
[4] Values can be higher for extremely high microorganism content and/or growth of organisms and plant/vegetation roots.

Table 5.7.—Critique of geosynthetic reduction factors

CATEGORY	CONFIDENCE IN VALUES	FOR CRITICAL APPLICATIONS
Strength-Related Applications		
• Installation damage	High	Use upper range value
• Creep	High	Use upper range value
• Chemical/biological degradation	Moderate	Site-specific testing
• Seams	High	Use upper range value
Flow-Related Applications		
• Soil clogging & binding	Moderate	Site-specific testing
• Creep reduction of voids	Moderate	Site-specific testing
• Intrusion	High	Use upper range value
• Chemical clogging	Low	Go beyond table limits
• Biological clogging	Low	Go beyond table limits

In attempting to use the above tabular guidance, following approximate equivalencies between Geosynthetics Institute's applications and those in dam construction are suggested. The pressure drainage function reasonably corresponds to the role played by relief wells and the filter element of those portions of the chimney and blanket drains subject to significant hydraulic gradients. The underdrain filter category reflects operational conditions similar to what likely would be expected in a geotextile filter element in the upper reaches of the chimney drain, the downstream portions of the drainage blanket and the toe drain. In those applications the hydraulic head across the fabric should be relatively small. A geotextile filter beneath slope armor experiences loads likely associated with both underdrain filters and gravity drains. Where one can reasonably argue that multiple categories apply, it would be prudent to meet the most stringent criteria. Finally, the drainage blanket function is similar to the gas venting and underdrainage role that geotextiles now provide for overlying geomembranes.

5.6 Caveats

The expanded use of geotextiles by the dam engineering community is in its infancy. Accordingly, due caution should be exercised in this effort. As already suggested the designer is well advised to assume that geotextile filters can tear or clog and introduce a weakened plane. In most cases the consequences of those conservative assumptions can be addressed. In the case of clogged filters, the designer needs to provide additional strategically located relief drains. Geometry changes to the chimney drain, a modest flattening of the downstream slope or toe berms can address stability concerns if they arise. Thus, while the Geosynthetic Institute's guidance sets a threshold on design capacity, the designer at this point in time has to be pessimistic about what can be achieved in the field. It is only with additional experience that reduction factors for dams can be refined.

5.7 Summary of design procedures

Table 5.8.—Recommended Design Approach System.

Design Classification	Description	Design Approach
A	Geotextile performs a function in internal locations in an embankment with no access, once installed. There is no redundant natural design element present.	Follow most rigorous design calculation procedures including evaluation of stresses during construction and after installation. Requires a thorough laboratory testing program using site soils and proposed construction materials. Perform filtration testing using varied overburden pressures, hydraulic gradients, and flow rates to evaluate both expected and worst case conditions. For erosive and unstable soils, test filtration properties of several candidate

		geotextile products. Installation requires thorough QA/QC procedures.
B	Geotextile performs a function in internal locations in an embankment with limited or no access, once installed. There is a redundant natural design element present.	Follow most rigorous design calculation procedures. Perform laboratory testing simulating expected installation conditions including redundant design element. For erosive and unstable soils, conduct filtration tests using varied applied loads, hydraulic gradients and flow rates to evaluate both expected and worst case conditions. Installation requires thorough QA/QC procedures.
C	Geotextile is installed in locations where it can be accessed without excessive cost and effort. There is no redundant natural design element present.	Geotextile selection based on either rigorous or simple design criteria. Perform laboratory filtration test to confirm design. For erosive and internally unstable soils, conduct laboratory tests to evaluate both expected and worst case conditions. Installation requires thorough QA/QC procedures.
D	Geotextile is installed in locations where it can be accessed without excessive cost and effort. There is a redundant natural design element present.	Geotextile can be selected using simple design criteria. Laboratory performance testing not required, except for erosive and internally unstable soils, confirm design with laboratory filtration tests. Installation requires thorough QA/QC procedures.

Chapter 6

Construction Methods and Considerations

The performance of a geotextile can be significantly affected by the quality of the installation. It is critical that the mechanical and hydraulic properties of the geotextile are not compromised during construction. Prolonged UV exposure, contamination, abrasion, puncture, tearing, and misalignment of geotextiles during construction must be avoided. To achieve a successful installation, the design must be feasible to construct, the geotextile must be able to accommodate the anticipated construction stresses, specifications must clearly spell out proper installation requirements, and quality control and quality assurance procedures must be strictly enforced.

6.1 Shipping and storage

Care in handling and storage is necessary to prevent damaging the fabric before it is installed. Standard guidance is available for proper geotextile handling and storage procedures (ASTM 2002). Rolls should be marked and/or tagged with the following information: 1. Product identification including manufacturer and type; 2. Lot number and roll number; 3. Roll length, width, and weight. This information should be provided in at least three locations: outer cover, roll, and inside roll cover.

All geotextile materials are usually covered with UV resistant packaging at the factory before being shipped to the site. At the factory geotextiles are typically rolled onto strong and durable cardboard tubes that allow for storage and easy movement and loading on trucks for shipping to the site. Storage areas at the site should be prepared prior to delivery. If stored on the ground, a smooth surface free of rocks should be prepared. Other storage methods include placing geotextile rolls on pallets, on sheets of plywood, or on asphalt or concrete pads. Once delivered, the rolls should be inspected for damage, see Figure 6.1. Careful unloading and movement about the site is best performed using canvas slings (see Figure 6.2), or spreader bars and a probe such as a steel pipe (see Figure 6.7) that can be inserted into the center of the roll to prevent tearing or puncturing the geotextile. These methods allow for the rolls to be relocated without dragging across the ground or using other improper methods such as lifting rolls with a fork lift or excavator bucket. Section 4.4.1 of this report discusses improper storage and handling methods which must be avoided.

Figure 6.1.—Photograph of a truck delivering geotextile rolls to a construction site. The tie down straps at the front of the truck are intruding into and have distorted the shape of the top roll. This roll must be carefully examined to verify that it has not been damaged during transport.

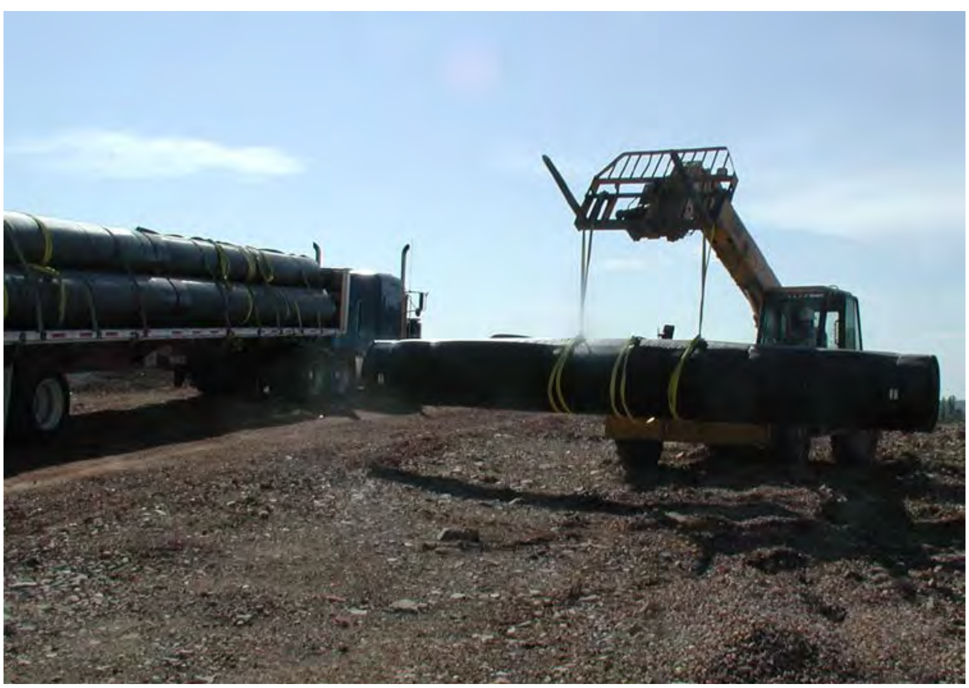


Figure 6.2.—Photograph showing proper offloading of geotextile product rolls. Cloth slings rather than the forks of the lift are used to properly unload this delivery.

Figure 6.3.—Photograph of geotextile storage. A layer of fine-grained soil was placed in the storage area to avoid placing the rolls directly on the rocky soil which is visible in the left side of the photograph. Damage to the ends of the protective wrappers is evident, the inspector required these rolls to be covered by a tarp to prevent contamination by dust and to avoid degradation from prolonged UV exposure.

The manufacturer usually specifies the maximum height of stacking for the rolls to ensure that the product is not crushed by the weight of the storage pile. The problem of degradation by UV light can originate from extended outside storage of geosynthetics where the protective covers have been damaged or removed. Because UV degradation is an invisible process, inspectors must be aware of the issue and be diligent in frequently reviewing the condition of storage piles to ensure that protective covers remain intact.

6.2 Foundation/subgrade preparation

Preparation of the foundation surface (subgrade) against which the geotextile will be placed is the initial step in the installation process. Subgrade preparation requirements are an important aspect of the project requirements. For most applications, the subgrade is required to be smooth and firm, free of voids and protruding rocks. For highway and road applications, a three-tiered classification system of subgrades has been developed (AASHTO, 1996). Based upon the quality of the subgrade, different strength requirements for the geotextile are established. For use in dams, no such classification system has been widely adopted. The Bureau of Reclamation in their design standard on geotextiles (Bureau of Reclamation, 1992) has a two-tiered classification of either Class A or Class B defined as follows:

Class A – Applications where installation stresses are considered more severe than Class B, very sharp angular aggregate is utilized/or is present in significant percentages, or where cover materials will be subjected to compaction greater than 95 percent.

Class B – Applications where the foundation/subgrade is smooth having no sharp angular projections, no sharp angular aggregate is used, and compaction requirements are less than 95 percent.

Regardless of the exact nature of the subgrade, geotextiles must be placed in intimate contact with the soil that they are being used in or on. For a stiff woven geotextile the soil surface should be as smooth as possible. Nonwoven geotextiles are more flexible and will conform better to an irregular surface but the goal should be to provide as smooth of a surface as possible for nonwovens geotextiles as well. Typically, the subgrade will be compacted with a smooth drum roller (fig. 6.4), bladed smooth with a motor patrol (if the slope is 3H to 1V or flatter) and then re-compacted with a smooth drum roller. For slopes steeper than 3H to 1V the roller will have to be secured in a safe manner to allow it to traverse up and down the slope. Depending on the material, vibration may be utilized. The goal is to have a smooth subgrade surface with no rock protruding. It is recommended that laborers walk the subgrade and remove rocks over ½ inch in size. Pockets of coarse fragments should be filled with sand to provide a smooth surface. The intent is to remove any sharp rock fragments that puncture and/or tear the geotextile and to fill voids in the subgrade.

Figure 6.4.—Photograph showing compaction equipment preparing a suitably smooth and firm subgrade surface for geotextile placement.

Figure 6.5.—Photograph showing a defect in a prepared subgrade surface. This portion of the subgrade was rejected by the inspector and had to be filled and smoothed.

Where geotextiles are placed in vertical or steeply-sloped trenches, it is often not possible to create a completely smooth surface. The sides of the trench can be can be lightly trimmed as needed and the trench bottom can be smoothed using a smooth excavator bucket (without teeth) just prior to geotextile installation to eliminate gross irregularities.

6.3 Installation

Construction installation requirements depend on the site conditions and specific geosynthetic application. The prepared subgrade surfaces that will receive the geotextile are usually inspected for approval immediately prior to geotextile placement. Requiring subgrade approval just before geotextile placement is necessary to ensure the prepared surfaces have not become degraded by equipment traffic or adverse weather.

Damage during deployment often results from improper handling. While rolled products can be safely deployed by hand labor, it must be done to minimize stresses from dragging over the ground surface. Dragging can abrade or tear the geotextile, and disrupt angular rock fragments from the subgrade leading to punctures. Typically, loaders or fork lifts are fitted with spreader bars that allow the geotextile rolls to be unrolled like a roll of paper towels onto the subgrade, see Figures 6.6 and 6.7.

Figure 6.6.—Photograph showing moving a geosynthetic roll with a pipe and spreader bar, and a spotter. The spotter (person walking in front of the equipment) is needed to insure that the geosynthetic product does not strike any other objects which could damage the material.

Figure 6.7.—Photograph of a steel pipe and slings being used to move a geosynthetic roll across a construction site to the installation area.

The geotextile should be placed in intimate contact with the soil. Care must be taken not to introduce wrinkles in the geotextile during placement. In near surface applications, such as underneath riprap, wrinkles can lead to formation of erosion channels beneath the geotextile. The geotextile is then forced to carry the load of the overlying soil in tension which is likely to result in tearing the material.

In general, the geotextile should be unrolled with the length of the roll in the direction of anticipated water flow or movement. Successive geotextile rolls are overlapped such that the upstream panel is placed over the downstream panel and/or upslope over downslope. Some geocomposite materials, such as a tri-planar geonet geocomposite, have a flow direction which must be aligned for the material to function properly. In reinforcement applications, geotextiles should be laid in strips transverse (perpendicular) to the centerline of the embankment.

Anchor trenches are typically used at the top of slopes to anchor the geotextile. Typically they are excavated a minimum 3 feet deep and 2 feet wide to allow hand tampers to be used to compact the backfill. The geotextile should extend down the side and across the bottom of the anchor trench. In certain application, if there is adequate space, swales or benches are excavated into long slopes to serve as intermediate anchor trenches see Figure 6.8. The use of a wide bench facilitates geotextile installation and allows the use of rubber tired loaders and other larger equipment to fill and compact the anchor trench after geotextile placement.

The process of the unrolling and positioning the geotextile panel may loosen the subgrade surface or cause rock fragments that were not exposed to become exposed. Therefore, it is important to walk the geotextile after it has been placed to make sure that there are no soft foundation areas or presence of protruding rock fragments that could puncture and/or tear the geotextile, or which have caused the geotextile to move away from close contact with the subgrade.

Figure 6.8.—Photograph showing preparations for geosynthetic installation. A swale is used to divide a long slope and provide an intermediate anchor trench location. Note the presence of proper equipment, sufficient labor, and adequate amounts of sand bags so materials can be efficiently installed and secured.

6.4 Seaming

Seaming types include overlapping, sewing, stapling, tying, heat bonding, welding and gluing. Thermal seaming methods are most efficiently installed.

A minimum overlap of 6-inches between adjacent roll ends and a minimum 6-inch overlap of adjacent rolls are recommended. If overlapping seams are used, it is common to increase the overlap distance to a range of two or three feet in order to guard against the geotextile shifting during covering operations.

The frictional resistance between overlapped fabric sections is considerably less than between fabric and soil. In addition, when proper overlap requirements are followed, laps can account for up to 25 percent of the total fabric cost. For the reason, sewing fabric sections together, either by pre-sewing at the factory or onsite, may be desirable both for cost effectiveness and to maintain strength requirements.

There are three basic types of seams used (Koerner, 2005a): flat or prayer type, J or Double J, or butterfly. A stitch density of about 400 stitches per 3 feet should be used for lighter weight geotextiles. About 200 stitches per 3 feet should be utilized for heavier weight geotextiles. A lock type stitch should be utilized because it is less likely to unravel. Single or double-thread chain stitch is also utilized. When constructed correctly, sewn seams can provide reliable stress transfer between adjacent geotextile panels.

Fabric seams should be evaluated for their potential to open up under load, possibly creating unprotected areas where soils could pipe under hydrostatic pressure or flow. Overlapping "J" type seams are preferable over lapped seams. It is recommended that double sewing be utilized. High strength polyester, polypropylene, or Kevlar thread should be used. Nylon thread could also be used, but some reduction in seam strength may occur over time due to wet-dry cycles.

With lighter weight geotextiles, it is possible to make seams that have a strength equal to 80 to 90 percent of the parent material. With high weight geotextiles, it is difficult to make seams stronger than 60 percent of the geotextile strength, or stronger than about 600 to 900 psi.

Heat bonding/welding is becoming more common as new lightweight type field welders are developed. These types of machines require operators that are trained and the equipment must be maintained. Temperature control and uniformity of the heating elements are critical to ensure that the geotextiles are not burned or damaged.

6.5 Covering

Once installed in the field, geotextile materials should be covered with the specified materials as soon as practicable. On many projects, the contractor wants to delay cover placement until all of the geotextile is placed. UV susceptible geotextiles should be covered within 3-5 days of exposure and within 21-30 days for UV treated and low UV susceptible polymer geotextiles. In addition, geotextiles (especially needlepunched nonwovens) exposed to rain absorb a considerable amount of water and become difficult to handle should repositioning be required. All geotextiles used as filters or transmissive media must be protected to prevent contamination by dust, dirt, and mud. In underwater applications, it is recommended that cover soils be placed the same day.

The covering operation must be carefully controlled to avoid damage to the geotextile. Immediately prior to covering, the installed geotextile should be inspected to ensure it is still in proper position and that the subgrade has not been compromised. The cover soil must meet the specification requirements. On slopes, cover soil placement should begin at the toe of a slope and proceed up the slope. A geotextile can be damaged by equipment operating on too thin of a cover. For heavy equipment hauling, cover layers should be increased, see Figure 6.9. The maximum allowable slope on which soil cover can be placed is equal to the lowest soil-geotextile friction angle. After the fill material is dumped, small low ground pressure (LGP) bulldozers and/or front end loaders may be used to spread the fill.

The use of LPG dozers typically eliminates excessive puncture stresses on the geotextile. However, of equal or greater importance is the shear stresses that are developed along the subgrade soil/geotextile (lower interface) and soil cover/geotextile(upper interface) interfaces during the action of pushing the cover soil over the geotextile. The potential for large interface shear stresses exist when an equipment operator tries to push too much material up-slope at any one time. If the resulting shear stresses below the geotextile exceed the interface shear strength, localized slipping will result causing stretching in the up-slope direction. This may tear the geotextile. Many construction-quality assurance inspectors are unlikely to recognize this situation. Usually, inspectors focus on the minimum required cover soil thickness and look for evidence of damage below the dozers blade and tracks. Inspectors need to be aware of the need to avoid pushing thick layers of cover soil. An excavator can be used to safely reduce the height of high dump truck loads of cover soil such as that seen in Figure 6.10. The trucks should not be allowed to dump directly onto the geotextile. It is preferred to have the trucks dump onto a previously placed layer of cover material.

Typically, no additional compaction of the initial lifts is necessary as sufficient compaction can be achieved by the static weight of the equipment. If compaction of the cover soil is required, the use of heavy equipment on the first lift should be avoided. A minimum of cover thickness of 12 inches should be maintained for low pressure equipment operation. The maximum depth of soil placed in any one layer should not exceed 18 inches. The gradation and angularity of the cover soil is an important variable. Coarse gravel covers should be placed no greater than 12 inches. Cover soils that have higher percentages of sand/clay or "pea gravel" such as that shown in Figure 6.11 can be spread in up to 18 inch lifts.

Figure 6.9.—Photograph showing a haul road where the cover layer has been temporally increased to 5 feet to protect the geotextile from heavy equipment loading.

Figure 6.10.—Photograph of an excavator removing the tops of thick piles of cover material. Attempting to move such thick piles with a bulldozer is likely to damage the geotextile because of the high traction forces that would be required to push such a thick layer of material.

Figure 6.11.—Photograph of a low-ground-pressure bulldozer grading cover material to a uniform thickness of 1.5 feet. Note the presence of an inspector who is closely monitoring the covering operation.

When a geotextile is installed as a filter in a trench drain, the aggregate fill should be carefully placed to ensure intimate contact of the geotextile with the trench bottom and walls (Ingold and Miller, 1988). An effective procedure for toe drains is to:

- Review the trench surfaces and remove sharp stones and projections.
- Lay the geotextile into the trench with extra material extending beyond both sides.
- Place small stones or gravel piles at intervals along the top edge of the trench to lightly hold the fabric in place. It is important that the fabric not be firmly restrained.
- Gently pull or reposition portions of the geotextile as needed to remove wrinkles.
- Use fine aggregate (0.75 to 1 inch maximum size) for filling so the geotextile will be supported against the trench soil in many places.
- Use clean drainage aggregate material without fines that might clog the drain.

- Slowly place clean drainage aggregate to form an initial bedding layer in the bottom of the trench. Avoid large drop heights.

- Place the drain pipe in the bedding.

- Slowly place additional thin layers of clean drainage aggregate. The geotextile should be allowed to partially slip into the trench as needed so it conforms to the variations in the side walls.

- Close the top of the filled trench by folding over the remaining geotextile flaps.

The placement of erosion protection materials over a geotextile will depend on the type of armoring to be used (riprap, articulating concrete mattresses, etc.). Small riprap is often directly placed onto a geotextile, see Figure 6.12. A protective soil cover (cushion layer) is normally used when large riprap is installed such as that seen in Figure 6.13. The following considerations are used by the Bureau of Reclamation (1992) when placing riprap for slope erosion protection:

- For slope surfaces, placement should always start from the base of the slope moving upslope and preferably from the center outward.

- For geotextiles placed on well prepared subgrade (Class B) with no cushion layer, the height of drop for stones less than 250 pounds should be less than 12 inches and stones weighing more than 250 pounds should be placed without freefall.

- For geotextiles placed on well prepared subgrade (Class B) with a cushion layer over the geotextile, the height of drop for stones weighing less than 250 pounds should be less than 36 inches and for stones greater than 250 pounds placed with no free fall.

- For geotextiles placed on poorly prepared subgrade (Class A) with no cushion layer the height of drop for stones less than 250 pounds should be less than 12 inches and stones greater than 250 pounds placed with no free fall.

- For geotextiles placed on poorly prepared subgrade (Class A) with a cushion layer the height of drop for stones less than 250 pounds should be less than 24 inches and stones greater than 250 pounds placed with no free fall.

Figure 6.12.—Photograph showing riprap placed directly onto a geotextile. The slope height that can be covered by this method is limited by the reach of the equipment.

Figure 6.13.—Photograph showing placement of large riprap as slope protection. Note that a layer of bedding soil has been placed as a cushion under each piece of riprap prior to gently placing the large rock into position.

6.6 Quality assurance/quality control

Problems with geotextile applications/installations are often attributed to poor product acceptance and construction monitoring procedures on the part of the owner and/or installation methods on the part of the contractor. Acceptance and rejection criteria should be clearly stated in the specifications. It is very important that all installations be observed by experienced and qualified inspector. There are ASTM standards for acceptance and rejection of geotextile shipments. In addition, there are standard sampling and testing requirements during construction (ASTM, 2002). A field inspection checklist is presented as follows:

- Review the construction plans and specifications.
- Check listed material properties of supplied geotextile against the specified property values.
- Check to see that the rolls are offloaded and properly stored onsite. Check for any damage.
- Check roll and lot numbers to verify that they match certification documents.
- Check that the subgrade and anchor trenches (if specified) are constructed in accordance with the specifications.
- Observe that the geotextiles are unrolled and placed over the subgrade without damaging them.
- Observe materials in each roll to ensure that they are the same. Observe rolls for flaws and nonuniformity.
- Obtain test samples according to the specifications.
- Check all seams, both factory and field, for any flaws. Note any seams that need repair.
- Collect samples of seams, both factory and field for testing.
- Observe all operations associated with placement of cover materials to ensure that the geotextile is not damaged,
- Repair all damaged areas that are observed.

All construction activities shall be recorded by photographs and in detailed daily reports.

Chapter 7

Conclusions and Recommendations

7.1 Current status

The use of geotextiles in embankment dams is a common practice worldwide. The vast majority of these uses are in shallow-burial applications such as a separator/filter underneath erosion control materials such as riprap, as filters in toe drains, and as protective cushions/drainage layers placed against waterproofing geomembranes.

In contrast to shallow burial applications, the use of geotextiles buried deep inside embankment dams is a far less common practice worldwide. In most agencies, their use in such instances is expressly prohibited. The principal deep-burial application that has found some use is the substitution of a geotextile for a granular filter. Use of a geotextile or a geonet composite drain in substitution for a granular drain within an embankment dam has only been documented in a very few cases (see Appendix A).

While the number of applications is very limited, geotextiles have been used as deeply buried filters in dams in France, Germany, South Africa, and a few other nations. Some of these installations have been in service for over a quarter of a century. The geotextile installed as a filter for Valcross dam has been successfully performing filtration for over 35 years. These applications remain controversial and are not considered to be consistent with accepted engineering practice within the United States.

As Chapter 1 noted, the major Federal agencies that design or have regulatory authority over dams, typically either preclude outright the use of geotextiles (FERC) or limit the roles they serve. Again, those limitations only allow placement of geotextile materials where they are accessible for inspection and replacement, if necessary. Deeper burial is only allowed where the geotextile serves in a backup capacity (Bureau of Reclamation). State Dam Safety programs fall variously between prohibition on geotextile use to no restrictions whatsoever.

7.2 Materials

Geotextiles are principally manufactured from polypropylene. Woven, nonwoven, and knitted geotextiles are used in embankment dam applications.

Woven geotextiles do not transmit flow in the plane of the geotextile, they act more like a sieve or screen and are capable of rapid drainage. Woven monofilament geotextiles provide high tensile strengths for reinforcement applications. Their principal filtration properties are the Apparent Opening Size and the Percent Open Area. Woven monofilament geotextiles are often selected for service underneath riprap as a separator/filter because they drain quickly and can perform well in reversing flow conditions. Slit film and other types of fibers for woven geotextiles are not recommended for dam applications.

Nonwoven geotextiles include both needlepunched and heat bonded fabrics. Needlepunched nonwoven geotextiles have a significant thickness and are able to transmit flow in the plane of the geotextile. These versatile fabrics serve as filters, drains, separators, and reinforcement in many applications. Heat bonded fabrics are thin and are typically used to filter fine-grained soils such as clays. A common application is their use in wick drains.

Knitted geotextiles are principally used as a filter wrapping around a drainage pipe that is embedded in a sand encasement. Knitted geotextiles are very prone to stretching and alteration of the Apparent Opening Size which has limited their application.

It is possible to manufacture two-layer, and multi-layer geotextiles by combining two or more layers of geotextile material. This has the advantage of allowing a geotextile that has been selected for its filtration performance to be joined with one which is more open and is selected for its strength. The concept is to produce a geotextile having superior filtration and strength performance as compared to single-layer geotextiles. Such two-layer geotextiles have been installed in several dams in France. Additional research using two-layer and multi-layer filters is recommended because it shows promise of providing a superior filtration product.

7.3 Performance problems

Chapter 4 identified and discussed the principal concerns with the use of geotextiles in embankment dams. Research and experience has shown that some previously cited concerns, such as unknown service life and biological degradation of geotextile polymers, are no longer the uncertain issues they once were. Service lives of 100 years or more are not unreasonable for buried geotextile applications. The geotextiles at Valcross dam have been in service for 35 years and samples have been exhumed on two occasions for testing to evaluate changes in the polymer. New geotextiles can be provided with anti-oxidation formulations that are expected to attain service lives of up to 200 years for buried applications.

There is no evidence that biological organisms attack the geotextile polymers themselves. Oxidation, ultraviolet light, and other factors can degrade geotextiles; however; burial of the material significantly reduces the rate of degradation.

Excessive clogging remains as a concern for geotextile applications. Knowledge of the effects of geotextile compression upon filtration properties, better filtration and permeability design criteria, and development of construction practices (use of fine gravel) to provide for intimate contact of the geotextile with the base soil, have provided more reasonable designs than past practices. Filtration testing can be conducted to evaluate filter performance for a proposed geotextile filter and soil combination.

The issue of installation damage from construction activities and post installation service remains as the most significant objection to the use of geotextiles in embankment dams. The issue includes:

- Installation damage that can occur during construction and may not be detected

- Plant intrusion after construction that clogs void space and reduces its permeability;

- Burrowing animal damage (holes or cuts) which compromises filter performance; and

- Tearing of the fabric due to settlement and cracking of the embankment.

- To avoid internal erosion, the geotextile filter must be constructed without holes, tears, or defects. This is difficult to achieve in typical construction operations.

7.4 Design and construction

Design criteria for geotextiles has advanced and in the area of filtration, existing government design guides are out of date and need to be revised. Current design criteria recognize soil conditions where geotextiles should not be used for filtration because of the difficulty in establishing a stable filter cake. Those instances principally involve dealing with two extremes: dispersive, narrowly graded, fine soils and broadly graded soils with very high uniformity coefficients (>50). These two groups of soils also are problematic for engineers working with traditional granular filters.

Because geotextiles are susceptible to construction damage, strict enforcement of quality control procedures is essential. Foundation surfaces must be suitably prepared, inspected, and approved prior to deployment, geotextile deployment must include proper handling and placement procedures, and covering operations must be properly planned and executed with full time independent inspection to guard against damage.

7.5 Expanding the role of geotextiles in embankment dams

To expand the use of geotextiles in dams in the United States, three conditions have to be met.

- It has to be shown that geotextiles do not have some "fatal flaw" that cannot be satisfactorily addressed through some combination of design, manufacture, and construction control.

- There has to be some compelling reason to select geotextiles over conventional dam construction materials. The principal advantages are lower costs, and ease and rapidity of construction.

- Restrictive agency policies need to be revised.

The decision as to the appropriate uses of geotextiles in dam construction is ultimately the choice of the design engineer, the owner and to a varying degree that of the regulatory body. The outright prohibition against any use of geotextiles in embankment dams is not defensible. Shallow burial applications are in widespread use. To continue to ignore such successful applications which do not threaten the integrity of the dam is illogical. In the case of deeper burial, such as a non-redundant filter, dam designers should always be cognizant of the public safety concern. One should continuously strive to minimize the threat dams pose to those downstream. It requires that one does not adopt new practices without rigorous proof testing. But, at the same time one cannot ignore the promise of new technology, particularly when it holds the promise of expediting resolving public safety threats posed by existing deficient dams.

How then is it possible that foreign practitioners can confidently design and install geotextiles filters in embankment dams while those in the United States have little confidence in a successful outcome? A common theme amidst the foreign engineers is the comprehensive program of design, testing, and construction quality assurance and control that is implemented. For a reliable filter installation the project must:

- Carefully evaluate filtration and clogging criteria
- Consider the effects of burial upon filter performance and strength requirements
- Conduct laboratory testing to simulate field conditions using candidate geotextiles and site soils
- Demand a high level of construction quality control
- Monitor installation results

The fact that a number of dams have incorporated geotextiles as a non-redundant critical filter does not prove the robustness of the application. More data regarding the nature of the soils being filtered and the seepage loading (piezometric surface and seepage rates) must be considered in a significant number of cases before reliability can be assured. It is possible that in some cases the core is already filtered by the downstream soils and that the geotextile is playing a minor role as a filter element. Only by critical review of detailed data can confidence in the application be realized. The industry has not yet achieved this level of proof, the necessary detailed data from years of monitoring is generally lacking from most published accounts of geotextile use.

7.6 Conclusions

Advancements have been made in the manufacture, design, testing, construction, and monitoring of geotextile applications. These advancements have been presented in the document for consideration by dam designers.

The lack of readily available detailed information is a major impediment to geotextile use. Design of geotextiles for embankment dam applications requires a significant level of specialized knowledge. Embankment dam designers have not traditionally been trained in geotextile design and the standard textbooks on the subject do not provide sufficient detail to inspire confidence in designing for dam applications. This problem leaves designers to perform time-consuming searches of difficult to find conference proceedings and specialty journals.

On overseas projects, filtration testing using candidate geotextiles and actual project soils is emphasized as an essential component of critical geotextile applications; however; there is no standardization from one country to another of such testing procedures and equipment. Researchers need to cooperate to develop standardized filtration testing apparatus.

Published design standards, such as those by the Bureau of Reclamation and U.S. Army Corps of Engineers, which prohibit geotextile use in critical applications, reflect the current main stream opinion regarding geotextile use. For non-critical applications, these design standards are useful, but do not reflect current filtration design practice and may not always yield optimal filtration design results.

Further, new products are being developed to address multiple design issues. An example is the bonding of different types of geotextiles into a single sheet to obtain a composite material with superior filtration and strength properties. Other materials emerging on the market are "smart geotextiles" which combine sensing elements such as fiber optics to monitor stress and moisture change in a buried geotextile.

Dam engineers have recognized the need for and insist upon a strict quality control program for granular filter construction including specifying handling procedures to avoid segregation and contamination, limiting maximum fines content to avoid clogging, and sampling and testing installed materials to verify material breakdown has not been excessive. A similar intensive effort must be applied to geotextile design and construction for a successful installation.

It is the policy of the National Dam Safety Review Board that geotextiles should not be used in locations that are critical to the safety of the dam.

7.7 Recommendations

A comprehensive document on the design, installation and monitoring of geotextiles in dams is needed. A rewrite of the 1992 Bureau of Reclamation Design Standards, Chapter 19 - Geotextiles, is a potential candidate. Such a document would benefit from the incorporation of a failure mode assessment of the dam's response to foreseeable problems with the geotextile. This assessment should be melded with the Design Classification scheme into a matrix to aid the designer in the appropriate use of geotextiles in dams. Appropriate use here refers to the combination of the steps taken to minimize the likelihood of the geotextile suffering a problem and the complementary measures provided to mitigate the consequences should the geotextile experience that problem.

- Multi-layered geotextiles are an advancement that may provide a "graded filter" with superior filtration and strength performance. Such new products are worthy of research efforts regarding dam embankment filtration applications.

- The anticipated loads and strength requirements for geotextile service in embankment dams should be developed.

- The collection of case histories and information on service life of existing installations does not provide sufficient detail to allow for critical evaluation of performance.

- Establish a database of case histories with sufficient information to understand the design, details of construction, and performance metrics that validate the geotextile performance.

- Dam designers are cautioned to fully consider the implications regarding the use geotextiles as filters and drains in embankment dams. This use remains controversial and is not yet considered to be standard practice for dam design in the United States.

Table 7.1.—Summary of concerns regarding geotextile use.

CONCERN	SUSCEPTIBILITY	DESIGN PROVISIONS	CONSTRUCTION PRACTICE	MITIGATION
Clogging that interferes with the drainage function	Function of geotextile type, AOS, thickness and stress state, & abutting upstream soil type	Select geotextile on filtering capability to pass appropriate small particles while retaining particles above the size necessary to retain the upgradient zone, exclude from consideration where bearing directly against problematic soils and environments fostering biological products and chemical precipitates	Protect geotextile from contamination in handling	Provide strategically located drains; select dam section that is safe under worst case gradients, provide piezometers to monitor porewater pressures in the core near the geotextile
Inability to satisfy filter criteria allowing piping of the upstream soil zone	Function of soil (most difficult for fine grained dispersive soils & broadly graded soils with large coefficients of uniformity), geotextile type, AOS, thickness and stress state	Exclude certain soils from direct bearing against the geotextile, configure geotextile interface so that it is in compression to maintain intimate contact, use current filter criteria & conduct tests based on Design Classification, e.g., in Class A application test design under anticipated stress state with representative samples.	Protect geotextile from contamination and damage in handling	Provide strategically located underdrain sumps with sediment traps to monitor fines loss
Post installation strains that adversely affect filtering ability and/or permeability	Large tensile and compressive stresses can change the void distribution affecting permeability & filtering	Model stress-strain response of the geotextile to dam section geometry to understand sense of strain behavior and run tests on the geotextiles that simulate those conditions.		
Installation conditions which result in cuts, folds, wrinkles, punctures or gaps in what was to be a continuous element, can locally short circuit it's filtering function	Service conditions where the geotextile would bear against angular particles or large particles that would act to distort the strain pattern locally and stress the geotextile in a manner not anticipated in the design	Select a geotextile product that includes protective layers to cushion loads and reduce incidences where the geotextile must resist stress concentrations. Installation procedures must eliminate flods and wrinkles, since they can provide unfiltered piping paths.	Require oversized and angular particles be removed that are immediately adjacent to the geotextile, protect geotextile from abrasion and cuts in handling, sew sheets together so as to develop the full sheet strength across seams	Based on Design Class - a select zone may be provided as a cushion, provide strategically located underdrain sumps with sediment traps to monitor fines loss presumably from a damaged geotextile
Plant intrusion that clogs void space and reduces permeability	Vulnerability is a function of the depth of burial, (the shallower the burial the more likely that roots would find conditions conducive to growth. Deeper burial would be associated with cooler temperatures, lack of light, minimal nutrients; the only plus would be a ready source of water) ,	Shallow burial increases exposure to this type of damage but at the same time it is practical to repair damage, deeper burial likely results in cold, wet, low nutrient environments that are not conducive to root penetration; to further discourage vegetation, if deemed necessary, the geotextile could be held back from an assumed root penetration zone and where it would be replaced with a conventional granular drain, appropriately armor pipe outfall area to minimize surfaces for plant growth to	Strip geotextile subgrade and drain outfall area of organic rich soils to remove conditions that foster plant growth	Stress vegetation control in the operation and maintenance program

	the aggressiveness of the vegetation control program.	flourish on.		
Burrowing animal damage (holes or cuts) that degrade the filter performance	Vulnerability is a function of the depth of burial, the type of animal and the aggressiveness of the normal animal control program	Shallow burial increases exposure to this type of damage but at the same time it is practical to repair damage, deeper burial likely results in cold wet conditions prevailing that comprises poor habitat for burrowing animals, bottom drains can be placed at depths where critical portions of their length are submerged effectively blocking off access		Stress animal control efforts in the operation and maintenance program
Unknown service lives that are alleged to be short in comparison to traditional dam building materials	Varies but there is reasonable confidence that when appropriately designed and installed, the useable life of geotextiles should exceed a hundred years	Utilize the best available data from accelerated age testing and corroborate to the extent practicable with dam case histories	Minimize exposure to heat and ultraviolet light	Specify a design life whereupon some further measures are taken to verify integrity. Allow for burial of material where it can be sampled and tested periodically to verify actual installation performance.

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Glossary

Abrasion (ASTM D 653, 2005): A rubbing and wearing away.

Acidic (Frobel, 1987): A term to describe a material having a pH of less than 7.0 in water. (See pH.)

Acidity: A measure of how acid water or soil may be. Water or soil with a pH of less than 7.0 is considered acidic.

Acre-foot (FEMA, 2004): A unit of volumetric measure that would cover 1 acre to a depth of 1 foot. An acre-foot is equal to 43,560 ft^3.

Adhesives (Frobel, 1987): In textiles, materials which cause fibers, yarns, or fabrics to stick together or to other materials.

Adhesion Strength (Frobel, 1987): The force required to cause a separation at the interface of two bonded (adhered) surfaces or components.

Aging: The process of changing properties over time.

Alkaline (Frobel, 1987): A term used to describe a material having a pH greater than 7.0 in water.

Anchor Trench (Frobel, 1987): A long narrow ditch on which the edges of a plastic sheet are buried to hold it in place or to anchor the sheet.

Anaerobic: An environment or a condition which is free of oxygen or an organism which can grow in the absence of oxygen.

Anisotropy (ASTM D 653, 2005): Having different properties in different directions.

Apparent opening size (AOS) (ASTM D-4439, 2004): *(O_{95}), n—for a geotextile,* a property which indicates the approximate largest particle that would effectively pass through the geotextile.

Atmosphere for testing geosynthetics (ASTM D-4439, 2004): *n* – air maintained at a relative humidity between 50 and 70 % and a temperature of 21 ± 2°C (70° ± 4°F).

Backward erosion piping (piping): The term "piping" has often been used generically in literature to describe various erosional processes, not all of which hold to the classic definition of the term piping. Piping in the classic sense is characterized by the formation of an open tunnel that starts at a downstream seepage exit point and progresses back upstream toward the reservoir. This classic type of piping is often termed "backward erosion piping," and this term is used in this document. Blowout (also known as heave or blowup) is another term used to describe the condition where hydraulic head loosens a uniform body of cohesionless sand to the point where the permeability of the sand increases and flow concentrates in that zone that is blown out. Failures by blowout may not be exactly the same as "backward erosion piping," but for the purposes of this document, are grouped under this blanket term. Backward erosion piping involves the following essential conditions:

- Backward erosion piping is associated with intergranular seepage through saturated soil zones, not along concentrated flow paths (such as cracks).

- Backward erosion piping begins at a seepage discharge face where soil particles can escape because of the lack of a filter or an improperly designed filter at the exit face. As particles are removed, erosion progresses backward toward the source of seepage.

- The material being piped must be able to support a "pipe" or "roof," or must be adjacent to a feature such as an overlying clay layer or concrete structure that would provide a roof.

- For backward erosion piping to progress to the point where a failure occurs, soils susceptible to backward erosion piping must occur along the entire flow path.

- Backward erosion piping requires a hydraulic gradient high enough to initiate particle movement in soils that are susceptible to this phenomenon. Piping can begin with relatively low gradients for horizontal flow. For flow exiting a deposit vertically, if gradients are very high, the soil may be loosened, creating a condition sometimes termed heave.

- The term blowout is used to describe backward erosion piping that results when a sand horizon is overlain by a clay horizon with a defect in it, and an excessive hydraulic gradient causes backward erosion piping through that defect in the blanket. Defects in the blanket may consist of crayfish holes, fence post holes, animal burrows, and drying cracks. The transported sand forms a conical deposit on top of the surface clay horizon that itself is resistant to backward erosion piping.

In this document, the term "backward erosion piping" is used to describe the condition where piping occurs as defined above. The term "internal erosion" is used to describe all other erosional processes where water moves internally through the soil zones of embankment dams and foundations.

Bedrock (FEMA, 2004): Any sedimentary, igneous, or metamorphic material represented as a unit in geology; being a sound and solid mass, layer, or ledge of mineral matter; and with shear wave threshold velocities greater than 2,500 ft/s.

Biological Stability (Frobel, 1987): Ability to resist degradation from exposure to microorganisms.

Blinding (ASTM D-4439, 2004): *n – for geotextiles,* the condition where soil particles block the surface openings of the fabric, thereby reducing the hydraulic conductivity of the system.

Bond (Frobel, 1987): The adhesive and cohesive forces holding two synthetic components in intimate contact.

Bonded Fabric (Frobel, 1987): A fabric containing two or more layers of cloth joined together with resin, rubber, foam or adhesive to form one ply.

Boot (Frobel, 1987): A bellows type covering to exclude dust, dirt, moisture, etc., from a flexible joint. In geomembrane installations, a prefabricated shape of the parent geomembrane material used to effect a transition due to mechanical protrusions such as pipes and drains.

Breach (FEMA, 2004): An opening through an embankment dam that allows the uncontrolled draining of a reservoir. A controlled breach is a constructed opening. An uncontrolled breach is an unintentional opening caused by discharge from the reservoir. A breach is generally associated with the partial or total failure of the embankment dam.

Bulking: The low density condition in fine sand that occurs when negative capillary stresses develop when the sands are placed at intermediate water contents. Sands placed at bulking water content have a much lower density than those placed very dry or saturated. Sands that may have been placed at bulking water content may be densified by flooding and vibratory compaction.

Calender (Frobel, 1987): (a) A precision machine equipped with two or more heavy internally heated or cooled rolls, revolving in opposite directions. Used for preparation of highly accurate continuous sheeting or plying up of rubber compounds and fractioning or coating of fabric with rubber or plastic compounds. (b) A machine used in finishing to impart a variety of surface effects to fabrics. A calendar essentially consists of two or more heavy rollers, sometimes heated, through which the fabric passes under heavy pressure.

Calendering (Frobel, 1987): This is the most frequently used manufacturing process for geomembranes. A calendered nonreinforced geomembrane is usually a single sheet of compound made by passing a heated polymeric compound through a series of heated rollers (calendar). Some calendered nonreinforced geomembranes are produced by simultaneously running two sheets of compound through heated rollers. The purpose of this process is to minimize the risk of having a pinhole through the entire thickness of the geomembrane. Calendered reinforced geomembranes are produced by simultaneously running sheets of compound and scrims through heated rollers. A three-ply calendered reinforced geomembrane is made of the following layers: compound/scrim/compound. A five-ply calendered reinforced geomembrane is made of the following layers: compound/scrim/compound/scrim/compound. The polymeric compound, when heated and pressed by the rollers, tends to flow through the openings of the scrim, thus providing adhesion between the sheets of compound located on both sides of the scrim. This adhesive mechanism is commonly known as "strike-through". (See Geomembrane Production, and Scrim).

Capillary Action (ASTM D 653, 2005): The rise or movement of water in the interstices of a soil or rock due to capillary forces.

Chemical Stability (Frobel, 1987): The ability to resist chemicals, such as acids, bases, solvents, oils and oxidation agents; and chemical reactions, including those catalyzed by light.

Chimney drain: A drainage element located (typically) immediately downstream of a chimney filter. A chimney drain parallels the embankment dam's core and is either vertical or near vertical and placed from one abutment completely to the other abutment.

Clay (ASTM D 653, 2005): Fine-grained soil or the fine-grained portion of soil that can be made to exhibit plasticity (putty-like properties) within a range of water contents, and that exhibits considerable strength when air-dry. The term has been used to designate the percentage finer than 0.0002 mm (0.005 mm in some cases), but it is strongly recommended that this usage be discontinued, since there is ample evidence from an engineering standpoint that the properties described in the above definition are many times more important.

Clogging (ASTM D-4439, 2004): *n – for geotextiles,* the condition where soil particles move into and are retained in the openings of the fabric, thereby reducing the hydraulic conductivity.

Clogging potential (ASTM D-4439, 2004): *n – in geotextiles,* the tendency for a given geotextile to decrease permeability due to soil particles that have either lodged in the geotextile openings or have built up a restrictive layer on the surface of the geotextile.

Cohesion (ASTM D 653, 2005): Shear resistance at zero normal stress (an equivalent term in rock mechanics is intrinsic shear strength).

Cohesion, c **(FL^{-2}) (ASTM D 653, 2005):** The portion of the shear strength of a soil indicated by the term *c*, in Coulomb's equation, $s = c + p \tan \phi$.

Apparent: Cohesion in granular soils due to capillary forces.

Cohesionless Soil (ASTM D 653, 2005): A soil that when confined has little or no strength when air-dried and that has little or no cohesion when submerged.

Cohesive Soil (ASTM D 653, 2005): A soil that, when unconfined has considerable strength when air-dried and that has significant cohesion when submerged.

Colloidal Particles (ASTM D 653, 2005): Particles that are so small that the surface activity has an appreciable influence on the properties of the aggregate.

Compaction (ASTM D 653, 2005): The densification of a soil by means of mechanical manipulation.

Compaction (FEMA, 2004): Mechanical action that increases density by reducing the voids in a material.

Controlled: A compaction process that includes requirements for maximum lift thickness and other criteria to ensure that the compacted soil has the intended properties.

Method: A compaction process that only specifies the equipment and its operation in compacting the soil.

Compatibility (Frobel, 1987): Capability of existing together without adverse effects. Applied primarily to combinations of waste fluids and geosynthetic materials.

Consequences (FEMA, 2004): Potential loss of life or property damage downstream of a dam caused by floodwater released at the embankment dam or by water released by partial or complete failure of the dam.

Contamination: The introduction of undesirable or unsuitable materials.

Copolymer (Frobel, 1987): A polymer composed of a combination of more than one monomer (usually two). Copolymers are the basis of some man-made fibers. (See Polymer.)

Core (FEMA, 2004): A zone of low permeability material in an embankment dam. The core is sometimes referred to as central core, inclined core, puddle clay core, rolled clay core, or impervious zone.

Crack: A narrow discontinuity.

Creep (ASTM D-4439, 2004): *n* – the time-dependent increase in accumulative strain in a material resulting from an applied constant force.

Cross-machine direction (ASTM D-4439, 2004): *n* – the direction in the plane of the fabric perpendicular to the direction of manufacture.

Cross section (FEMA, 2004): An elevation view of an embankment dam formed by passing a plane through the dam perpendicular to the axis.

Cutoff trench (FEMA, 2004): A foundation excavation later to be filled with impervious material to limit seepage beneath an embankment dam.

Dam (FEMA, 2004): An artificial barrier that has the ability to impound water, wastewater, or any liquid-borne material, for the purpose of storage or control of water.

Earthfill (FEMA, 2004): An embankment dam in which more than 50 percent of the total volume is formed of compacted earth layers comprised of material generally smaller than 3 inches.

Embankment (FEMA, 2004): Any dam constructed of excavated natural materials, such as both earthfill and rockfill dams, or of industrial waste materials, such as a tailings dams.

Rockfill (FEMA, 2004): An embankment dam in which more than 50 percent of the total volume is comprised of compacted or dumped cobbles, boulders, rock fragments, or quarried rock generally larger than 3 inches.

Tailings (FEMA, 2004): An industrial waste dam in which the waste materials come from mining operations or mineral processing.

Dam failure (FEMA, 2004): A catastrophic type of failure characterized by the sudden, rapid, and uncontrolled release of impounded water or the likelihood of such an uncontrolled release. There are lesser degrees of failure, and any malfunction or abnormality outside the design assumptions and parameters that adversely affect an embankment dam's primary function of impounding water is properly considered a failure. These lesser degrees of failure can progressively lead to or heighten the risk of a catastrophic failure. They are, however, normally amenable to corrective action.

Dam safety (FEMA, 2004): Dam safety is the aft and science of ensuring the integrity and viability of dams, such that they do not present unacceptable risks to the public, property, and the environment. Dam safety requires the collective application of engineering principles and experience, and a philosophy of risk management that recognizes that an embankment dam is a structure whose safe function is not explicitly determined by its original design and construction. Dam safety also includes all actions taken to identify or predict deficiencies and consequences related to failure, and to document and publicize and unacceptable risks, and reduce, eliminate, or remediate the to the extent reasonably possible.

Defect (Frobel, 1987): In nondestructive examination, a discontinuity or group of discontinuities whose indications do not meet specified acceptance criteria.

Defect: A discontinuity whose size, shape, orientation, location, or properties make it detrimental to the useful service of the structure in which it occurs.

Deformation (ACI, 2000): A change in dimension or shape due to stress.

Degradation (Frobel, 1987): The loss of desirable physical properties by a material as a result of some process or physical/chemical phenomenon.

Delamination (Frobel, 1987): Separation of the plies in a geomembrane system or separation of laminated layers. Delamination is also defined as a separation of layers.

Denier (Frobel, 1987): A weight-per-unit-length measure of any linear material. Officially, it is the number of unit weight of 0.05 grams per 450-meter length. This is numerically equal to the weight in grams of 9,000 meters of the material. Denier is a direct numbering system in which the low numbers represent the finer sizes and the higher numbers the coarser sizes. In the U.S., the denier system is used for numbering filament yarns (except glass), man-made fiber staple (but not spun yarns), and tow. In most countries outsides the U.S., the denier system has been replaced by the tex system (q.v). The following denier terms are in use: (a) Denier per Filament (dpf) - The denier of an individual continuous filament or an individual staple fiber if it were continuous. In filament yarns, it is the yarn denier divided by the number of filaments; (b) Yarn Denier - The denier of a filament yarn. It is the product of the denier per filament and the number of filaments in the yarn; and (c) Total Denier - The denier of a tow before it is crimped. It is the product of the denier per filament and the number of filaments in the two. The total denier after crimping (called crimped total denier) is higher because of thee resultant increase in weight per unit length.

Desiccation: The process for evaporating water or removing water vapor from a material.

Design: An iterative decision-making process that produces plans by which resources are converted into products or systems that meet human needs or solve problems.

Designer: A registered engineer representing a firm, association, partnership, corporation, agency, or any combination of these who is responsible for the supervision or preparation of plans and specifications associated with an embankment dam and its appurtenances.

Deterioration (ACI, 2000): Disintegration or chemical decomposition of a material during a test or service exposure.

Differential settlement (ASTM D 653, 2005): Settlement that varies in rate or amount, or both, from place to place across a structure.

Direct Shear Test (ASTM D 653, 2005): A shear test in which soil or rock under an applied normal load is stressed to failure by moving one section of the sample or sample container (shear box) relative to the other section.

Dispersive clays: Dispersive clays differ from "normal" clays because of their electrochemical properties. Dispersive clays usually have a preponderance of sodium cations on the clay particles compared to a preponderance of calcium and magnesium on "normal" clays. The imbalance of electrical charges that result from this makeup causes dispersive clays to deflocculate in the presence of water. This deflocculation occurs because the interparticle forces of repulsion exceed the attractive forces. The clay particles go into suspension even in slowly moving or standing water. This means that dispersive clays are extremely erosive, and flow through cracks in dispersive clays that can quickly erode the cracks and lead to rapid enlargement of the cracks. Failures caused by internal erosion in dispersive clay dams are common. Dispersive clays are not detectable with normal soil tests, such as mechanical analyses and Atterberg limit tests, and special tests such as the crumb test, double hydrometer, and pinhole test, are required to detect the presence of dispersive clays.

Drain: A pipe that collects and directs water to a specified location.

Dry density (ASTM D 653, 2002): The mass of solid particles per the total volume of soil or rock.

Dry unit weight (ASTM D 653, 2005): The weight of soil or rock solids per unit of total volume of soil or rock mass.

Ductility (ASTM D 653, 2005): Condition in which material can sustain permanent deformation without losing its ability to resist load.

Durability (Frobel, 1987): Having the quality of lasting or continuing without perishing or wearing out; not perishable or changeable.

Durability (ACI, 2000): The ability of a material to resist weathering, chemical attack, abrasion, and other conditions of service.

Earth Pressure (ASTM D 653, 2005): The pressure or force exerted by soil on any boundary.

	Symbol	Unit
Pressure	p	FL^{-2}
Force	P	F or FL^{-1}

Active, P_A, p_A: The minimum value of earth pressure. This condition exists when a soil mass is permitted to yield sufficiently to cause its internal shearing resistance along a potential failure surface to be completely mobilized.

Earth pressure at rest, P_0, p_0: The value of the earth pressure when the soil mass is in its natural state without having been permitted to yield or without having been compressed.

Passive, P_p, p_p: The maximum value of earth pressure. This condition exists when a soil mass is compressed sufficiently to cause its internal shearing resistance along a potential failure surface to be completely mobilized.

Earthquake (FEMA, 2004):
A sudden motion or trembling in the earth caused by the abrupt release of accumulated stress along a fault.

Effective Diameter (Effective Size) (ASTM D 653, 2005): D_{10}, D_e(L) – Particle diameter corresponding to 10% finer on the grain-size curve.

Elongation at break (ASTM D-4439, 2004): *n* – the elongation corresponding to the breaking load, that is, the maximum load.

Emergency (FEMA, 2004): A condition that develops unexpectedly, which endangers the structural integrity of an embankment dam and/or downstream human life or property, and requires immediate action.

Emergency Action Plan (EAP) (FEMA, 2004): A plan of action to be taken to reduce the potential for property damage and loss of life in an area affected by an embankment dam failure or large flood.

Emergency classification: The act of classifying an emergency at an embankment dam, to determine the severity of the emergency condition and the proper response to prevent a dam failure, and to reduce loss of life and property damage, should the dam fail.

Engineer: A person trained and experienced in the profession of engineering; a person licensed to practice the profession by the appropriate authority.

Environmental Stress Cracking (Frobel, 1987): The development of cracks in a material that is subjected to stress or strain in the presence of specific chemicals.

Equivalent Opening Size (EOS) (Frobel, 1987): Number of the U.S. Bureau of Standards sieve (or its opening size in millimeters or inches) having openings closest in size to the diameter of uniform particles which will allow 5% by weight to pass through the fabric when shaken in a prescribed manner.

Erosion (FEMA, 2004): The wearing away of a surface (bank, stream bed, embankment, or other surface) by floods, waves, wind, or any other natural process.

Ethylene (Frobel, 1987): A petroleum derivative, C_2H_4, which is the raw material for polyethylene.

Extruded (Frobel, 1987): Forced through the shaping die of an extruder. The extrusion may be of solid or hollow cross-section. (See Extrusion Process.)

Extrusion Process (Frobel, 1987): A method whereby molten polymer, usually of the polyolefin family (such as polyethylene, polypropylene), is extruded into a non-reinforced sheet. Immediately after extrusion, when the sheet is still warm, it can be laminated with a fabric, through light calendering; the geomembrane thus produced is reinforced. (See Calendering.)

Failure (ASTM, D 4439, 2004): In testing geosynthetics, water or air pressure in the test vessel at failure of the geosynthetic.

Failure (ASTM D-4439, 2004): *n* – an arbitrary point beyond which a material ceases to be functionally capable of its intended use.

Failure mode (FEMA, 2004): A physically plausible process for an embankment dam failure, resulting from an existing inadequacy or defect related to a natural foundation condition, the dam or appurtenant structure's design, the construction, the materials incorporated the operation and maintenance, or aging process, which can lead to an uncontrolled release of the reservoir.

Fibers (Frobel, 1987): Basic element of fabrics and other textile structures, characterized by having a length at least 100 times its diameter or width which can be spun into a yarn or otherwise made into a fabric. (See Yarn.)

Filament (Frobel, 1987): A fiber of extreme length.

Filament Yarn (Frobel, 1987): Yarn made from continuous filament fibers. (See Yarn, Woven Geotextiles.)

Filling (Frobel, 1987): Yarn running form selvage to selvage at right angles to the warp in a woven fabric.

Film (Frobel, 1987): An optional term for sheeting having nominal thickness not greater than 0.010in.

Filter: A zone of material designed and installed to provide drainage, yet prevent the movement of soil particles due to flowing water.

Chimney: A chimney filter is a vertical or near vertical element in an embankment dam that is placed immediately downstream of the dam's core. In the case of a homogenous embankment dam, the chimney filter is typically placed in the central portion of the dam.

Collar: A limited placement of filter material that completely surrounds a conduit for specified length within the embankment dam. The filter collar is located near the conduit's downstream end. The filter collar is usually included in embankment dam rehabilitation only when a filter diaphragm, in that a filter diaphragm is usually located within the interior of the embankment dam.

Diaphragm: A filter diaphragm is a zone of filter material constructed as a diaphragm surrounding a conduit through an embankment. The filter diaphragm protects the embankment near the conduit from internal erosion by intercepting potential cracks in the earthfill near and surrounding the conduit. A filter diaphragm is intermediate in size between a chimney filter and a filter collar. The filter diaphragm is placed on all sides of the conduit and extends a specified distance into the embankment.

Filter (Protective Filter) (ASTM D 653, 2005): A layer or combination of layers of pervious materials designed and installed in such a manner as to provide drainage, yet prevent the movement of soil particles due to flowing water.

Filter Cake (Frobel, 1987): Soil stratification developed upstream of a geotextile by separating the suspended soil from water as the mixture attempts to pass through a soil fabric system.

Filter cake: A thin layer of soil particles that accumulate at the face of a filter when flowing water carries eroding particles to the face. The filter cake forms when eroded particles embed themselves into the voids of the filter.

Filtration (Frobel, 1987): The process of retaining soils while allowing the passage of water (fluids).

Fines (ASTM D 653, 2005): Portion of a soil finer than a No. 200 (75μm) U.S. standard sieve.

First filling: Usually refers to the initial filling of a reservoir or conduit.

Fish Mouth (Frobel, 1987): A half-cylindrical or half-conical opening formed by an edge wrinkle in a geomembrane seam. A seam defect due to the unequal lengths of the mating surfaces.

Flood (FEMA, 2004): A temporary rise in water surface elevation resulting in inundation of acres not normally covered by water. Hypothetical floods may be expressed in terms of average probability of exceedance per year, such as 1-percent-chance flood, or expressed as a fraction of the probable maximum flood or other reference flood.

Force-elongation curve (ASTM D-4439, 2004): *n – in a tensile test*, a graphical representation of the relationship between the magnitude of the externally applied force and the change in length of the specimen in the direction of the applied force – synonym for “stress-strain curve”.

Foundation (FEMA, 2004): The portion of a valley floor that underlies and supports an embankment dam.

Friction Angle (Frobel, 1987): An angle, the tangent of which is equal to the ratio of the friction force per unit area to the normal stress between two materials.

Frost heave (ASTM D 653, 2002): The raising of a structure due to the accumulation of ice in the underlying soil or rock.

Fungicides (Frobel, 1987): Additives to the base polymer used to prevent fungi and bacteria from attacking the polymer.

Geocell (IGS, 2000): A three-dimensional, permeable, polymeric (synthetic or natural) honeycomb or web structure, made of strips of geotextiles, geogrids or geomembranes linked alternatingly and used in contact with soil/rock and/or any other geotechnical material in civil engineering applications.

Geocomposite (ASTM D-4439, 2004): *n* – a product composed of two or more materials, at least one of which is a geosynthetic.

Geofoam (ASTM D-4439, 2004): *n* – a block or planar rigid cellular foamed polymeric material used in geotechnical engineering applications.

Geogrid (ASTM D-4439, 2004): , *n* – a geosynthetic formed by a regular network of integrally connected elements with apertures grater than 6.35 mm (1/4 inch) to allow interlocking with surrounding soil, rock, earth, and other surrounding materials to function primarily as reinforcement.

Geonet (ASTM D-4439, 2004): *n* – a geosynthetic consisting of integrally connected parallel sets of ribs, overlying similar sets at various angles for planar drainage of liquids or gases.

Geomembrane (ASTM D-4439, 2004): *n* – an essentially impermeable geosynthetic composed of one or more synthetic sheets.

Geosynthetic (ASTM D-4439, 2004): *n* – a planar product manufactured from polymeric material used with soil, rock, earth, or other geotechnical engineering related material as an integral part of a man-made project, structure, or system.

Geosynthetic clay liner (ASTM D-4439, 2004): *n* – a manufactured hydraulic barrier consisting of clay bonded to a layer or layers of geosynthetic materials.

Geotechnical engineering (ASTM D-4439, 2004): *n* – the engineering application of geotechnics.

Geotechnics (ASTM D-4439, 2004): *n* – the application of scientific methods and engineering principles to the acquisition, interpretation; and use of knowledge of materials of the earth's crust to the solution of engineering problems.

Geotextile (ASTM D-4439, 2004): *n* – a permeable geosynthetic comprised solely of textiles.

Geotextile (IGS, 2000): A planar, permeable, polymeric (synthetic or natural) textile material, which may be nonwoven, knitted or woven, used in contact with soil/rock and/or any other geotechnical material in civil engineering applications.

Geotextile, knitted: A geotextile produced by interlooping one or more yarns, fibers, filaments or other elements.

Geotextile, nonwoven: A geotextile in the form of a manufactured sheet, web or batt of directionally or randomly orientated fibers, filaments or other elements, mechanically and/or thermally and/or chemically bonded.

Geotextile, woven: A geotextile produced by interlacing, usually at right angles, two or more sets of yarns, fibers, filaments, tapes or other elements.

Geotextiles (FEMA, 2004): Any fabric or textile (natural or synthetic) when used as an engineering material in conjunction with soil, foundations, or rock. Geotextiles have the following uses: drainage, filtration, separation of materials, reinforcement, moisture barriers, and erosion protection.

Geotextile Fibers (Frobel, 1987): The basic elements of a geotextile are its fibers. There are three types of synthetic fibers. (a) Filament - These are produced by extruding melted polymer through dies or spinnerets. Since this processing is continuous, filaments are sometimes called "continuous filaments". After extrusion, a filament is usually drawn (i.e. pulled along its longitudinal axis) to orient its molecules in the same direction. As a result of the draw, the filament is strengthened. (See Extrusion Process.) (b) Staple Fibers - These are obtained by cutting filaments to a short length, typically 2 to 10 cm (1 to 4 in). (c) Slit films - These are flat tape-like fibers, typically 1 to 30 mm (40 to 120 mils) wide, produced by slitting with blades an extruded plastic film. After the slitting of the film, the tape-like fibers are drawn. As a result of the draw, molecules become oriented in the same direction and the strength of the fibers increases. (See Extrusion Process.)

Grab test (ASTM D-4439, 2004): *n* – in fabric testing, a tension test in which only a part of the width of the specimen is gripped in the clamps.

Gradation (grain size distribution) (texture) (ASTM D 653, 2005): The proportions by mass of a soil or fragmented rock distributed in specified particle-size ranges.

Gradation (ASTM C 822, 2002): The distribution of particles of granular material among standard sizes, usually expressed in terms of cumulative percentages larger or smaller than each of a series of sieve openings.

Grain-Size Analysis (Mechanical Analysis) (Frobel, 1987): The process of determining gradation or grain-size distribution.

Gradient ratio (ASTM D-4439, 2004): *n – in geotextiles,* the ratio of the hydraulic gradient through a soil-geotextile system to the hydraulic gradient through the soil alone.

Gravel (ASTM D 653, 2002): Rounded or semi-rounded particles of rock that will pass a 3-inch (76.2-mm) and be retained on a No. 4 (4.75-µm) U. S. standard sieve.

Grids (Frobel, 1987): A geosynthetic made by drawing, in one or two perpendicular directions, a perforated plate made of a polymer such a polyethylene or polypropylene. In the process, the small perforations become large rectangular openings, usually one to 10 centimeters (0.5 inch to 4 inches). The strands have a large degree of molecular orientation as a result of the draw. Grids are typically used for soil reinforcement.

Hazard (FEMA, 2004): A situation that creates the potential for adverse consequences, such as loss of life, or property damage.

Hazard potential classification: A system that categorizes embankment dams according to the degree of adverse incremental consequences of a failure or misoperation of a dam. The hazard potential classification does not reflect in any way on the current condition of the embankment dam (i.e., safety, structural integrity, flood routing capacity).

Heat Bonded (Frobel, 1987): A process by which fabric filaments are welded together at their contact points by subjection to a relatively high temperature.

High-Density Polyethylene (HDPE) (Frobel, 1987): A polymer prepared by low-pressure polymerization of ethylene as the principal monomer. (See Polymer.)

Homogeneous: Constructed of only one type of material.

Hydraulic conductivity (ASTM D-4439, 2004): *(k), n* – the rate of discharge of water under laminar flow conditions through a unit cross-sectional area of a porous medium under a unit hydraulic gradient and standard temperature conditions (20°C).

Hydraulic fracture: A separation in a soil or rock mass that occurs if the applied water pressure exceeds the lateral effective stress on the soil element. Hydraulic fracture may occur if differential foundation movement is allowed. Soils compacted dry of optimum water content are more susceptible to hydraulic fracture.

Hydraulic Gradient (ASTM D 653, 2005): The change in total hydraulic head per unit distance of flow.

Critical Hydraulic Gradient - Hydraulic gradient at which the intergranular pressure in a mass of cohesionless soil is reduced to zero by the upward flow of water.

Hydraulic transmissivity (ASTM D-4439, 2004): (L^2 T^{-1}), *n* – for a geotextile or related product, the volumetric flow rate of water per unit width of specimen per unit gradient in a direction parallel to the plane of the specimen.

Hydrostatic Pressure, u_0 (FL^{-2}) (ASTM D 653, 2005): A state of stress in which all the principal stresses are equal (and there is no shear stress), as in a liquid at rest; the product of the unit weight of the liquid and the difference in elevation between the given point and the free water elevation.

Excess hydrostatic pressure (hydrostatic excess pressure), $\bar{u}$, u (FL^{-2}): The pressure that exists in pore water in excess of the hydrostatic pressure.

Hydrostatic pressure: The pressure exerted by water at rest.

Ice lens: A mass of ice formed during the construction of an embankment dam, when a moist soil is exposed to freeing temperatures. In certain types of soils (silts and silty soils) the size of the ice mass will increase as it draws unfrozen capillary water from the adjacent soil. A void in the soil may remain after the ice lens melts.

Impervious: Not permeable; not allowing liquid to pass through.

Index test (ASTM D-4439, 2004): *n* – a test procedure which may contain a known bias but which may be used to establish on order for a set of specimens with respect to the property of interest.

Inspection: The review and assessment of the operation, maintenance, and condition of a structure.

Inspector: The designated on-site representative responsible for inspection and acceptance, approval, or rejection of work performed as set forth in the contract specifications. The authorized person charged with the task of performing a physical examination and preparing documentation for inspection of the embankment dam and appurtenant structures.

In-plane flow (ASTM D-4439, 2004): *n* – fluid flow confined to a direction parallel to the plane of a geotextile or related product.

Internal erosion: A general term used to describe all of the various erosional processes where water moves internally through or adjacent to the soil zones of embankment dams and foundation, except for the specific process referred to as "backward erosion piping." The term "internal erosion" is used in this document in place of a variety of terms that have been used to describe various erosional processes, such as scour, suffusion, concentrated leak piping, and others.

Internal Friction (shear resistance) (FL^{-2}) (Frobel, 1987): The portion of the shearing strength of a soil or rock indicated by the terms p tan φ in Coulomb's equation $s = c + p \tan \varphi$. It is usually considered to be due to the interlocking of the soil or rock grains and the resistance to sliding between the grains.

Isotropic Material (ASTM D 653, 2005): A material whose properties do not vary with direction.

Laboratory sample (ASTM D-4439, 2004): *n* – a portion of material taken to represent the lot sample or the original material, and used in the laboratory as a source of test specimens.

Laminar flow (ASTM D-4439, 2004): *n* – flow in which the head loss is proportional to the first power of the velocity.

Laminate (Frobel, 1987): A produce made by bonding together two or more layers of material or materials.

Leakage (FEMA, 2004): Uncontrolled loss of water by flow through a hole or crack.

Lining (FEMA, 2004): With reference to a canal, tunnel, shaft, or reservoir, a coating of asphaltic concrete, reinforced or unreinforced concrete, shotcrete, rubber or plastic to provide watertightness, prevent erosion, reduce friction, or support the periphery of the outlet pipe conduit.

Lot (ASTM D-4439, 2004): *n* – a unit of production, or a group of other units or packages, taken for sampling or statistical examination, separable from other similar units.

Lot sample (ASTM D-4439, 2004): *n* – one or more shipping units taken at random to represent an acceptance sampling lot and used as a source of laboratory samples.

Machine direction (ASTM D-4439, 2004): *n* – the direction in the plane of the fabric parallel to the direction of manufacture.

Mastic: A permanently flexible waterproofing material used for sealing water-vulnerable joints.

Mil (Frobel, 1987): An abbreviation for one-thousandth of an inch.

Minimum average roll value (MARV) (ASTM D-4439, 2004): *n – for geosynthetics,* a manufacturing quality control tool used to allow manufacturers to establish published values such that the user/purchaser will have a 97.7% confidence that the property in question will meet published values. For normally distributed data, "MARV" is calculated as the typical value minus two (2) standard deviations from documented quality control test results for a defined population from one specific test method associated with one specific property.

DISCUSSION – MARV is applicable to a geosynthetic's intrinsic physical properties such as weight, thickness, and strength. MARV may not be appropriate for some hydraulic, performance or durability properties.

Moisture content: The water content in a soil.

Monitoring: The process of measuring, observing, or keeping track of something for a specific period of time or at specified intervals.

Monofilament (Frobel, 1987): (a) A single filament. (b) A single filament which can function as a yarn in commercial textile operations, that is, it must be strong and flexible enough to be knitted, woven, or braided, etc.

Mullen Bursting Strength (Frobel, 1987): An instrumental method which measures the ability of a fabric to resist rupture by pressure exerted by an inflated diaphragm.

Multi-axial tension (ASTM D-4439, 2004): *n* – stress in more than one direction.

Multifilament (Frobel, 1987): A yarn consisting of many continuous filaments or strands. (See yarn.)

Necking (Frobel, 1987): The localized reduction in cross section which may occur in a material under tensile stress. (See Tensile Stress.)

Needle-punched (Frobel, 1987): Subjecting a web of fibers to repeated entry of barbed needles that compact and entangle individual fibers to form a fabric (FHWA).

Nominal (ASTM D-4439, 2004): *n* – representative value of a measurable property determined under a set of conditions, by which a product may be described.

Nonwoven Geotextiles: See Geotextiles – Nonwoven.

Normal direction (ASTM D-4439, 2004): *n – for geotextiles*, the direction perpendicular to the plane of the geotextile.

Open Area (Frobel, 1987): That portion of the plane of the fabric in which there are no filaments, fibers, or films between the upper and lower surfaces of the fabric. This is expressed as a percentage of the total area. (See Percent Open Area.)

Optimum moisture content (optimum water content) (ASTM D 653, 2002): The water content at which a soil can be compacted to a maximum dry unit weight by a given compactive effort.

Overlap (Frobel, 1987): That section or width of adjacent geosynthetic panels or blankets that are in contact – one under the other forming a seamed or unseamed joint.

Particle Size (Frobel, 1987): The effective diameter of a particle measured by sedimentation, sieving, or micrometric methods (SSSA, 1970).

Peel Adhesion (Frobel, 1987): The force required to delaminate a structure or to separate the surface layer from a substrate.

Percent Open Area (Frobel, 1987): The net area of a fabric that is not occupied by fabric filaments, normally determinable only for woven and nonwoven fabrics having distinct visible and measurable openings that continue directly through the fabric.

Performance property (ASTM D-4439, 2004): *n* – a result obtained by conducting a performance test.

Performance test (ASTM D-4439, 2004): *n* – a test which simulates in the laboratory as closely as practical selected conditions experienced in the field and which can be used in design - synonym for "design test".

Permeability (ASTM D 653, 2005): The capacity of a rock to conduct liquid or gas. It is measured as the proportionality constant, k, between flow velocity, v, and hydraulic gradient, I:, $v = kI$.

Permeability (ASTM D-4439, 2004): *n* –the rate of flow of a liquid under a differential pressure through a material.

Permeability (ASTM D-4439, 2004): *n –for geotextiles*, hydraulic conductivity

Permittivity (ASTM D-4439, 2004): (T^{-1}), *n – for geotextiles*, the volumetric flow rate of water per unit cross sectional area per unit head under laminar flow conditions, in the normal direction through a geotextile.

Pervious: Permeable, having opening s that allow water to pass through.

pH (ASTM D 653, 2005): An index of the acidity or alkalinity of a soil in terms of the logarithm of the reciprocal of the hydrogen ion concentration.

Piezometer (ASTM, 2000): An instrument for measuring fluid pressure (air or water) within soil, rock, or concrete.

Piping (ASTM D 653, 2005): The progressive removal of soil particles from a mass by percolating water, leading to the development of channels.

Polymer (Frobel, 1987): A macromolecular material formed by the chemical combination of monomers having either the same or different chemical composition. Plastics, rubbers, and textile fibers are all high molecular weight polymers. Only synthetic polymers are used to make synthetics. The most common types of polymers presently used as base products in the manufacture of geosynthetics can be classified as follows: (a) Thermoplastics - Polyvinyl Chloride (PVC); Oil Resistant PVC (PVC-OR); Thermoplastic Nitrile-PVC (TN-PVC); Ethylene Interpolymer Alloy (EIA). (b) Crystalline Thermoplastics - Low Density Polyethylene (LDPE); High Density Polyethylene Alloy (HDPE-A); Polypropylene; Elasticized Polyolefin. (c) Thermoplastic Elastomers - Chlorinated Polyethylene (CPE); Chlorinated Polyethylene Alloy (CPE-A); Chlorosulfonated Polyetylene (CSPE), also commonly referred to as "Hypalon"; Thermoplastic Ethylene-Propylene Diene Terpolymer (T-EPDM). (d) Elastomers - Isoprene-Isobutylene Rubber (IIR), also commonly referred to as Butyl Rubber; Ethylene Propylene Diene Terpolymer (EPDM); Polychloroprene (CR), also commonly referred to as "Neoprene"; Epichlorohydrin Rubber (CO).

Polyolefin Fiber (Frobel, 1987): A fiber produced form a polymerized olefin, such as polypropylene or polyethylene.

Polypropylene (PP) (Frobel, 1987): A polymer prepared by the polymerization of propylene as the sole monomer. (See Polymers.)

Polypropylene Fiber (Frobel, 1987): An olefin fiber made from polymers or copolymers of propylene. Polypropylene fiber is produced by melt spinning the molten polymer, followed by stretching to orient the fiber molecules. Characteristics: Polypropylene fibers have a number of advantages over polyethylene fibers in the field of textile applications. The degree of crystallinity, 72 to 75%, results in a fiber which is strong and resilient, and does not fibrillate like high density polyethylene. Polypropylene has a high work of rupture, which indicates a tough fiber, and may be made with tenacities as high as 8.0 to 8.5 grams per denier. The melting point of polypropylene is 165°C, which is low by comparison with nylon or polyester, but is high enough to make it suitable for most applications. So light that it actually floats, polypropylene fiber provides greater coverage per pound than any other fiber. It is highly resistant to mechanical abuse and chemical attack.

Polyvinyl Chloride (PVC) (Frobel, 1987): A synthetic thermoplastic polymer prepared from vinyl chloride as the sole monomer. PVC can be compounded into flexible and rigid forms through the use of plasticizers, stabilizers, fillers, and other modifiers; rigid forms used in pipes and well screens, flexible forms used in manufacture of sheeting.

Porosity, *n* (ASTM D 653, 2005): The ratio of the aggregate volume of voids or interstices in a rock or soil to its total volume.

Proctor (Compaction Test) (Frobel, 1987): Standard proctor or standard AASHTO test used to determine the proper amount of mixing water to use when compacting a soil test in the field and the resulting degree of density which can be expected from compaction at this optimum water content. (See Compaction)

Pre-fabricated vertical drain (PVD) (ASTM D-4439, 2004): *n* – a geocomposite consisting of geotextile cover and drainage core installed vertically into soil to provide drainage for accelerating consolidation of soils. DISCUSSION – Also known as band or wick drain.

Puncture (Frobel, 1987): To pierce or perforate with a pointed instrument or object.

Puncture Resistance (Frobel, 1987): Extent to which a material is able to withstand the action of a sharp object without perforation. Examples of test of this property are Federal Test Method Standard No. 101B, Methods 2031 or 2065.

Quality (Frobel, 1987): The totality of features and characteristics of a material, product, service, system, or environment that bear on its capability to satisfy a specified need(s).

Quality assurance (Frobel, 1987): The verification of the conformance of materials and methods of application to the governing specifications, in order to achieve the desired results.

Quality assurance (ASTM D-4439, 2004): *n* – all those planned or systematic actions necessary to provide adequate confidence that a material, product, system, or service will satisfy given needs.

Quality control (ASTM D-4439, 2004): *n* – the operational techniques and the activities which sustain a quality of material, product, system, or service that satisfy given needs; also the use of such techniques and activities.

Rate of creep (ASTM D-4439, 2004): *n* – the slope of the creep-time curve at a given time.

Reinforcement (Frobel, 1987): Strengthening of a soil-fabric system by contributions of the fabric inclusion.

Relative Density D_d, I_D **(ASTM D 653, 2005):** The ratio of: (1) the difference between the void ratio of a cohesionless soil in the loosest state and any given void ratio to (2) the difference between its void rations in the loosest and in the densest states.

Relative density: A numerical expression that defines the relative denseness of a cohesionless soil. The expression is based on comparing the density of a soil mass at a given condition to extreme values of density determined by standard tests that describe the minimum and maximum index densities of the soil. Relative density is the ratio, expressed as a percentage, of the difference between the maximum index void ratio and any given void ratio of a cohesionless, free-draining soil; to the difference between its maximum and minimum index void ratios.

Reservoir (FEMA, 2004): A body of water impounded by an embankment dam and in which water can be stored.

Resin (Frobel, 1987): (a) A general term for solid or semi-solid natural organic substances, usually of vegetable origin and amorphous and yellowish to brown, transparent or translucent, and soluble in alcohol or ether but not in water.
(b) Any of a large number of man-made products made by polymerization or other chemical processes and having the properties of natural resins. (See Resin Bonded.)

Resin Bonded (Frobel, 1987): Joining of fibers at their intersection points by resin in the formation of a nonwoven geotextile or Geocomposite. (See Nonwoven Geotextile.)

Resin-Treated (Frobel, 1987): Usually a term descriptive of a textile material which has received an external resin application for stiffening.

Revetment (ASTM D 653, 2005): Bank protection by armor, that is, by facing of a bank or embankment with erosion-resistant material.

Riprap (FEMA, 2004): A layer of large, uncoursed stone, precast blocks, bags of cement, or other suitable material, generally placed on the slope of an embankment or along a watercourse as protection against wave action, erosion, or scour. Riprap is usually placed by dumping or other mechanical methods and in some cases, is hand placed. It consists of pieces of relatively large size, as distinguished from a gravel blanket.

Risk (FEMA, 2004): A measure of the likelihood and severity of adverse consequences (National Research Council, 1983). Risk is estimated by the mathematical expectation of the consequences of an adverse event occurring, that is, the product of the probability of occurrence and the consequence, or alternatively, by the triplet of scenario, probability of occurrence, and the consequence.

Sample (ASTM D-4439, 2004): *n* – (1) a portion of material which is taken for testing or for record purposes. (2) A group of specimens used, or group of observations made, which provide information that can be used for making statistical inferences about the population(s) from which the specimens are drawn. (See also **laboratory sample**, **lot sample**, and **specimen**).

Sand (ASTM D 653, 2005): Particles of rock that will pass the No. 4 (4.75-µm) sieve and be retained on the No. 200 (0.075-mm) U.S. standard sieve.

Scaling: The deposition and adherence of insoluble products on the surface of a material.

Scarification: The process of roughening the surface of a previously compacted lift of soil before placement of the next lift. Scarification is accomplished with discs, harrows, and similar equipment. The purpose of scarification is to promote bonding of lifts and reduce interlift permeability. Scarification is usually required in construction specifications written by designers concerned over stratification of earthfills.

Scour: The loss of material occurring at an erosional surface, where a concentrated flow is located, such as a crack through a dam or the dam/foundation contact. Continued flow causes the erosion to progress, creating a larger and larger eroded area.

Scrim (Frobel, 1987): A type of open weave fabric with a low mass per unit area (i.e., a "lightweight" fabric) used in the reinforcing of geomembranes. Sometimes scrims are made thinner by calendaring them prior to calendaring the compound. A scrim is characterized by its count and the linear density of its yarns. The count is the number of yarns per unit width (in meter, centimeter, or inch) in each direction (warp and filling). The linear density of a yarn is its mass per unit length. Units for linear density are kg/m or, more conveniently, tex which is 10^{-6} kg/m (i.e. g/km or mg/m). The mass per unit area of a scrim is derived by multiplying the count by the linear density in both directions and adding. (See Calendering.)

Seam (ASTM D-4439, 2004): *n* – a permanent joining of two or more materials.

Seam (ASTM D-4439, 2004): *n* – the connection of two or more pieces of material by mechanical, chemical, or fusion methods to provide the integrity of a single piece of the material.

Seam allowance (ASTM D-4439, 2004): *n* – the width of fabric used in making a seam assembly, bounded by the edge of the fabric and the furthest stitch line.

Seam assembly (ASTM D-4439, 2004): *n* – the unit obtained by joining fabrics with a seam, including details such as fabric direction(s), seam allowance, sewing treads used, and number of stitches per unit length; and sometimes additional details of fabrication such as sewing-machine type and speed, needle type and size, etc.

Seam design engineering (ASTM D-4439, 2004): *n* – the procedures used to select a specific thread, a specific stitch type, and a specific seam type to achieve the required seam strength.

Seam efficiency, sewn (ASTM D-4439, 2004): *n – in sewn fabrics*, the ratio expressed as a percentage of seam strength to fabric strength.

Seaming Methods (Geotextile Seaming) (Frobel, 1987): The seaming of geotextiles has evolved from overlapping of fabric, seam joining with pins or staples, heat sealing or securing seams with adhesives, to the sewn seam. Often, the best choice is to specify the sewing of seam joints. By eliminating the wasteful overlapping of fabric, sewn seams can offer a reduction in labor costs, quicker completion of the installation phase, and superior results. Once a determination is made to join seams by sewing, a decision must be made about seam and stitch type. There are three primary seam types that can be used for geotextile field sewing: “flat” seam, “J” seam, and “Butterfly” seam. There are only two stitch types that can be effectively used in field sewing of geotextiles: the single-thread chainstitch (101) and the two-thread chainstitch (401). No “hard and fast” rule can be made about how far from the “turned” edge the stitching should be done. Typically, it is from 2-inch to 4-inch. The following are currently used geotextile seaming methods: (a) J Seam - Two parallel pieces of fabric are mated together, turned in the same direction and sewn with the required rows of stitches (Ssn-1; Ssn-2). (b) Flat Seam - Two parallel pieces of fabric are mated and sewn together with either a single row of stitched (designated Ssa-1) or possibly with two or more rows of stitches (Ssa-2, Ssa-3). This is also called a superimposed seam or prayer seam. (c) Butterfly Seam - This seam type should be considered when the fabric being used is loosely woven or has a tendency to "fray" at the edges. Two parallel pieces of fabric are mated together. Each piece is turned back and then sewn with the rows of stitched required (Ssd-1; Ssd-2). (d) Single-Thread Chainstitch (101) - A single thread chain stitch creates a line of stitches that has a bottom side appearance of "figure 8's" end-to-end in a row. Although this stitch will give good seam strength, relative to the break strength of the thread used, a broken stitch anywhere along the seam compromises the integrity of the whole seam. However, for light to medium weight fabric installation, the 101 chainstitch (with the proper sewing thread) should yield satisfactory results. (e) Two-Thread Chain Stitch (401) - A two-thread chainstitch has a bottom side appearance of double interlocking "figure 8's". This stitch type offers superior seam strength plus the added protection of restricting a broken stitch. In effect, this means that each stitch must be individually broken before the integrity of the seam is jeopardized. The 401 is recommended for medium to heavy weight geotextile fabric installations.

Seam Peel Strength (Frobel, 1987): A representative specimen is taken across the seam and placed in a tensile testing machine. For the peel test, one end and the closest end of the adjacent piece are gripped, placing the seamed portion between them to be in a tensile mode. The resistance to peel is measured.

Seam Shear Strength (Geomembranes) (Frobel, 1987): A representative specimen is taken across the seam and placed in a tensile testing machine. For the shear test, the two separate pieces of geomembrane are pulled apart, placing the joined or seamed portion in shear. The resistance to shear is measured.

Seam Strength (Frobel, 1987): Strength of a seam of linear material measured either in shear or peel modes. Strength of the seams is reported either in absolute units, e.g., pounds per inch of width, or as a percent of the strength of the sheeting.

Seam type (ASTM D-4439, 2004): *n – in sewn fabrics*, an alphanumeric designation relating to the essential characteristics of fabric positioning and rows of stitching in a specific sewn fabric seam (see Federal Standard 751).

Seepage (ASTM D 653, 2005): The infiltration or percolation of water through rock or soil to or from the surface. The term seepage is usually restricted to the very slow movement of ground water.

Seepage Force (ASTM D 653, 2005): The frictional drag of water flowing through voids or interstices in rock, causing an increase in the intergranular pressure, that is, the hydraulic force per unit volume of rock or soil which results from the flow of water and which acts in the direction of flow.

Segregation: The tendency of particles of the same size in a given mass of aggregate to gather together whenever the material is being loaded, transported, or otherwise disturbed. Segregation of filters can cause pockets of coarse and fine zones that may not be filter compatible with the material being protected.

Seismic activity: The result of the earth's tectonic movement.

Self-healing: The property of a sand filter that reflects its ability to deform and fill a crack that is transmitted to the filter.

Selvage (ASTM D-4439, 2004): *n* – the woven edge portion of a fabric parallel to the warp.

Service life: Expected useful life of a project, structure, or material.

Settlement (FEMA, 2004): The vertical downward movement of a structure or its foundation.

Sewing thread (ASTM D-4439, 2004): *n* – a flexible, small diameter yarn or strand, usually treated with a surface coating, lubricant, or both, intended to be used to stitch one or more pieces of material or an object to a material.

Sewn seam (ASTM D-4439, 2004): *n* – *in sewn fabrics*, a series of stitches joining two or more separate plies of a material or materials of planar structure such as textile fabric.

Sewn seam strength (ASTM D-4439, 2004): *n* – *for geotextiles*, the maximum resistance, measured in kilonewtons per metre, of the junction formed by stitching together two or more planar structures.

Shear Stress: Stress acting parallel to the surface of the plane being considered.

SI (Frobel, 1987): The international System of Units (abbreviation for "le Systemè International d'Unites") as defined by the General Conference on Weights and Measures (CGPM) – based upon seven base units, two supplementary units, and derived units, which together form a coherent system.

Sieve (Frobel, 1987): An apparatus with apertures for separating sizes of material.

Silt (Inorganic silt) (Rock flour) (Frobel, 1987): Material passing the No. 200 (75 micron) U.S. standard sieve that is non-plastic or very slightly plastic and that exhibits little or no strength when air-dried.

Silt size (ASTM D 653, 2005): That portion of the soil finer than 0.02 mm and coarser than 0.002 mm (0.05 mm and 0.005 mm in some cases).

Sink Hole (Frobel, 1987): A depression in the substrate, usually caused by settlement or substrate particle removal by water migrating behind the lining. The hole is deep in comparison to its diameter.

Sinkhole:A depression, indicating subsurface settlement or particle movement, typically having clearly defined boundaries with a sharp offset.

Silt-Film Yarn (Frobel, 1987): Yarn of a flat, tape-like character produced by slitting an extruded film.

Slope (FEMA, 2004): Inclination from the horizontal. Sometimes referred to as batter when measured from vertical.

Soil (ASTM D 653, 2002): Sediments or other unconsolidated accumulations of solid particles produced by the physical and chemical disintegration of rocks, and which may or may not contain organic matter.

Soil Fabric Fraction (Frobel, 1987): The resistance to sliding between engineering fabric and soil, excluding the resistance from soil cohesion. Soil fabric fraction is usually quantified in terms of friction angle.

Specific gravity (ASTM D-4439, 2004): *n* –the ratio of the density of the substance in question to the density of a reference substance at specified conditions of temperature and pressure.

Specifications: The written requirements for materials, equipment, construction systems, and standards.

Specification (ASTM D-4439, 2004): *n* – a precise statement of a set of requirements to be satisfied by a material, product, system or service that indicates the procedures for determining whether each of the requirements is satisfied.

Specimen (ASTM D-4439, 2004): *n* – a specific portion of a material or laboratory sample upon which a test is performed or which is taken for that purpose - synonym for "test specimen.

Spray Bonding (Frobel, 1987): Application of a non-woven binder by spraying.

Spun Bonding Products (Frobel, 1987): Fabrics formed by filaments which have been extruded, drawn, then laid on a continuous belt. Bonding is accomplished by several methods such as by hot-roll calendering or by passing the web through a saturated-steam chamber at an elevated pressure. (See Extrusion Process, Calendering.)

Spun Fabric (Frobel, 1987): A fabric made from staple fibers which may contain one or a blend of two or more fiber types. (See Staple Fibers.)

Stability (ASTM D 653, 2005): The condition of a structure or a mass of material when it is able to support the applied stress for a long time without suffering any significant deformation or movement that is not reversed by the release of stress.

Stabilizers, UV (Frobel, 1987): Additives to a geosynthetic such as carbon black which helps resist the damaging effects of the sun and absorbs UV radiation.

Standard proctor compaction test: A standard laboratory or field test procedure performed on soil to measure the maximum dry density and optimum dry density and optimum water content of the soil. The test uses standard energy and methods specified in ASTM Standard Testing Method D 698.

Staple Fiber (Frobel, 1987): Fibers produced in short lengths as distinguished from filaments.

Stitch (ASTM D-4439, 2004): *n* – the repeated unit formed by the sewing thread in the production of seams in a sewn fabric (see Federal Standard 751a).

Strain (ASTM D-4439, 2004): *n* – the change in length per unit of length in a given direction.

Strength (Frobel, 1987): Maximum stress which a material can resist without falling for any given type of loading. (ISRM)

Strength, Bursting (Frobel, 1987): The force required to rupture a textile with a force, applied at right angles to the plane of the fabric, under specified conditions. (See Mullen Bursting Strength.)

Strength, Tearing [F], kn. (Frobel, 1987): The force required either to start or to continue or propagate a tear in a fabric under specified conditions.

Stress Crack (ASTM, D 4439, 2004): An external or internal crack in a plastic caused by tensile stresses less than its short-time mechanical strength.

Subgrade (ASTM D 653, 2005): The soil prepared and compacted to support a structure or a pavement system.

Subgrade Intrusion (Frobel, 1987): Localized aggregate penetration of a soft cohesive subgrade and resulting displacement of the subgrade into the cohesionless material.

Subgrade Pumping (Frobel, 1987): The displacement of cohesive or low-cohesion fines from a saturated subgrade into overlying aggregate, as the result of hydraulic forces created by transmittal of wheel-load stresses to the subgrade.

Subgrade Restraint (Frobel, 1987): The action of engineering fabric to resist subgrade deformation.

Subsoil (ASTM D 653, 2005): (1) Soil below a subgrade of fill, or (2) that part of a soil profile occurring below the "A" horizon.

Suffosion: Seepage flow through a material that causes part of the finer grained portions of the soil matrix to be carried through the coarser grained portion of the matrix. This type of internal erosion is specifically relegated only to gap graded soils (internally unstable soils) or to soils with an overall smooth gradation curve, but with an overabundance of the finer portions of the curve represented by a "flat tail" to the gradation curve. While a crack is not needed to initiate this type of internal erosion, a concentration of flow in a portion of the soil is needed.

Survivability (Frobel, 1987): The ability of a fabric to be placed and to perform its intended function without undergoing degradation.

Tailings: The fine-grained waste materials from an ore processing operation.

Tearing strength (ASTM D-4439, 2004): F, (F), *kN, n* – the force required either (1) to start or (2) to continue or propagate a tear in a fabric under specified conditions.

Tensile modulus (ASTM D-4439, 2004): J, (FL^{-1}), Nm^{-1}, *n – for geotextiles*, the ratio of the change in tensile force per unit width to a corresponding change in strain (slope).

Tensile strength (ASTM D-4439, 2004): *n – for geotextiles*, the maximum resistance to deformation developed for a specific material when subjected to tension by an external force.

Tensile test (ASTM D-4439, 2004): *n – in textiles*, a test in which a textile material is stretched in one direction to determine the force-elongation characteristics, the breaking force, or the breaking elongation.

Tension (Frobel, 1987): The force or load that produces a specified elongation.

Testing (Frobel, 1987): An element of inspection which generally denotes the determination by technical means of the properties or elements of supplies, or components thereof, and involves the application of established scientific principles and procedure.

Tex (Frobel, 1987): Denier divided by nine (9). (See Denier.)

Thermal Shrinkage [L], mm. (Frobel, 1987): For a geotextile, decrease in length, or width, or both as measured in the atmosphere for testing geotextiles or an unrestrained specimen that has been subjected to a specified temperature for a specified length of time.

Thermoplastic (Frobel, 1987): Capable of being repeatedly softened by increase of temperature and hardened by decrease in temperature. Most polymeric liners are supplied in thermoplastic form because the thermoplastic form allows for easier seaming both in the factory and on the field.

Thermosetting Plastic (Frobel, 1987): A plastic which, when cured by application of heat or chemical means, changes into a substantially infusible and insoluble product.

Thickness t, [L], mm. (Frobel, 1987): The normal distance between two surfaces of a geosynthetic. Note: Thickness is usually determined as the distance between an anvil, or base, and a presser foot used to apply a specified compressive stress.

Thickness, Compressed [L], mm. (Frobel, 1987): Thickness under a specified stress applied normal to the material.

Thickness, Nominal [L], mm. (Frobel, 1987): Of a geotextile, thickness under a compressive stress of 2.0 kPa applied normal to the material.

Thread Count (Frobel, 1987): The number of threads per inch in each direction with the warp mentioned first and the fill second, e.g., a thread count of 20 x 10 means 20 threads per inch in the warp, and 10 threads per inch in the fill direction. (See Warp)

Tight Selvage (Frobel, 1987): In woven fabrics, selvage yarns shorter than warp yarn in the body of the fabric.

Toe of the embankment dam (FEMA, 2004): The junction of the downstream slope or face of a dam with the ground surface; also referred to as the downstream toe. The junction of the upstream slope with ground surface is called the heel or the upstream toe.

Topsoil (ASTM D 653, 2005): Surface soil, usually containing organic matter.

Toughness, Breaking T, (E/m),Jm^{-2} (Frobel, 1987): For geotextiles, the actual work per unit surface area of material that is required to rupture the material. It is proportional to the area under the load-elongation curve from the origin to the breaking point. Discussion: for geotextiles, breaking toughness is calculated from work-to-break divided by the width. Breaking toughness is expressed in Jm^{-2} (in.-lbf/in).

Tow (Frobel, 1987): A large strand of continuous man-made fiber filaments without definite twist collected in loose, rope-like form, usually held together by crimp. Tow is the form which most man-made fiber reaches before being cut into staple. (See Staple Fiber.)

Transmissivity (Frobel, 1987): For a geotextile, the volumetric flow rate per unit thickness under laminar flow conditions, in the in-plane direction of the fabric.

Transverse crack: A crack that extends in an upstream and downstream direction within an embankment dam.

Trench: A narrow excavation (in relation to its length) made below the surface of the ground.

Turbulent flow (ASTM D-4439, 2004): *n* – that type of flow in which any water particle may move in any direction with respect to any other particle, and in which the head loss is approximately proportional to the second power of the velocity.

Ultimate Elongation (Frobel, 1987): The elongation of a stretched specimen at the time of break. Usually reported as percent of the original length. Also called elongation at break.

Ultimate Strength (Frobel, 1987): The maximum stress developed in a specimen.

Ultraviolet Degradation (Frobel, 1987): Breakdown of polymeric structure when exposed to ultraviolet light.

Unconfined Compressive Strength (ASTM D 653, 2005): The load per unit area at which an unconfined prismatic or cylindrical specimen of material will fail in a simple compression test without lateral support.

Unified Soil Classification System (Frobel, 1987): A classification system based on the identification of soils according to their particle size/gradation, soil generics, physical properties of soil in respect to water, chemical and physical properties of soils.

Unit Weight, γ (FL^{-3}) (ASTM D 653, 2005): Weight per unit volume (with this, and all subsequent unit-weight definitions, the use of the term weight means force).

Dry unit weight (unit dry weight), γ_d, γ_e (FL^{-3}): The weight of soil or rock solids per unit of total volume of soil or rock mass.

Effective unit weight, γ_e (FL^{-3}): That unit weight of a soil or rock which, when multiplied by the height of the overlying column of soil or rock, yields the effective pressure due to the weight of the overburden.

Maximum unit weight, γ_{max} (FL^{-3}): The dry unit weight defined by the peak of a compaction curve.

Saturated unit weight, γ_G, γ_{sat} (FL^{-3}): The wet unit weight of a soil mass when saturated.

Submerged unit weight (buoyant unit weight), γ_m, γ', γ_{sub} (FL^{-3}): The weight of the solids in air minus the weight of water displaced by the solids per unit of volume of soil or rock mass; the saturated unit weight minus the unit weight of water.

Unit weight of water, γ_w (FL^{-3}): The weight per unit volume of water; nominally equal to 62.4 lb/ft^3 or 1 g/cmt^3.

Wet unit weight (mass unit weight), γ_m, γ_{wet} (FL^{-3}): The weight (solids plus water) per unit of total volume of soil or rock mass, irrespective of the degree of saturation.

Zero air voids unit weight, γ_z, γ_s (FL^{-3}): The weight of solids per unit volume of a saturated soil or rock mass.

Uplift (ASTM D 653, 2005): The hydrostatic force of water exerted on or underneath a structure, tending to cause a displacement of the structure.

UV: Ultraviolet light.

Vacuum Box (Frobel, 1987): A device used to assess the integrity of field seams in membrane liners in which a vacuum is drawn on a seam section and leaks detected by air moving through a soap solution.

Vertical strip drain (ASTM D-4439, 2004): *n* – a geocomposite consisting of a geotextile cover and drainage core installed vertically into soil to provide drainage for accelerating consolidation of soils.

Virgin Material (Frobel, 1987): A plastic material in the form of pellets, granules, powder, floc, or liquid that has not been subjected to use or processing other than that required for its initial manufacture.

Void (ASTM D 653, 2005): Space in a soil or rock mass not occupied by solid mineral matter. This space may be occupied by air, water, or other gaseous or liquid material.

Void (Frobel, 1987): The open spaces in a geosynthetic material through which flow can occur.

Void: A hole or cavity within the foundation or within the embankment materials.

Void Ratio (e, (D)) (ASTM D 4439, 2004): The ratio of the volume of void space to the volume of solids.

Warp (ASTM D-4439, 2004): *n* – the yarn running lengthwise in a woven fabric.

Water content (ASTM D 653, 2002): The ratio of the mass of water contained in the pore spaces of soil or rock material, to the solid mass of particles in that material, expressed as a percentage.

Waterproofing (Frobel, 1987): Treatment of a surface or structure to prevent the passage of water under hydrostatic pressure.

Water Resistant (Frobel, 1987): (Coated Fabric) The property of retarding both penetration and wetting by liquid water.

Water Table (ground-water table) (ASTM D 653, 2005): The surface of a ground-water body at which the water pressure equals atmospheric pressure. Earth material below the ground-water table is saturated with water.

Weathering (ASTM D 653, 2005): The process of disintegration and decomposition as a consequence of exposure to the atmosphere, to chemical action, and to the action of frost, water, and heat (ISRM).

Webs (Frobel, 1987): Plastic strips, typically 2 to 10 cm (1 to 4 inches) wide, which are used to make coarse woven fabrics known as webs or webbings. Webs look like very coarse slit film woven fabric. They are typically used for erosion control, bank protection, and soil reinforcement.

Weft (ASTM D-4439, 2004): *n* – yarn running from selvage to selvage at right angles to the warp in a woven fabric – synonym for "filling".

Weld-Line (Frobel, 1987): A discontinuity in a molded plastic part formed by the merging of two or more streams of plastic flowing together.

Weld-Mark (Frobel, 1987): A visible weld line.

Wicking (Frobel, 1987): Transmission of a gas or liquid along the fibers of the textile due to pressure differential or capillary action (D-1566).

Wide strip tensile test (ASTM D-4439, 2004): *n – for geosynthetics*, a tensile test in which the entire width of a 200-mm (8.0-inch) wide specimen is gripped in the clamps and the gage length is 100 mm (4.0 inches).

Wide-width strip tensile test (ASTM D-4439, 2004): *n – for geotextiles*, a uniaxial tensile test in which the entire width of a 200-mm (8.0-inch) wide specimen is gripped in the clamps and the gage length is 100 mm (4.0 inches).

Width: w, [L], mm. (Frobel, 1987): For a geotextile, the cross direction edge-to-edge measurement of a fabric in a relaxed condition on a flat surface.

Work-to-break (ASTM D-4439, 2004): (W, LF)**,** *n – in tensile testing*, the total energy required to rupture a specimen

Xenon-Arc Lamp (Frobel, 1987): A type of light source used in fading lamps. It is an electric discharge In an atmosphere of xenon gas at a little below atmospheric pressure, contained in a quartz tube.

Yarn (Frobel, 1987): A generic term for continuous strands of textile fibers or filaments in a form suitable for knitting, weaving, or otherwise intertwining to form a textile fabric. It may comprise: (a) a number of fibers twisted together, (b) a number of filaments laid together without twist (a zero twist yard), (c) a number of filaments laid together with more or less twist or, (d) a single filament with or without twist, (a monofilament).

Yield point (ASTM D-4439, 2004): *n – in geosynthetics*, the point on the force-elongation curve at which the first derivative equals zero (the first maximum).

Yield Strength (Frobel, 1987): The stress at which a material exhibits a specified limiting deviation from the proportionality of stress to strain.

Young's Modulus (ASTM D 653, 2005): The ratio of the increase in stress on a test specimen to the resulting increase in strain under constant transverse stress limited to materials having a linear stress-strain relationship over the range of loading. Also called elastic modulus.

Zone: An area or portion of an embankment dam constructed using similar materials and similar construction and compaction methods throughout.

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Appendix A

Case Histories

This appendix contains a table of examples drawn from the technical literature and is followed by a few individual case histories.

Table: The table found on the following pages summarizes the use of geotextiles in embankment dams. As many examples of the use of geotextiles in filtration and drainage were included as could be found in the literature. For more routine applications, such as use of geotextiles as cushions to protect waterproofing geomembranes, or as a filter used beneath rip rap revetments, only a few examples are provided.

Individual Case Histories:

Many Farms Dam toe drain filter
Aspen Lake Dam Rehabilitation

Use of Geotextiles in Embankment Dams

Geotextile Function	Name and Location of Embankment	Embankment Height (Meters)	Geosynthetic Installed	Date Installed	Installation Details	References
Filter	Valcros Dam, France	17	Nonwoven geotextile 300 g/m^2 (9 oz./yd^2) with 0.15 mm openings	1970	Geotextile filter formed by wrapping the fabric around the gravel drain located underneath the downstream embankment slope. Embankment is a homogeneous fill of silty sand having a d_{85} of 7 mm and a d_{28} of 0.75 mm. The gravel drain was 8 to 13 mm (0.3 to 0.5 inch) size material.	(Grioud and Gross, 1993), (Faure, and others 1999).
Filter	Valcros Dam, France	17	Nonwoven geotextile 400 g/m^2 (12 oz./yd^2)	1970	Geotextile filter placed on upstream dam slope between embankment material and riprap erosion protection layer. Embankment is a homogeneous fill of silty sand. Some minor erosion of soil from under the geotextile was experienced.	(Grioud and Gross, 1993),
Filter and Drain	Brugnens Dam, France	11	Needlepunched nonwoven geotextile	1973	A thick geotextile was placed to act both as a filter and as a drain to convey flow within the plain of the geotextile.	(Giroud, 1992)

Filter	Tucurui Dam Brazil	103	Nonwoven polyester geotextile with O_{95} .059 mm, permeability under load of 40 mm/s	Circa 1976	11,000 m^2 of geotextile placed over high permeability soil in cutoff trench to prevent piping. Because of its inaccessible location, "a clayey alluvial gravelly sand was placed on top of the geotextile to complement the anti-piping barrier."	(Aguiar, 1993)
Filter	James Bay Cofferdams, Canada	15 max.	Needlepunched nonwoven geotextile	1975-1982	250,000 m^2 of geotextile filter was placed in many cofferdams as a filter between rockfill and moraine. Most of the fabric was placed underwater using a dragline crane and a backhoe. Overlap seams used with divers to assure that 1.5 m of overlap was obtained.	(Lafleur and Pare, 1991)
Filter	Hans Strijdom Dam, South Africa	57	Nonwoven geotextile: 340 g/m^2 (10 $oz./yd^2$) PET	1975	A geotextile used between core and sand filter. The geotextile gave designer the confidence to thin the sand filter to 1 meter thick.	(Hollingworth and Druyts, 1982)
Filter, Drain, and Crack Stopper	Formitz Dam, Germany	33	Needlepunched nonwoven geotextile	1975	A geotextile was installed behind a soil-cement vertical diaphragm wall to convey seepage and filter particles should the diaphragm wall crack.	(Giroud, 1992), (List, 1982), (List, 1993a)

Filter, Drain, and Crack Stopper	Frauenau Dam, Germany	86	Needlepunched nonwoven geotextile	1980	A geotextile was installed behind a soil-cement vertical diaphragm wall to convey seepage and filter particles should the diaphragm wall crack. Another geotextile was placed on the downstream side of the key trench and downstream shell between the weathered rock foundation and the embankment to act as a protective filter.	(List, 1982), (List 1993b)
Filter	Kilburn Dam, South Africa	51	Needlepunched Nonwoven	1980	Vertical chimney drain filter constructed from a geotextile.	(Giroud, 1992)
Filter	Schonstadt Dam, Germany	22	Nonwoven geotextile 1100 g/m^2 (31 oz./yd^2)	1982-1986	Used as filter between upstream shell and rock fill, as transition filter between core and downstream coarse granular filter, and as filter around relief wells and the toe drain.	(List, 1993a)
Filter and Drain	Emerald No. 1 Coal Refuse Disposal Area, USA	111	Nonwoven polypropylene geotextile with 0.212 mm apparent opening size	1982 to 2002	Geotextile filter formed by wrapping the fabric around a coarse, well sorted aggregate drainage material at several horizons within a coarse coal refuse embankment for an internal drainage system	(Robert Snow, Personal Communication, 2007)
Filter	Chateauvieux Dam, France	14	Nonwoven geotextile	1983	Chimney drain uses a geotextile filter placed on a 2H:1V slope. The geotextile has an opening size of 80 microns to filter a clay with d_{85} = 100 microns.	(Degoutte, 1987), (Giroud, 1992)

Filter	Ait Chouarit Dam, Morocco	150	Needlepunched nonwoven geotextile 550 g/m^2 (16 oz./yd^2) polyester	1983-1986	Acting in combination with a processed granular filter the geotextile is a redundant filter around a horizontal blanket drain covering the downstream foundation of the dam	(Biche, 1987)
Filter and Drain	Cumberland No. 1 Coal Refuse Disposal Area, USA	119	Nonwoven polypropylene geotextile 51 g/m^2 to 271 g/m^2 (1.5 oz/yd^2 to 8 oz/yd^2)	1983 to 2003	Geotextile filter formed by wrapping the fabric around a coarse, well sorted aggregate drainage material at several horizons within a coarse coal refuse embankment for an internal drainage system	(Robert Snow, Personal Communication, 2007)
Filter	Maizihe Dam, China	21	Nonwoven geotextile	1984	Built in 1955 the dam experienced high seepage slope failures. A geotextile filter was installed in the downstream toe area around a sandy gravel (5 to 80 mm) drain. This controlled seepage and eliminated piping of the foundation soils. Geotextiles were also used under upstream slope protection.	(Tong and others, 1987).
Filter and Drain	Roquebrune Dam, France	10	Geocomposite drain	1985	Installed in three near-horizontal layers as drains downstream of a clay diaphragm core to remove runoff water that infiltrates.	(Degoutte, 1987), (Giroud, 1992)

Filter	Richards Bay Tailings Dam, South Africa	14	Geonet composite drain consisting of a woven geotextile surrounding a tri-plainer drainage core.	1985	The geonet composite drain forms a drainage blanket extending 7 meters upstream from the toe along the dam foundation surface. At the toe the drain enters a shallow vertical trench to complete the toe drain.	(Water Power & Dam Construction, 1989).
Filter	Yangdacheng Dam, Jilin province China	17	Nonwoven geotextile 400 g/m^2 (12 oz./yd^2) with maximum opening size O_{90} 0.062 mm	1986	Geotextile used as a filter to wrap a concrete pipe placed in a downstream toe drain trench. Using a natural granular filter was estimated to be 7 times more costly than the geotextile.	(Wei, 1993)
Filter and Drain	La Parade Dam, France	10	Geocomposite filter/drain, geotextiles opening size of 0.115 mm	1987	Geocomposite shaft drain built by placing alternately on the upstream and downstream slopes as fill was brought up across the core. Many other dams of similar design built.	Navassartian, Gourc, and Brochier, 1993).

Filter	Torcy-Vieux Dam, France	12.7	Geotextile 550 g/m^2 (16 oz./yd^2) with opening size 0.05 mm	1988	Dam rehabilitated by placing a geotextile wrapped gravel drain on the downstream slope and covering it with a soil buttress. Ten years after geotextile installation, piezometers showed elevated water levels. The geotextile permittivity decreased to 10% of original value due to iron hydroxide clogging. The clogged geotextile was still more permeable than the embankment soil and the elevated water levels did not pose a failure risk to the dam, no repairs were required.	(Degoutte and Fry, 2002)
Filter	Lautaro Dam, Chile	30	Nonwoven geotextile with AOS 70-100 sieve size	1989	Geotextile placed horizontally on ground below downstream toe to act as a filter to control upwelling seepage. The geotextile option was more economical than a granular filter which also was considered.	(Arrau and Astorga, 1991)
Filter and Drain	Reeves Lake Dam, Georgia USA	10.7	Geonet core placed between two geotextile filters	1990	Rehabilitation of a high-hazard dam used a geonet geocomposite to filter and transmit seepage flows. The geocomposite forms a chimney drain (2H:1V slope) and blanket drain. It was selected as being more efficient than a traditional sand/gravel/filter cloth drain.	(Wilson, 1992)

Filter	Mafeteng Dam, Lesotho, South Africa	20	16,500 m^2 of nonwoven geotextile 800 g/m^2 (23.5 $oz./yd^2$)	1993	The homogeneous embankment dam failed due to internal erosion of dispersive clay. A geomembrane, geotextile, and geogrid were placed upstream. On the downstream side a geotextile filter was placed between the dispersive clay and a gravel drainage layer. The original sand filter blanket was retained.	(Hedrich, 1994)
Filter and drain	Teppe Rosse Dam, Corsica	13	Nonwoven geotextile	1995	Dam rehabilitation added a berm with a geotextile placed on the original embankment downstream face to serve as a filter and drain and was connected to a horizontal geotextile drainage blanket.	(Degoutte and Fry, 2002)
Filter and drain	Lavaud-Gelade Dam, France	22	Geonet geocomposite with geotextiles having an AOS of 0.22 mm	1996	A geocomposite consisting of a geonet placed between two nonwoven geotextiles was under a downstream berm used to rehabilitate a homogenous embankment of decomposed granite that was at risk from internal erosion.	(Degoutte and Fry, 2002)
Filter and Drain	Turris Coal Slurry Impoundment, Illinois, USA	30	Nonwoven geotextile	1996	Geotextile filter formed by wrapping the fabric around a coarse, well sorted aggregate drainage material at several horizons within a coarse refuse embankment for an internal drainage system	Snow, Olson, and Schultz, 2000)

Filter	Many Farms Dam, Arizona, USA	13.7	Knitted polyester with AOS 0.6 mm (# 30 sieve)	2000	Geotextile wrapping around a toe drain pipe eliminated the need for a second stage gravel filter between the filter sand and the toe drain pipe. The knitted geotextile “sock” wrapping around slotted corrugated HDPE toe drain pipe was placed in a sand-filled trench. The sand is the primary filter for a dispersive clay embankment core.	(Swihart, 1999)
Filter	Dzoumogne Dam, Mayotte Island, French Territory	24.5	Nonwoven geotextile with opening size of 0.080 mm	2000	Geotextile is the filter around a gravel chimney (1H:1V slope) and blanket drain protecting a homogenous clay embankment, the clay has a PI=50 and $d85 < 0.080$ mm.	(Artieres and Tcherniavsky, 2003)
Filter and Drain	Emerald No. 2 Coal Refuse Disposal Area, USA	110 (Proposed, facility currently under construction)	Woven polypropylene geotextile with 0.6 mm apparent opening size and 250 g/m^2 (7.4 oz/yd^2)	2000 to Present	Geotextile filter formed by wrapping the fabric around a coarse, well sorted aggregate drainage material at several horizons within a coarse coal refuse embankment for an internal drainage system	(Robert Snow, Personal Communication, 2007)
Filter	Samira Dam, Niger	18	Nonwoven geotextile with AOS 0.1 mm	2001	Geotextile used to wrap a 6 meter high vertical sand drain and horizontal blanket to filter a homogenous embankment of fine lateritic soil. Used “Bidim F” a composite geotextile.	(Artieres and Tcherniavsky, 2003)

Filter	Montaubry Dam, France		Nonwoven geotextile with opening size of 0.08 mm	2001	Embankment rehabilitation consists of a sand filter placed on the downstream slope which leads to a geotextile drainage blanket. Used “Bidim F” a composite geotextile.	(Degoutte and Fry, 2002)
Filter	Sidi M’Hamed Ben Taiba, Algeria	64	Nonwoven geotextile with opening size 0.08 mm.	2003	Geotextiles wrapped around horizontal drainage trenches installed on the upstream side of the dam. To guard against puncture two layers of the geotextile were placed in each location. The clay core is protected by conventional granular filters. Used “Bidim F” a composite geotextile.	(Artieres and Tcherniavsky, 2003)
Protective cushion for a geomembrane	Pactola Dam, South Dakota, USA	67	Nonwoven geotextile placed under a 1 mm HDPE geomembrane	1987	Geotextile used as cushion and filter under a geomembrane in the upper 1 meter of the dam as a means of increasing the crest height for additional flood protection.	(Lippert and Hammer, 1989), (Engemoen, 1993)
Protective cushion for a geomembrane	Aubrac Dam, France	15	Nonwoven geotextile 500 g/m^2 (15 $oz./yd^2$)	Circa 1985	Geotextile layers were placed under and over a 48 mil smooth PVC geomembrane. Placed on a 2.5H:1V slope and covered with gravel and riprap. The slope failed, investigation showed that the interface friction between the geotextile and the smooth geomembrane was lower than shear box testing indicated.	(Girard and others, 1990).

Protective cushion for a geomembrane	Bovilla Dam, Albania	91	Nonwoven polypropylene geotextile 800 g/m^2 (24 oz./yd^2)	1996	The upstream 1.6 H:1V slope of the gravel fill dam was made watertight by covering it with a geocomposite geomembrane (120 mil PVC geomembrane bonded to a 22 oz. nonwoven polyester geotextile). A 24 oz. geotextile was placed over the geocomposite and concrete slabs were cast in place to protect the geosynthetics from exposure.	(Sembenelli, and others, 1998)
Protective cushion and drainage layer for a geomembrane	La Galaube Dam, France	43	Nonwoven geotextile	2000	Geotextile placed as protective layer/drain between concrete slab and bituminous geomembrane waterproofing for a rockfill dam. The geomembrane was made by impregnating a nonwoven polyester geotextile with bitumen.	(Gautier, and others, 2002)
Reinforcement filter, and erosion protection	Maraval Dam, France	8	Woven geotextile 750 g/m^2 (22 oz./yd^2) PET	1974	Geotextile placed to form a vertical downstream slope of dam.	(Cazzuffi, 2000), (Cassard and others, 1996) (Degoutte and Fry, 2002)
Separator	Weber Dam, Nevada, USA	17	Nonwoven geotextileAOS 100 (10 oz/yd^2)	2007	11,000 yd^2 of geotextile placed between gravel drain and downstream shell to act as a separation layer to prevent shell from contaminating outer edge of gravel drain.	(F. Blackett, Personal Communication, 2007)

Project: Many Farms Dam

Location: Navajo Indian Reservation, Apache County, Arizona, USA

Geosynthetic Materials Installed: Geotextile-wrapped perforated HDPE drainage pipe. The geotextile functions as a filter around the toe drain pipe which is a single-wall-corrugated pipe with 1/16–inch wide slotted perforations. A knitted polyester geotextile sock with an apparent opening size (AOS) of a #30 sieve (0.6 mm) covers the pipe.

Installation Date: July, 2000

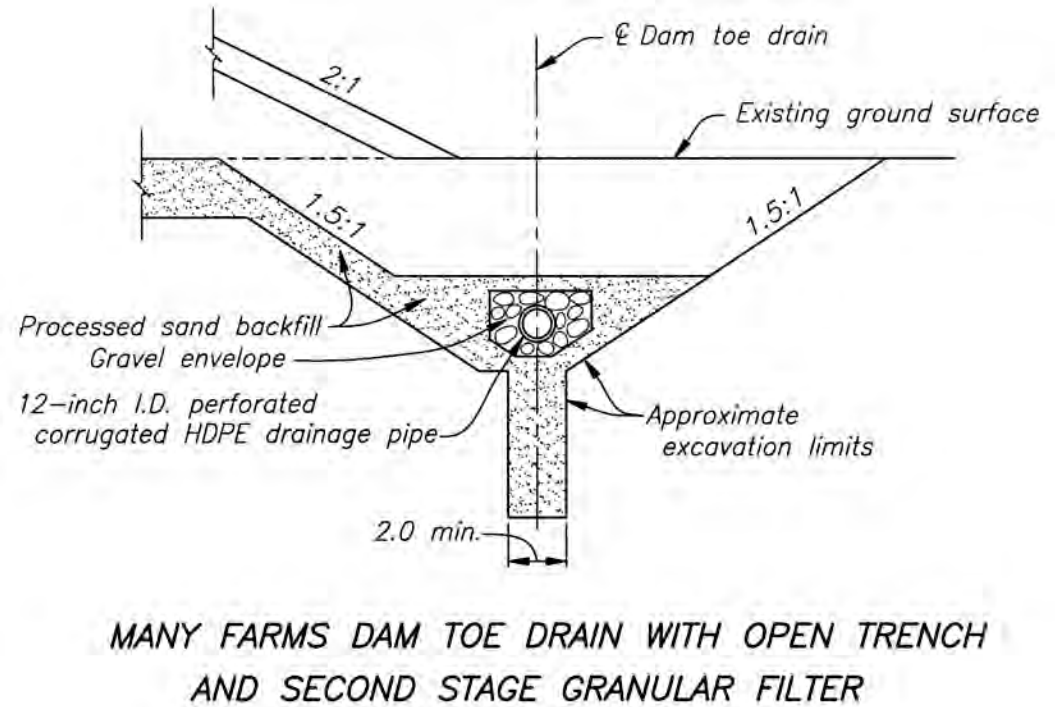
Summary: Geotextile wrapping around a toe drain pipe eliminated the need for a second stage gravel filter between the filter sand and the toe drain. This design approach allowed excavation and installation of the filter sand and toe drain pipe using a shielded-wheel trenching machine in a vertical trench which did not need to be dewatered.

Project Details: The Many Farms Dam has an impermeable core constructed from local silty soils containing highly dispersive clays. The dam embankment and its foundation suffered from internal erosion of the dispersive soil material. Rehabilitation of the dam included installation of a filter and drainage system including a downstream toe drain.

The highly dispersive clay soils at the site required the specification of a sand filter with a fine gradation. Design of the toe drain pipe indicated that the sand was too fine and would be liable to erode through the slots in the drainage pipe. A secondary filter comprised of fine gravel would normally be placed between the drain pipe and the filter sand.

The dam is 2,700 feet long and at a remote location where filter sand and clean gravel must be imported at considerable expense. There was a strong desire to economize on the required amounts of filter sand and gravel and to use a trenching machine to minimize the size of the excavation and gain the productivity of the machine installation. Trenching machines can install backfill and a pipe at the same time; however; they are limited to installing only one type of backfill material. Because a two-stage granular filter could not be efficiently placed by machine, a geotextile-wrapped drainage pipe was substituted for gravel in the re-designed toe drain as shown in Figure MF1.

The design change also provided an economy with respect to the size of excavation and required amounts of costly filter material used as backfill. The economy of the excavation is illustrated in Figure MF2.



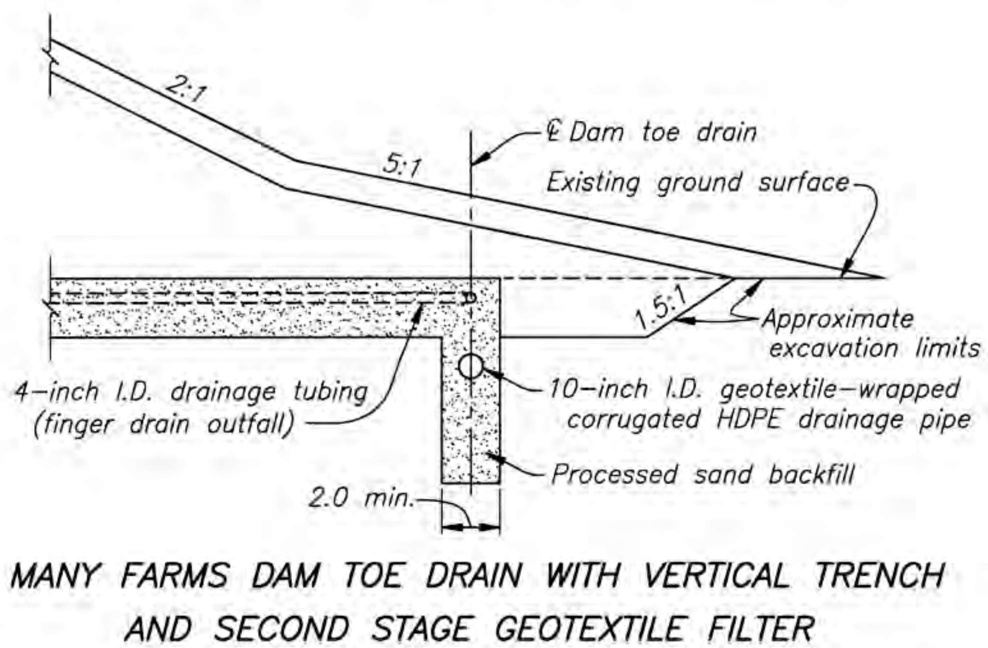


Figure MF1. Illustration showing the original Many Farms toe drain design with a two-stage granular filter (at top), and the redesigned toe drain with a single granular filter containing a geotextile-wrapped pipe.

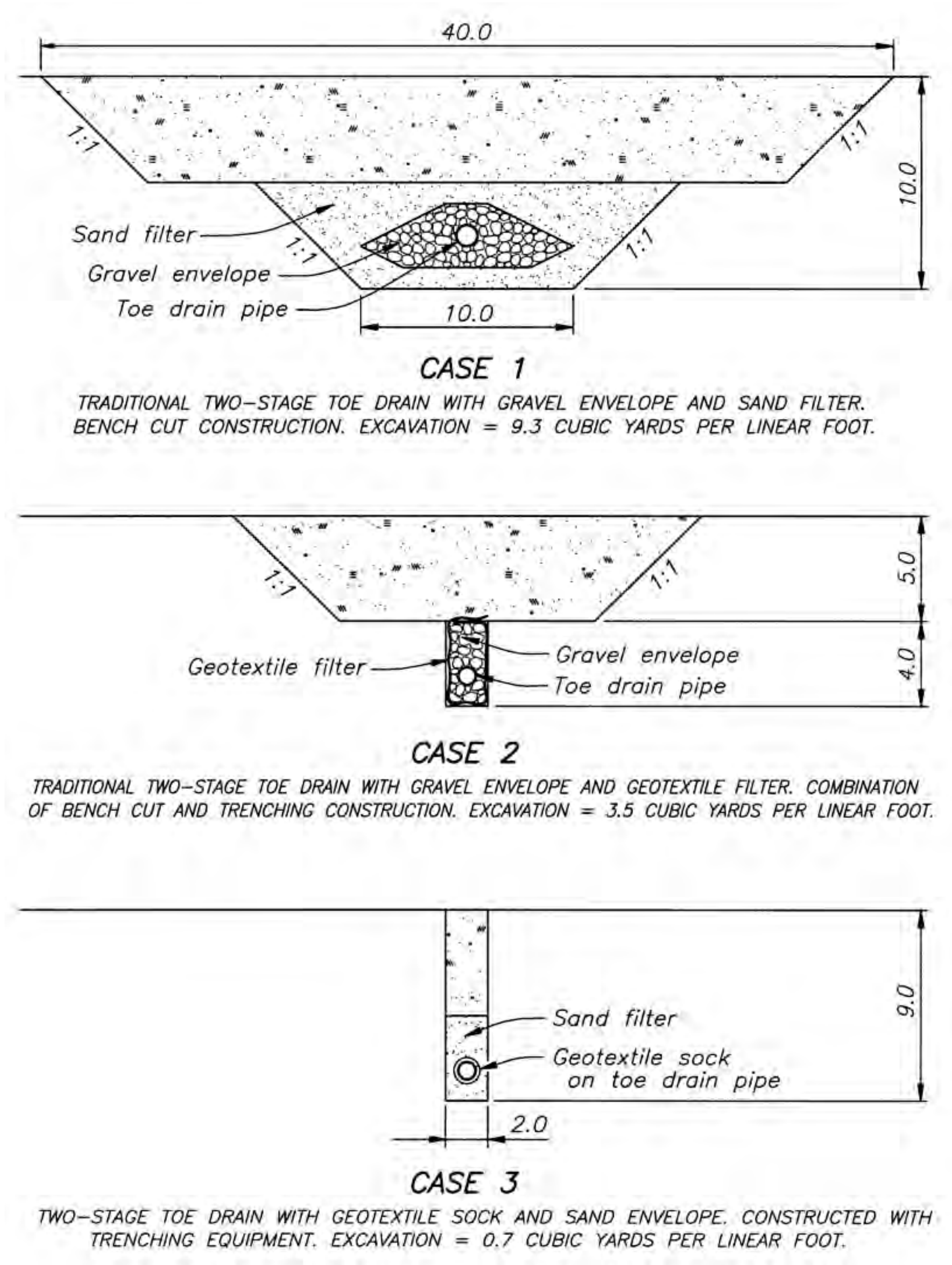


Figure MF2. Illustration showing the required amounts of excavation for three different toe drain configurations.

The unconventional design raised concerns at the Bureau of Reclamation regarding the loss of fines or the potential for clogging of the geotextile over time. The geotextile/corrugated pipe combination would need to retain the primary stage filter (fine sand) material without significant loss of fines through the geotextile and into the drainage pipe. The geotextile would also need to transmit significant seepage flows without becoming clogged which could reduce the flow capacity of the toe drain system.

The concerns about loss of fines and geotextile clogging were addressed by conducting a full-scale laboratory test using the specified filter sand and a sample of the proposed geotextile wrapped pipe (Swihart, 1999). A water tight test box was constructed to simulate the toe drain system. The box was sealed in a manner that all flow had to exit one end of the drainage pipe. Water was pumped into the box causing flow to move through the filter sand, across the geotextile and into the slots in the corrugated drain pipe. The initial flow rate was increased until the test box began to overflow. The flow rate was reduced slightly and the system was found to accommodate a maximum steady flow rate of 7.3 gpm per foot of pipe length. This flow rate is almost 100 times the design seepage rate of 0.08 gpm per foot predicted for the actual installation.

The test was run at the maximum flow rate for 13 days. Water exiting the pipe was directed into a reservoir where sand removed by flow through the system was captured. The lost filter material was periodically removed, dried and weighed and plotted in relation to time. The test showed a loss of 1,000 grams of filter material per foot of pipe length after which a stable filter formed with no further loss of material. This loss of material equates to a thickness of 0.087 inches of material around the circumference of the pipe.

The box was opened after the test and the filter sand was carefully excavated to expose the area around the geotextile. A graded sand filter was seen to have built up around the outside of the geotextile-wrapped pipe. The filter was about 1-inch thick below the pipe invert and thinner (less than ½ inch thick) around the remainder of the pipe perimeter. Because the amount of material loss was higher than anticipated, the design was revised to provide a slightly coarser filter sand gradation as shown in the following table:

Sieve Size	Original Filter Specification % finer	Revised Filter Specification % finer
0.75	100	100
0.375	100	85-100
#4	95-100	70-90
#8	90-100	60-80

#16	70-100	50-70
#30	40-85	35-60
#50	20-55	20-45
#100	10-30	10-30
#200	0-3	0-5

Performance: The quarry supplying filter sand to the site could not keep up with the demands of the highly productive trenching machine installation, see Figure MF3 and MF4.

Figure MF3. Photograph of a trenching machine excavating a trench and backfilling it with a geotextile-wrapped pipe surrounded by a sand backfill.

Figure MF4. Photograph of the toe drain trench showing geotextile-wrapped pipe without sand backfill. The trenching machine was so efficient that sand deliveries to the site could not keep up with pipe installation rates.

For future projects the specifications will require that sufficient sand stockpiles be placed at the site prior to initiation of the trenching and pipe installation operation. The site experienced an extended drought after rehabilitation of the dam, first filling of the reservoir occurred in 2005. Flow in the toe drains has not yet been observed.

Figure MF5. Photograph of a geotextile-wrapped pipe emerging from a completed segment of the Many Farms dam toe drain trench.

References: Swihart, J. (1999) Full scale laboratory testing of a toe drain with a geotextile sock. Bureau of Reclamation, Materials and Engineering Research Laboratory, DSO-98-014, Denver, Colorado.

Project: Aspen Lake Dam Rehabilitation

Location: Okanogan County, Washington, USA

Geosynthetic Materials Installed: Synthetic Industries Geotex 401[1] - a needle punched, non-woven geotextile. The material was initially provided to serve as a zone separator and containment for an abutment seep. The geotextile role was expanded to act as a soil retention zone when the borrow site turned out to have insufficient quantities of well graded fill.

Installation Date: May, 2005

Project Details: The dam is a 20-foot high, earthen structure with a low downstream hazard setting, built by an unknown party likely without benefit of any engineering. The Dam Safety Office first inspected the dam in 1997 and found it to have inadequate spillway capacity, an overly-steep downstream slope, diffuse seepage emerging from the face, and one prominent spring in the right abutment.

A rehabilitation was devised that involved a pipe spillway and a drained buttress that incorporated a central drain for the spring. A geotextile was provided in the design as shown on Figure 1 as an encapsulating wrap for a pea gravel drain. The drain's primary function was to drain a spring which was flowing clear at some 20 gpm (0.0012 m^3/sec) from the abutment. A geotextile with a low permeability both in-plane and cross-plane was desirable to retain the spring flow within the pea gravel. This minimized wetting of the adjacent fill, facilitating the construction of the buttress. Further, it served to isolate the spring discharge so that its quantity and character could be better monitored over time. Figures 2 and 3 are construction photos illustrating the work.

The site is in a remote area of steep terrain. The plans anticipated generating the majority of the buttress fill from the excavation of a ridge jutting into the reservoir. Shallow test pits explorations of the ridge had encountered a highly jointed and weathered rock that broke down into a well graded clayey sand and gravel. The only imported materials were to be concrete sand, serving as a filter and drain at the buttress contact with the existing dam and foundation, and pea gravel for the principal drains. A typical section and detail of the work are presented in Figures 4 and 5. During the course of construction the borrow site was found to vary dramatically in the degree of weathering. Unfortunately, much of the fill came out as slightly clayey angular gravel. The gap graded, coarser fills were judged inadequate to meet filter criteria for the concrete sand and thus could allow the sand to be piped into the new buttress. Accordingly, the design was modified in the field with the concurrence of the engineer of record to use the above cited geotextile as a retaining

[1] http://www.geo-synthetics.com/pdf/products/SI/product_139.pdf#search=%22synthetic%20industries%20401%22

feature on the downstream side of the concrete sand. To protect the geotextile from abrasion and punctures, a thin, select zone of well graded borrow was placed directly against the downstream side of the geotextile. The revised section is shown on Figure 6 and construction of the section is shown on Figure 7.

The secondary use of the geotextile at this project illustrates the flexibility these materials provide the engineer during construction to address unanticipated field conditions. Unfortunately, many remedial projects lack the budget to do extensive programs of field exploration to refine the rehabilitation design. Rather, conservative assumptions are made regarding the existing dam section and it is anticipated that the proposed rehabilitation will require field adjustments to maximize its impact based on actual conditions. Again, geotextiles greatly aid the process.

Performance: Satisfactory

References: Construction records Dam Safety Office, Washington State Department of Ecology

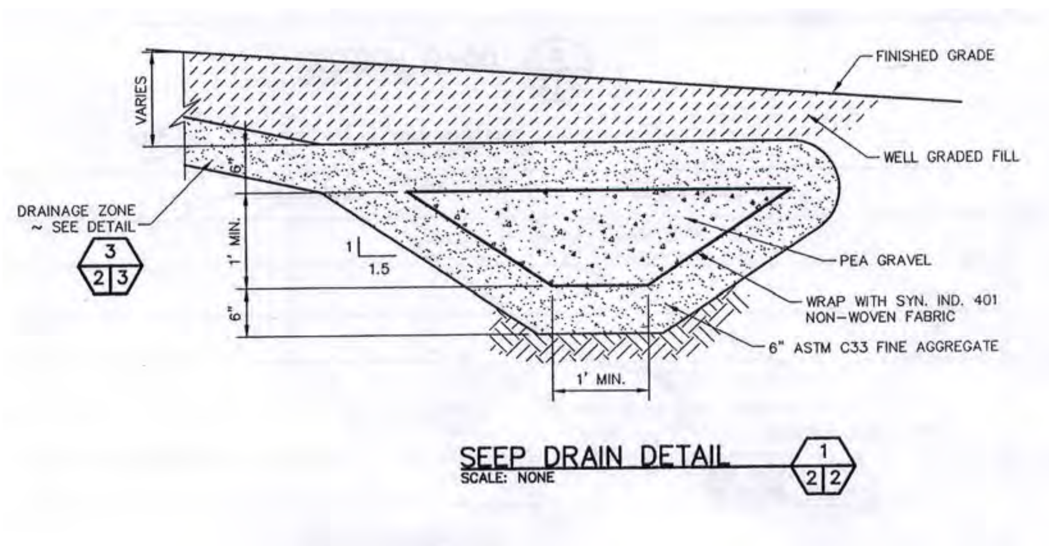


Figure 1 – Encapsulated pea gravel zone whose primary function is to carry off flow from isolated abutment seep across the foundation. The geotextile functioned to confine the spring allowing the quantity and character to be monitored.

Figure 2 – The downstream segment of the geotextile wrapped drain has been placed and buried under a protective cushion of ASTM C 33 fine aggregate for concrete. The seep discharge from the abutment is still visible.

Figure 3 – Pea gravel drainage zone prior to encapsulating it in the geotextile.

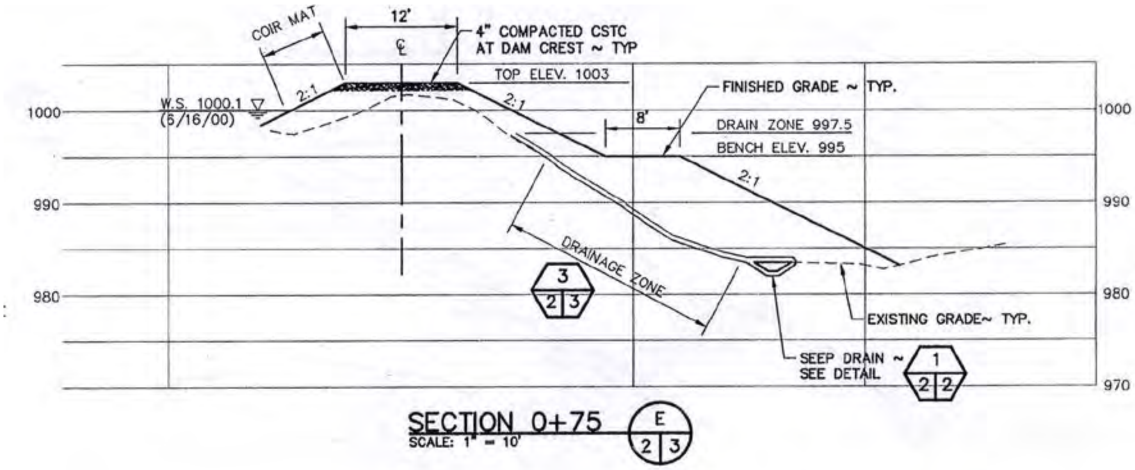


Figure 4 – The original drained buttress section developed with the presumption that the borrow site would yield sufficient quantities of well graded fill. Note, the drainage zone needs to be extended to a higher elevation than shown in anticipation that the buttress will impede drainage from the face and elevate the phreatic surface.

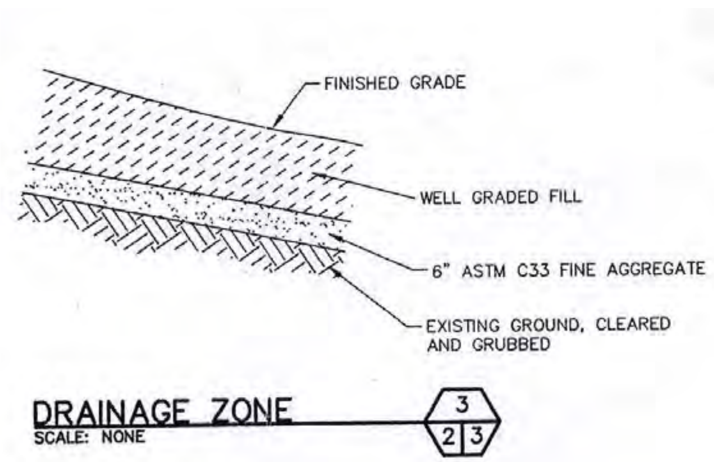


Figure 5 – Detail of the drained buttress, i.e. filter and drainage zone consisting of ASTM C 33 fine aggregate for concrete and the well graded fill comprising the mass of the buttress. Note that the plans called for field locating pea gravel finger drains within the fine aggregate zone at the intersection of the buttress and the stripped original embankment face where any concentrated seeps were encountered.

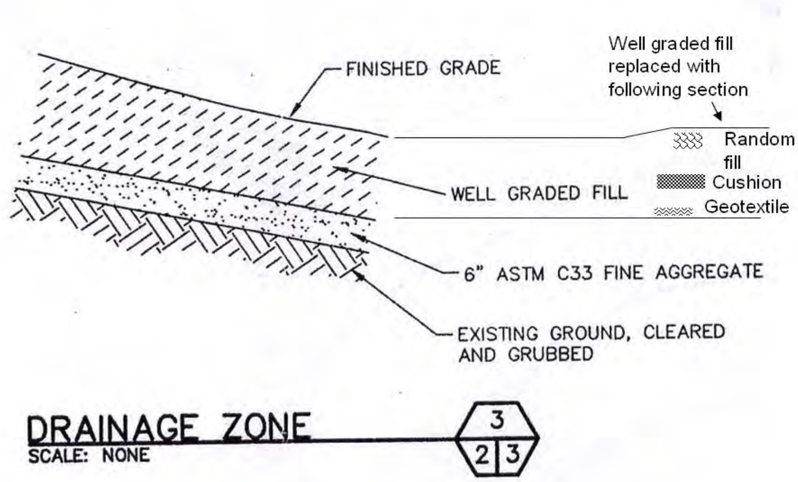


Figure 6 – Revised cross-section for the zone immediately abutting the downstream side of the fine aggregate filter/drainage zone. The design change incorporates a cushion layer to protect the geotextile from damage.

Figure 7 – C 33 sand placed below geotextile as filter and drain. The geotextile was covered with a cushion a fine grained soils with minimal angular coarse gravel particles to protect the geotextile from cuts and abrasion.

Appendix B

Current Research

The following research reports are available from the Geosynthetics Research Institute:

REPORT NO. 1 - Environmental Stress Cracking of HDPE Geomembrane Seams and Related Studies - March 20, 1988 - STATUS - Superseded by GRI Report #9

REPORT NO. 2 - A Quantification and Assessment of Installation Damage to Geotextiles - December 7, 1988

REPORT NO. 3 - Biological Clogging of Geotextiles Used in Landfill Filters - June 27, 1989 - NTIS (Report #PB91-213660 - Superseded by GRI Report #15)

REPORT NO. 4 - The Photo-Initiated Degradation of Seven Nonwoven Needle Punched Geotextiles - June 21, 1990

REPORT NO. 5 - Finite Element Modeling of Soil-Geogrid Interaction with Applications to the Behavior of Geogrids in Pullout Loading Condition - October 1, 1990

REPORT NO. 6 - Parametric Evaluation of Primary Leachate Collection System Behavior Using the "HELP" Model - June 18, 1992

REPORT NO. 7 - Geotextile Specifications for Transportation Applications: GRI's Second Survey - December 9, 1992

REPORT NO. 8 - Stability Analysis of Multilined Slopes in Landfill Applications - December 9, 1992

REPORT NO. 9 - Stress Cracking Behavior of HDPE Geomembranes and its Prevention - June 24, 1993

REPORT NO. 10 - Experimental Puncture Behavior of HDPE Geomembranes Without, Then With, Various Protection Materials - July 27, 1993

REPORT NO. 11 - A Survey of State Municipal Solid Waste (MSW) Liner and Cover Systems - August 10, 1993

REPORT NO. 12 - FEM Behavior of Analysis of Plastic Pipe at High Normal Stresses - June 22, 1994

REPORT NO. 13 - Design Methodology for Geomembrane Protection Materials - September 26, 1994

REPORT NO. 14 - Drainage to Retaining Structures Using Geocomposite Sheet Drains: The State-of-the-Practice in the USA - February 3, 1995

REPORT NO. 15 - Leachate Clogging Assessment of Geotextile and Soil Landfill Filters - July 5, 1995

REPORT NO. 16 - Long Term Durability of HDPE Geomembranes Part I - Depletion of Antioxidants - December 11, 1995

REPORT NO. 17 - Behavior of Waves in High Density Polyethylene Geomembranes - June 17, 1996

REPORT NO. 18 - Cover Soil Slope Stability Involving Geosynthetic Interfaces - December 9, 1996

REPORT NO. 19 - The Design of Drainage Systems Over Geosynthetically Lined Slopes - June 17, 1997

REPORT NO. 20 - Earth Retaining Wall Costs in the USA - June 18, 1998

REPORT NO. 21 - A Survey of Solid Waste Landfill Liner and Cover Regulations: Part I - USA Status - December 7, 1998

REPORT NO. 22 - Analysis and Critique of Ten Large Solid Waste Landfill Failures - December 18, 1998

REPORT NO. 23 - A Survey of Solid Waste Landfill Liner and Cover Regulations: Part II - World Wide Status - March 30, 1999

REPORT NO. 24 - Geosynthetic Reinforced and Geocomposite Drained Retaining Walls Utilizing Low Permeability Backfill Soils - July 30, 1999

REPORT NO. 25 - Installation Guide for Drainage Materials Associated With Segmental Retaining Walls (SRWs) - December 20, 2000

REPORT NO. 26 - Field Monitoring and Laboratory Study of Geosynthetics in Reinforcement Applications - August 1, 2001

REPORT NO. 27 - Internal Drainage of Low Permeability Backfill Soils of Geosynthetic Reinforced Earth Walls - January 9, 2002

REPORT NO. 28 - A GRI White Paper on the Questionable Strategy of Soil-Only Landfill Covers - August 7, 2002

REPORT NO. 29 - Selected Papers on the Design Decision of Using Peak versus Residual Shear Strengths - September 30, 2003

REPORT NO. 30 - Direct Shear Database of Geosynthetic-to-Geosynthetic and Geosynthetic-to-Soil Interfaces - June 14, 2005

E. The following research topics are currently under investigation by GRI:

1. Stress Cracking of Geomembranes
2. Durability and Lifetime Prediction
3. Durability of Polypropylene Geotextile Fibers and HDPE Geogrid Ribs
4. Durability of Polyester Geotextile Fibers and Polyester Geogrid Yarns
5. In-Situ Temperature Monitoring of Liner and Cover Geomembranes in Dry and Wet Landfills
6. Bioreactor (aka Wet) Landfill Behavior and Properties
7. Flow Behavior of Fully Degraded Waste
8. Hydrostatic Creep Puncture of Geomembranes
9. Long-Term Benefits of Geotextile Separators
10. UV Exposure of Geomembranes
11. Generic Specifications
12. Technical Guidance Document on QC/QA of Waste Containment Facilities

Appendix C

Laboratory Test Procedures

A. ASTM

D 1987-02	Test Method for Biological clogging of Geotextile or Soil/Geotextile Filters
D 4354-04	Practice for Sampling of Geosynthetics for Testing
D 4355-05	Test Method for Deterioration of Geotextiles from Exposure to Ultraviolet Light and Water (Xenon-Arc Type Apparatus)
D 4439-04	Terminology for Geosynthetics
D 4491-04	Test Methods for Water permeability of Geotextiles by Permittivity
D 4533-04	Test Method for Index Trapezoid Tearing Strength of Geotextiles
D 4594-03	Test Method for Effects of Temperature on Stability of Geotextiles
D 4595-01	Test Method for Tensile Properties of Geotextiles by the Wide-Width Strip Method
D 4632-03	Test Method for Grab Breaking Load and Elongation of Geotextiles
D 4716-04	Test Method for Constant Head Hydraulic Transmissivity (In-Plane Flow) of Geotextiles and Geotextile Related Products
D 4751-04	Test Method for Determining Apparent Opening Size of a Geotextile
D 4759-02	Practice for Determining the Specification Conformance of Geosynthetics
D 4833-00	Test Method for Index Puncture Resistance of Geotextiles, Geomembranes, and Related Products
D 4873-02	Guide for Identification, Storage, and Handling of Geotextiles
D 4884-03	Test Method for Seam Strength of Sewn Geotextiles
D 4886-02	Test Method for Abrasion Resistance of Geotextiles (Sand Paper/Sliding Block Method)
D 5101-01	Test Method for Measuring the Soil-Geotextile System Clogging Potential by the Gradient Ratio
D 5141-04	Test Method for Determining Filtering Efficiency and Flow Rate of a Geotextile for Silt Fence Application Using Site-Specific Soil
D 5199-01	Test Method for Measuring Nominal Thickness of Geotextiles and Geomembranes
D 5261-03	Test Method for Measuring Mass per Unit Area of Geotextiles
D 5321-02	Test Method for Determining the Coefficient of Soil and Geosynthetic or Geosynthetic and Geosynthetic Friction by the Direct Shear Method

D 5322-03	Practice for Immersion Procedures for Evaluating the Chemical Resistance of Geosynthetics to Liquids
D 5493-03	Test Method for the Permittivity of Geotextiles Under Load
D 5494-99	Test Method for the Determination of Pyramid Puncture Resistance of Unprotected and Protected Geomembranes
D 5496-98	Practice for In-Field Immersion Testing of Geosynthetics
D 5514-01	Test Method for Large Scale Hydrostatic Puncture Testing of Geosynthetics
D 5567-01	Test Method for Hydraulic Conductivity Ratio (HCR) Testing of Soil/Geotextile Systems
D 5617-04	Test Method for Multi-Axial Tension Test for Geosynthetics
D 5819-05	Guide for Selecting Test Methods for Experimental Evaluation of Geosynthetic Durability
D 6364-04	Test Method for Determining the Short-Term Compression Behavior of Geosynthetics
D 6389-99	Practice for Tests to Evaluate the Chemical Resistance of Geotextiles to Liquids
D 6461-99	Specification for Silt Fence Materials
D 6685-01	Guide for the Selection of Test Methods for Fabrics Used in Fabric Formed Concrete
D 6707-05	Specification for Circular-knit Geotextile for Use in Subsurface Drainage Applications
D 6917-03	Guide for Selection of Test methods for prefabricated Vertical Drains (PVD)
D 6992-03	Test Method for Accelerated Tensile Creep and Creep-Rupture of Geosynthetic Materials Based on Time-Temperature Superposition using the Stepped Isothermal Method
D 7005-03	Test Method for Determining the Bond Strength (Ply Adhesion) of Geocomposites

B. GRI TEST METHODS **Note Cross-out entries have been superseded.**

Geotextile (GT) Related

GT1 Geotextile Filter Performance via Long Term Flow (LTF) Tests

~~GT2 Biological Clogging of Geotextile or Soil/Geotextile Filters (1987)~~ (superseded by ASTM D1987)

~~GT3 Deterioration of Geotextiles from Outdoor Exposure~~ (superseded by ASTM D5970)

~~GT4 Geotextile Permittivity-Under-Load (1991)~~ (discontinued, superseded by ASTM D5493)

~~GT5 Tension Creep Testing of Geotextiles (April 6, 1992)~~ (superseded by ASTM D5262)

~~GT6 Geotextile Pullout~~ (superseded by ASTM D6706)

GT7 Determination of Long-Term Design Strength of Geotextiles

GT8 Fine Fraction Filtration Using Geotextile Filters

GT9 Grip Types for Use in Wide Width Testing of Geotextiles and Geogrids
GT10 Test Methods, Properties and Frequencies for High Strength Geotextile Tubes used as Coastal and Riverine Structures
GT11 Installation of Geotextile Tubes used as Coastal and Riverine Structures
GT12(a) Test Methods and Properties for Nonwoven Geotextiles Used as Protection (or Cushioning) Materials - ASTM Version
GT12(b) Test Methods and Properties for Nonwoven Geotextiles Used as Protection (or Cushioning) Materials - ISO Version
GT13 Test Methods and Properties for Geotextiles Used as Separation Between Subgrade Soil and Aggregate
GT14 Hanging Bag Test for Field Assessment of Fabrics Used for Geotextile Tubes and Containers

Geogrid (GG) Related

GG1 Geogrid Rib Tensile Strength (superseded by ASTM D6637)
GG2 Geogrid Junction Strength
~~GG3(a) Tension Creep Testing of Stiff Geogrids (Jan. 30, 1991)~~ (superseded by ASTM D5262)
~~GG3(b) Tension Creep Testing of Flexible Geogrids (Jan. 30, 1991)~~ (superseded by ASTM D5262)
GG4(a) Determination of the Long-Term Design Strength of Stiff Geogrids
GG4(b) Determination of the Long-Term Design Strength of Flexible Geogrids
~~GG5 Test Method for Geogrid Pullout~~ (superseded by ASTM D6706)
GG6 Grip Types for Use in Width Testing of Geotextiles and Geogrids
GG7 Carboxyl End Group Content of PET Yarns
GG8 Determination of the Number Average Molecular Weight of PET Yarns Based on a Relative Viscosity Value
GG9 Torsional Behavior of Bidirectional Geogrids When Subjected to In-Plane Rotation

Geonet (GN) Related

~~GN1 Compression Behavior of Geonets~~ (superseded by ASTM D6364)

Geomembrane (GM) Related

GM1 Seam Evaluation by Ultrasonic Shadow Method
GM2 Embedment Depth for Anchorage Mobilization
~~GM3 Large Scale Hydrostatic Puncture Test~~ (superseded by ASTM D5514)
~~GM4 Three Dimensional Geomembrane Tension Test~~ (superseded by ASTM D5617)
~~GM5(a) Notched Constant Tensile Load (NCTL) Test for Polyolefin Resins or Geomembranes (1992)~~ (superseded by ASTM D5397)
~~GM5(b) Single Point NCTL Test for Polyolefin Resin or Geomembranes~~ (superseded by ASTM D5397 Appendix)

GM5(c) Seam Constant Tensile Load (SCTL) Test for Polyolefin Geomembrane Seams
GM6 Pressurized Air Channel Test for Dual Seamed Geomembranes
GM7 Accelerated Curing of Geomembrane Test Strip Seams Made by Chemical Fusion Methods
~~GM8 Measurement of the Core Thickness of Textured Geomembranes~~ (superseded by ASTM D5994)
GM9 Cold Weather Seaming of Geomembranes
GM10 The Stress Crack Resistance of HDPE Geomembrane Sheet
GM11 Accelerated Weathering of Geomembranes Using a Fluorescent UVA Device
GM12 Asperity Measurement of Textured Geomembranes using a Depth Gage
GM13 Test Properties, Testing Frequency and Recommended Warranty for High Density Polyethylene (HDPE) Smooth and Textured Geomembranes
GM14 Selecting Variable Intervals for Taking Geomembrane Destructive Seam Samples Using the Method of Attributes
~~GM15 Determination of Ply Adhesion of Reinforced Geomembranes~~ (superseded by ASTM D6636)
GM16 Observation of Surface Cracking of Geomembranes
GM17 Test Properties, Testing Frequency and Recommended Warranty for Linear Low Density Polyethylene (LLDPE) Smooth and Textured Geomembranes
GM18 Test Properties, Testing Frequency and Recommended Warrant for Flexible Polypropylene (fPP and fPP-R) Nonreinforced and Reinforced Geomembranes
GM19 Seam Strength and Related Properties of Thermally Bonded Polyolefin Geomembranes
GM20 Selecting Variable Intervals for Taking Geomembrane Destructive Seam Samples Using Control Charts
GM21 Test Methods, Properties, Frequency and Recommended Warranty for Ethylene Propylene Diene Terpolymer (EPDM) Nonreinforced and Scrim Reinforced Geomembrane

Geosynthetic Clay Liner (GCL) Related

~~GCL1 Swell Measurement of the Clay Component of GCL's~~ (superseded by ASTM D5890)
~~GCL2 Permeability of Geosynthetic Clay Liners (GCLs)~~ (superseded by ASTM D5887 and ASTM D6766)

Geocomposite (GC) Related

GC1 Soil-Filter Core Combined Flow Test
GC2 Strip Drain Flow Rate Under Load
GC3 Strip Drain Kinking Efficiency
GC4 Compression Behavior of Prefabricated Edge Drains and Sheet Drains
GC5 Erosion Control Systems to Protect Against Soil Detachment by Rainfall Impact and Overload Flow Transport
GC6 Erosion Control Systems for High Velocity Flows in Channels

~~GC7 Determination of Adhesion and Bond Strength of Geocomposites~~ (superseded by ASTM D7005)
GC8 Determination of the Allowable Flow Rate of a Drainage Geocomposite

Geosynthetic (GS) Related (i.e., Multipurpose)

~~GS1 CBR Puncture Strength~~ (superseded by ASTM D6241)
GS2 Rupture Strength of Geosynthetics by Pendulum Impact
GS3 Selecting In-Situ Monitoring Methods and Devices for the Evaluation of Geosynthetic Performance
GS4 Time Dependent (Creep) Deformation Under Normal Pressure
GS5 Impregnation of Geosynthetics Under Load
~~GS6 Interface Friction Determination by Direct Shear Testing (Jan. 30, 1991)~~ (superseded by ASTM D5321)
GS7 Determining the Index Friction Properties of Geosynthetics
GS8 Determining the Connection Strength of Mechanically Anchored Geosynthetics
~~GS9 Oxidative Induction Time of Polyethylene Geosynthetics by High Pressure Differential Scanning Calorimetry~~ (superseded by ASTM D5885)
~~GS10 Accelerated Tensile Creep and Creep-Rupture of Geosynthetic Materials Based on Time-Temperature Superposition Using the Stepped Isothermal Method~~ (superseded by ASTM D6992)

Appendix D

Specifications

Sample specifications are shown in the following pages:

A. USBR Standard Specification for Geotextile Materials and Installation
   4-, 8-, and 16-oz needle punched nonwoven

SECTION 02342 **GEOTEXTILE**
GUIDE SPECIFICATION DEPARTMENT OF THE INTERIOR - BUREAU OF RECLAMATION
REVISIONS Reference Standards Checked/Updated: 11/12/07 Content Revisions: 8/12/04 Added RSN to submittals. Added burst strength to material requirements. Minor revisions. 7/8/03 Revised values in table for 16 oz fabric. Changed subgrade imperfections to 1-1/2 inch and added vibratory roller. Added LGP equipment. Updated name of ASTM. Minor revisions. 6/15/01 Added and revised footnotes for seaming. 2/9/01 Changed "bid" to "offered". 7/21/00 Added tables for two more geotextile weights and corrected table values. 8/14/98 First CSI95 draft Editorial/Format Revisions: 11/12/07 Changed template and added blank page code at end. 7/1/02 First MS Word version Template: CSI_02a.dot
NOTES
Please provide comments on guide specifications to LAN address: TalkToGuideSpecs (talktoguidespecs@do.usbr.gov)

SECTION 02342 - GEOTEXTILE

PART 1 GENERAL

1.01 MEASUREMENT AND PAYMENT

A. Geotextile:

1. Measurement: Surface area required to be covered [2][including geotextile placed in anchor trench], except no allowance will be made for seam overlap, repairs, or waste.
2. Payment: Square yard price offered in the schedule.

1.02 REFERENCES

A. ASTM International (ASTM)

1.	ASTM D 3786-06	Hydraulic Bursting Strength of Textile Fabrics – Diaphragm Bursting Strength Tester Method
2.	ASTM D 4355-07	Deterioration of Geotextiles by Exposure to Light, Moisture, and Heat in a Xenon-Arc Type Apparatus
3.	ASTM D 4491-99a(2004)	Water Permeability of Geotextiles by Permittivity
4.	ASTM D 4533-04	Trapezoid Tearing Strength of Geotextiles
5.	ASTM D 4632-91(2003)	Grab Breaking Load and Elongation of Geotextiles
6.	ASTM D 4751-04	Determining Apparent Opening Size of a Geotextile
7.	ASTM D 4833-00	Index Puncture Resistance of Geotextiles, Geomembranes, and Related Products
8.	ASTM D 5261-92(2003)	Measuring Mass per Unit Area of Geotextiles

1.03 SUBMITTALS

A. Submit the following in accordance with Section 01330 - Submittals

B. RSN 02342-1, Manufacturer's certification:

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[2] Include if anchor trench required.

1. Geotextile furnished meets specified chemical, physical, and manufacturing requirements.

C. [3]RSN 02342-2, Samples:

1. Include manufacturer's certified test results covering properties listed in Table 02342B - Geotextile Physical Properties.
2. Samples: One yard in length from entire roll width.
3. Mark samples:
    a. Project name and contract number.
    b. Product identification.
    c. Lot number.
    d. Roll number.
    e. Machine direction.
    f. Quantity represented.
4. [4][Number of samples: {1} {Table 02342A - Geotextile Sampling Requirements. Frequency of sampling may be increased if a geotextile sample does not meet specification requirements.

[5][Table 02342A. - Geotextile Sampling Requirements.

Number of rolls to be furnished	Number of rolls to be sampled
1 - 2	1
3 - 8	2
9 - 27	3
28 - 64	4
65 -125	5
126 - 216	6
217 - 343	7
344 - 512	8
513 - 729	9

[3] Recommended submittal time: At least [45] days before delivery to job site. When TSC responsible for submittal review, submit to 86-68180.

[4] For most jobs, one sample should be sufficient. Include table only for larger jobs.

[5] Edit table to reasonably correspond with number of rolls expected to be furnished. Number of samples is cube root of top number in range.

[5][Table 02342A. - Geotextile Sampling Requirements.

Number of rolls to be furnished	Number of rolls to be sampled
730 - 1000	10

D. [6]RSN 02342-3, Protection method:

1. Method to protect exposed geotextile, when covering is not possible within 14 days.

E. [7]Sewn seams, if used:

1. Certification stating that polymeric threads to be used for sewing have chemical resistance properties equal to or exceeding those of geotextile.
2. Include data showing that sewn seams have tensile strength of not less than specified percent of parent geotextile material.

1.04 DELIVERY, STORAGE, AND HANDLING

A. Wrap geotextile rolls in relatively impermeable and opaque protective covers.

B. Mark or tag geotextile rolls with manufacturer's name, product identification, lot number, roll number, and roll dimensions.

C. Mark geomembrane with special handling requirements such as "This Side Up" or "This Side Against Soil to be Retained."

D. Protect geotextile from ultraviolet light exposure, temperatures greater than 140 degrees F (60 degrees C), precipitation or other inundation, mud, dirt, dust, puncture, cutting, or other damaging or deleterious conditions.

E. Elevate and cover material stored outside with waterproof membrane.

PART 2 PRODUCTS

2.01 GEOTEXTILES

A. Needle-punched, nonwoven geotextile comprised of long-chain polymeric filaments composed of at least 85 percent, by weight, polyolefins or polyesters.

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6 Recommended submittal time: At least [45] days before delivery to job site. When TSC responsible for submittal review, submit to 86-68180.

7 Recommended submittal time: At least [45] days before delivery to job site. When TSC responsible for submittal review, submit to 86-68180.

B. Orient filaments into stable network which retains its structure during handling, placement, and long-term service.

C. Stabilizers or inhibitors added to filament base material: Resist deterioration due to ultraviolet or heat exposure.

D. Geotextile edges: Selvaged or otherwise finished to prevent outer material from pulling away.

E. Conform to roll values listed in Table 02342B - Geotextile Physical Properties.

1. Values listed are minimum average roll values (MARV=s), unless otherwise noted.
2. Test results for weaker principal direction shall meet or exceed minimum values listed in the table.
3. Mass per unit area is a nominal value and is provided for information purposes only.

F. Direct exposure to sunlight: Withstand 14 days with no measurable deterioration.

[8][Table 02342B. - Geotextile Physical Properties

Property	Test Method	Required Values
Mass per unit area, nominal	ASTM D 5261	4 oz/yd^2
Grab tensile	ASTM D 4632	90 Lbs
Elongation at break	ASTM D 4632	50 percent
Trapezoidal tear	ASTM D 4533	40 lbs
Puncture strength	ASTM D 4833	50 lbs
Burst strength	ASTM D 3786	140 lb/in^2
Permittivity	ASTM D 4491	1.5 sec^{-1}
Apparent opening size (minimum US Sieve No. / maximum opening size)	ASTM D 4751	70 US Sieve
UV resistance – tensile strength retained at 500 hours, minimum	ASTM D 4355	70 percent

8 Select table(s) based on design and construction requirements. Delete table(s) not required. Renumber table(s) if more than one weight of textile required.

Table 02342B. - Geotextile Physical Properties

Property	Test Method	Required Values
Mass per unit area, nominal	ASTM D 5261	8 oz/yd^2
Grab tensile	ASTM D 4632	200 lbs
Elongation at break	ASTM D 4632	50 percent
Trapezoidal tear	ASTM D 4533	70 lbs
Puncture strength	ASTM D 4833	90 lbs
Burst strength	ASTM D 3786	300 lb/in^2
Permittivity	ASTM D 4491	1.0 sec^{-1}
Apparent opening size (minimum US Sieve No. / maximum opening size)	ASTM D 4751	70 US Sieve
UV resistance – tensile strength retained at 500 hours, minimum	ASTM D 4355	70 percent

Table 02342B. - Geotextile Physical Properties

Property	Test Method	Required Values
Mass per unit area, nominal	ASTM D 5261	16 oz/yd^2
Grab tensile	ASTM D 4632	380 lbs
Elongation at break	ASTM D 4632	50 percent
Trapezoidal tear	ASTM D 4533	140 lbs
Puncture strength	ASTM D 4833	230 lbs
Burst strength	ASTM D 3786	700 lb/in^2
Permittivity	ASTM D 4491	0.5 sec^{-1}
Apparent opening size (minimum US Sieve No. / maximum opening size)	ASTM D 4751	100 US Sieve
UV resistance – tensile strength retained at 500 hours, minimum	ASTM D 4355	70 percent

2.02 PINS

A. Pins: 3/16-inch diameter, 18-inches long steel pins, pointed at one end, and fitted with 1-1/2 inch diameter washer at other end.

2.03 CRUSHED GRAVEL

A. In accordance with section [9][02_] - Gravel.

PART 3 EXECUTION

3.01 SUBGRADE PREPARATION

A. Prepare surface upon which geotextile is to be placed to a firm surface, reasonably even and smooth, and free of offsets, abrupt indentations, and protruding materials greater than 1-1/2 inches.

B. [10][Roll with vibratory roller.]

C. Fill low spots with crushed gravel or compacted native material.

D. Obtain COR approval of subgrade before installing geotextile.

3.02 INSTALLATION

A. Place geotextile in the manner and at locations shown on drawings.

B. Lay geotextile smoothly, free of tension, stress, folds, wrinkles, or creases so far as is practical and except where required in these specifications.

C. Shingle overlaps on slopes with upstream roll placed over downstream roll.

    1. [11][On slopes steeper than _H:_V, roll out geotextile up or down slope.]

D. Pin, staple, or weight to hold geotextile in position. [12][Do not puncture underlying geomembrane with anchors.]

E. Anchor terminal ends of geotextile with key trenches or aprons at crest and toe of slopes.

F. In the presence of wind, weight geotextiles with sandbags or equivalent until cover material placed.

G. Do not entrap stones, soil, excessive dust, or moisture in geotextile that could damage geotextile or hamper subsequent seaming.

H. Do not drive or operate equipment directly on geotextile.

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[9] Complete section number.
[10] Include when very smooth surface required and subgrade is coarse, especially angular, material.
[11] Include when geotextile required to be placed on relatively steep slope. Insert definition for steep slope.
[12] Delete if geomembrane not used on job.

1. Cover material depth required for equipment travel over geotextile, minimum: [13][__] inches.

I. [14][Place cover material with low ground pressure (LGP) wide track crawler type dozer.

1. Ground pressure, maximum: 5 lb /in^2.

2. Maintain 1.5 feet of cover material under LGP tracks during placement.

3. Maintain maximum of 1.5 feet of push height on dozer blade when spreading material on slope areas.

4. Push cover material upslope.]

J. Drop height of cover material on to geotextile, maximum: [15][ ].

K. Cover geotextile within 14 days after geotextile placement.

1. If covering geotextile with specified material is not possible within 14 days, protect exposed geotextile with suitable cover approved by the Government.

2. Replace geotextile not protected.

L. [16][Compact fill against geotextile in accordance with Section 02302 - Compacting Earth Materials.]

3.03 SEAMING

A. Join adjacent sheets of geotextile by [17][overlapping, sewing, or thermal welding].

B. Overlapped seams:

1. Overlap minimum: [18][ ].

2. Upstream/upslope roll placed over the downstream/downslope roll.

3. Weight or pin on 3-foot centers to secure the overlap during placement of cover material.

a. Do not use pins when installed over geomembrane.

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13 Insert depth of cover material required

14 Include when equipment travel required over geotextile to place cover material.

15 Specify drop height depending on construction conditions. Typical values are 1 foot, 2 feet, or 3 feet.

16 Include when cover material is required to be compacted. Minimum density for geotextile cover material is often not required.

17 Select type of seaming to be allowed.

18 Specify overlap depending on subgrade firmness. Typical values are 12 inches, 24 inches, or 36 inches.

C. [19][Sewn seams:

1. Interlocking or sewn twice.

2. Thread:

    a. Contrasting color.

    b. Chemical resistance: Equal to geotextile.

3. Sew geotextiles continuously. Spot sewing is not allowed.

4. Sewn seam strength: Not less than 70 percent of parent material strength.]

3.04 [20][RIPRAP INSTALLATION

A. Place riprap or backfill material so as not to damage geotextile.

1. Type 1 riprap: Place directly on 4 oz geotextile with drop height not exceeding 3 feet.

2. Type 2 riprap: Place directly on 16 oz geotextile with drop height not exceeding 1 foot.

3. Type 3 riprap: Use with 4 inch gravel cushion over 16 oz. geotextile. Place with drop height not exceeding 1 foot.

B. Before placing riprap, demonstrate that placing technique will not damage geotextile or underlying geomembrane. If the demonstration does not show that riprap can be installed without damaging geotextile, modify riprap placing technique (such as reducing drop height, installing additional layer of sacrificial geotextile, or installing additional gravel cushion).

C. Begin riprap placement at toe and proceed up slope.]

3.05 REPAIRS

A. At placement, geotextile will be rejected if it has defects, rips, holes, flaws, deterioration, contamination, or damage.

B. Replace or repair geotextile damaged during installation or placement of cover in the following manner:

1. Remove cover from damaged area of geotextile.

2. Remove any soil or other material which may have penetrated torn geotextile.

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[19] Delete if sewn seams not allowed or required.

[20] Delete if riprap not used on job. Modify as appropriate for other materials. If riprap is used, delete redundancies between this section and Section 02375 – Riprap.

3. Repair damaged geotextile by placing additional layer of geotextile to cover damaged area and [21][either sew the patch to undamaged geotextile according to sewing requirements stated above or] overlap undamaged geotextile by at least 3 feet on all sides.

3.06 [22][SAFETY

A. If white colored geotextile is used, take precautions against "snowblindness" of personnel.]

3.07 FIELD QUALITY CONTROL

A. After installation, examine entire geotextile surface to ensure that potentially harmful foreign objects (such as needles) are not present.

B. Remove foreign objects or replace geotextile.

END OF SECTION

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21 Delete if sewn seams are not included.
22 Include only for large jobs. Delete for most jobs.