Promoting Geosynthetics Use on Federal Lands Highway Projects

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U.S. Department of Transportation
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Federal Lands Highway
Commitment to Excellence

Central Federal Lands Highway Division
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FOREWORD

The Federal Lands Highway (FLH) of the Federal Highway Administration (FHWA) promotes development and deployment of applied research and technology applicable to solving transportation related issues on Federal Lands. The FLH provides technology delivery, innovative solutions, recommended best practices, and related information and knowledge sharing to Federal agencies, Tribal governments, and other offices within the FHWA.

The objective of this study was to provide guidance and recommendations on the potential of systematically including geosynthetics in highway construction projects by the FLH and their client agencies. The study included a literature search of existing design guidelines and published work on a range of applications that use geosynthetics. These included mechanically stabilized earth walls, reinforced soil slopes, base reinforcement, pavements, and various road applications. A survey of personnel from the FLH and its client agencies was performed to determine the current level of geosynthetic use in their practice. Based on the literature review and survey results, recommendations for possible wider use of geosynthetics in the FLH projects are made and prioritized. These include updates to current geosynthetic specifications, the offering of training programs, development of analysis tools that focus on applications of interest to the FLH, and further studies to promote the improvement of nascent or existing design methods.

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Notice

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16. Abstract

Geosynthetics are currently perceived to be "under-used in the Federal Lands Highway (FLH) practice." Accordingly, this study aims to develop recommendations to identify, promote, and advance the use of geosynthetic materials across the FLH in the Roadway, Bridge/Structures, and Geotechnical areas. Personnel from the FLH and its client organizations were surveyed to determine current use and barriers to implementation of geosynthetic technologies. A review of recent literature and existing national design guidelines was undertaken to determine the current state of practice and possible technologies that could be implemented in the near future. Recommendations are formulated to provide the basis for a multi-year effort that will culminate in advancing the use of geosynthetic materials in the FLH projects. These include updates to current geosynthetic specifications, development of training programs and analysis tools that focus on applications of interest to the FLH, and needed further studies to promote the improvement of nascent or existing design methods.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	Millimeters	mm
ft	feet	0.305	Meters	m
yd	yards	0.914	Meters	m
mi	miles	1.61	Kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	Gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	Newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	Kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	Kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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EXECUTIVE SUMMARY

This study provides guidance and recommendations to identify, promote, and advance the use of geosynthetic materials across Federal Lands Highway Division (FLHD) in the Roadway, Bridge/Structures, and Geotechnical areas. Personnel from FLHD and its client organizations were surveyed to determine current use and barriers to implementation of geosynthetic technologies. A review of recent literature and existing national design guidelines was undertaken to determine the current state of practice and possible technologies that could be implemented in the near future. Recommendations were formulated to provide the basis for a multi-year effort that will culminate in advancing the use of geosynthetic materials in FLHD highway projects. Target technical areas included slopes, walls, deep patches for soft shoulders, reinforced soil foundations (embankments, shallow foundations), moisture barriers, liners to control/prevent seepage, unbound pavement layers and bound pavement layers.

The advanced recommendations are classified into three categories: i) Broad guidelines for specifications updating, ii) Implementation of specific design approaches for expedient utilization of best practice technologies, and iii) System-level recommendations for further development prior to wide acceptance for a particular technology application.

The broad guidelines include updating FLHD geosynthetics usage procedures to include design guidelines and to update the standard specifications in light of these guidelines. In addition, it is imperative to include design guidance on using both geotextile and geogrids in reinforcement applications. This will likely not be a part of an updated FP-03, but should at least be a recognized set of documents that will guide and standardize relatively simple designs. It is also recommended to develop/adopt procedures to evaluate proprietary systems that use geosynthetics.

The implementation of state of practice design approaches is recommended to assist FLHD professionals with the design of geosynthetics structures that are commonly used in practice today. There are well documented design approaches for MSE walls, reinforced soil slopes, and embankments on reinforced soil foundations. A standard design process for these applications can include the development of charts that standardize the design of reinforced walls or slopes while being sufficiently flexible to economize such a design. Simple computer modules could also be developed to aid FLHD personnel in investigating the sensitivity of the design to key input parameters. Such modules could be developed for designs of many of the applications listed above.

FLHD could also adopt a series of short courses with a logical sequence to specifically emphasize applications of interest to them. This series of educational efforts should be specifically designed and targeted toward FLHD professionals, and should be digitally recorded and distributed agency wide. This effort should also include an aggressive education program for construction managers, engineers, and technicians who inspect MSE walls, reinforced soil slopes, and other projects on which geosynthetics are used.

System-level recommendations for further developments include specific suggestions for the nine areas considered in this study. For all technical areas covered in this report, previously built structures should be revisited to collect of data on their performance (in a non-destructive or destructive manner as circumstances allow). Such performance data should be presented in context of the as-built design and document any lessons learned.

The proposed recommendations also identify suggested priorities for future FLHD development in each of the nine areas of study. These priorities were determined in concert with FLHD personnel and reflect the items most likely to significantly affect geotechnical and roadway practice in the next three to five years. In some cases, action on these prioritized recommendations can be solely contained to FLHD. In other cases, FLHD will likely need to partner with other organizations to accommodate some of the development efforts needed to produce a widely accepted, calibrated design method for deployment in practice.

CHAPTER 1 – INTRODUCTION

Geosynthetics are a construction material made from polymers. These materials are manufactured as textiles, grids, nets, solid membranes or as a combination of one or more of the above. The type of geosynthetic selected for a particular project depends on the intended application, which can include drainage, separation of different materials, filtration of soil particles from draining water, reinforcement, confinement and containment. Geosynthetic usage has steadily increased in both public and private construction projects and innovative uses and new products continue to appear on the market.

The Federal Lands Highway Division (FLHD) seeks to optimize highway work through broader use of geosynthetic materials, in a manner that can lead to cost effective design. In general, geosynthetics have been successfully used in numerous highway construction projects including reinforcement and stabilization, separation and filtration, erosion control, and as moisture barriers. However, it has been recognized by FLHD engineers that geosynthetics may be underused within FLHD and by many state departments of transportation across the nation. The inability to capture some of the benefits of geosynthetics can be partly attributed to the lack of standardized design approaches that can be used to address certain project situations faced by FLHD.

It is apparent that in many cases geosynthetics are implemented in practice by FLHD due to “individual” effort without specific system-wide guidance. Accordingly, this study was motivated by FLHD engineers to seek direction, guidance and procedures that can lead to increased use of geosynthetics materials in geotechnical and pavement applications, when such use is advantageous.

PROBLEM STATEMENT

It has been identified by engineers from FLHD that geosynthetics are “under-used in Federal Lands Highway practice and under-represented in the FP-03 ‘Standard Specification for Construction of Roads and Bridges on Federal Highway Projects’ when compared to how prevalent geosynthetics are used in highway and other civil construction applications.” Accordingly, this study aims to develop recommendations and guidelines to identify, promote, and advance the use of geosynthetic materials across FLHD in the Roadway, Bridge/Structures, and Geotechnical areas.

STUDY OBJECTIVE AND TARGET APPLICATIONS

The main objective of this study is to develop systematic recommendations to guide a three to five year effort that will culminate in advancing the use of geosynthetic materials in FLHD highway projects across their three divisions. The target areas include geotechnical, structural, and roadway applications. Structural/geotechnical focus applications include:

- Slopes
- Walls

- Embankment reinforcement
- Reinforced soil (shallow) foundations
- Moisture barriers
- Deep patches for soft shoulders, and
- Liners to control/prevent seepage

Roadway applications will include both paved and unpaved roadways and will be focused on:

- Unbound Layers
- Bound Layers

Note that erosion control and drainage applications of geosynthetics were excluded from this scope of work and therefore are not addressed in great details.

TASKS

The study was separated into three major tasks. Two of the tasks involved investigating the current state-of-art and state-of-practice on geosynthetic utilization in target applications. The third synthesized the results of the investigation into recommendations for the future advancement of geosynthetics use in FLHD. The study proceeded along the following tasks:

Literature Review

In each target area, the opportunities and needs for geosynthetics applications were reviewed. Initially, the existing guidance documents from the American Association of State Highway and Transportation Officials (AASHTO) and the Federal Highway Administration (FHWA) were reviewed for applicable contents. A literature review was then performed to determine recent advancements in the appropriate target areas. These sources are summarized as the state-of-art in design and research guidelines.

Survey of FLHD Engineers

In parallel, a survey was developed to collect information on current approaches and practices of various engineers in agencies related to FLHD. The survey was e-mailed to a list of professionals identified by FLHD engineers. The survey collected data on several aspects of geosynthetics usage in the engineers' areas of practice. These included:

a. The extent of including geosynthetics in highway projects,
b. Examples of past projects and typical applications,
c. Approaches followed in designing geosynthetics in pavement, structural, and geotechnical applications, and,
d. Advantages and disadvantages defined as a result of using geosynthetics (i.e., past experience).

The survey results are compiled and trends are identified. A summary is presented on the current state of FLHD practice.

Study Recommendations

Once the survey and literature review were compiled, gaps in current practice, as well as possible future directions were identified for each target area. The level of maturity of a particular application was assessed, as well as research needs and the likelihood that implementation of geosynthetics for a particular application will be successful. The study recommendations target "discrete and attainable" work items for future sponsorship and deployment within FLH divisions.

Guidelines regarding types of field validation for various projects involving geosynthetics, and criteria for assessing the acceptability of new application and/or products are recommended. This information is also used to establish the type of empirical evaluations of performance that are needed for informed decisions. Furthermore, the need for proposed training and workshops to be held throughout a multi-year plan to increase the staff awareness of geosynthetics applications is presented.

REPORT ORGANIZATION

This report is organized into seven chapters. Chapter 1 introduces the study and its objectives. Chapter 2 reviews existing AASHTO, FHWA and FLH specifications, design procedures and design manuals for projects that include geosynthetics. Chapter 3 summarizes the results of the survey of the engineers selected by the FLHD. Chapters 4 through 6 deal with a particular target area as defined below:

- Chapter 4: Walls and Slopes
    - Mechanically Stabilized Earth Walls
    - Reinforced Soil Slopes
    - Deep Patches for Soft Shoulders
- Chapter 5: Reinforced Soil Foundations
    - Embankments over Soft Soils
    - Column Supported Embankments
    - Shallow Foundations on Reinforced Soils
    - Bridging Subsurface Voids
- Chapter 6: Paved and Unpaved Road Applications
    - Paved Roads: Unbound Layers and Subgrade
    - Paved Roads: Bound Layers
    - Permanent Unpaved Roads
    - Temporary Unpaved Roads (Construction Platforms)
    - Moisture Barriers
    - Liners to Control/Prevent Seepage

Chapter 7 provides a summary of the above work, including final conclusions and recommendations for where the authors feel resources should be directed in coming years.

CHAPTER 2 – REVIEW OF EXISTING NATIONAL GUIDELINES

In this chapter, national guidance for geosynthetic materials and applications as presented by AASHTO, FHWA, and Federal Lands Highway Divisions (FLHD) programs are reviewed. The documents summarized here range from standard construction specifications that define minimum properties for a particular product to be used on a given site, to manuals/guidelines and specifications giving step-by-step instructions for certain design and construction procedures.

AASHTO has a number of design and material specifications involving geosynthetics, mainly in the broader areas of pavement structures and retaining walls. Design guidelines are primarily for reinforcement of pavement subgrades and mechanically stabilized earth (MSE) walls. Material guidelines are wider ranging, specifying minimum survivability requirements for pavement overlays, filtration and separation geosynthetics, edge drains, erosion control and silt fences. These publications will be briefly reviewed here, focusing on applications within the scope of this study.

AASHTO Guide for Design of Pavement Structures

AASHTO (1993, 2002) contains no explicit guidelines for design of base course reinforcement with geosynthetics, subgrade stabilization, or for paving fabrics in rehabilitated asphalt overlays. However, this guide is often integral to the design procedures noted in the Federal Highway Documents discussed later in the “Pavement Overlays” chapter of the Geosynthetics Manual by Holtz et al. (1998). AASHTO’s geosynthetic guidance for pavements seems only to be included in provisional standards or specifications.

AASHTO M 288-00

AASHTO M 288-00, “Geotextile Specification for Highway Applications” dictates target physical and material properties of a geotextile to be used on projects constructed using AASHTO specifications (AASHTO 2002). This document covers geotextiles for subsurface drainage (these are actually filtration specifications designed to prevent the migration of fines into a drainage media), separation, stabilization, permanent erosion control, silt fences, and paving fabrics. Drainage, erosion control and silt fences will not be covered in this report. The appendices of AASHTO M 288-00 include construction guidance which particularly cover thicknesses, required overlaps as a function of soil strength, and edge drain requirements.

AASHTO M 288-00 requires the geotextiles to be manufactured from long-chain synthetic polymers, and at least 95% by weight must be either polyesters or polyolefins (most likely polypropylene). The properties specified by AASHTO M 288-00 are all minimum average roll values (MARV) in the weakest direction. Apparent Opening Size (AOS) is the one exception, where the value specified is the maximum average roll value. The number of samples for quality control purposes of a geotextile is based on ASTM D

4759, and is usually determined by the smaller of a truckload or the entire shipment. ASTM D 4354 specifies how samples are collected for testing.

The AASHTO MARV values specified in AASHTO M 288-00 are reproduced in tabular form here for convenience. Table 1 shows the required properties relating to geotextile strength, as well as ASTM standards used for testing.

Table 1. AASHTO M 288-00 Geotextile Strength Property Requirements.

	Class 1		Class 2		Class 3	
	Elongation < 50%	Elongation ≥ 50%	Elongation < 50%	Elongation ≥ 50%	Elongation < 50%	Elongation ≥ 50%
Grab Strength	1400 N	900 N	1100 N	700 N	800 N	500 N
Sewn Seam Strength	1260 N	810 N	990 N	630 N	720 N	450 N
Tear Strength	500 N	350 N	400 N	250 N	300 N	180 N
Puncture Strength	500 N	350 N	400 N	250 N	300 N	180 N

For woven monofilament geotextiles, the minimum tear strength is 250 N.

Table 2 shows MARVs for the separation function, which is mainly to prevent mixing of subgrade and aggregate cover material. These values are applicable for soils with a California Bearing Ratio (CBR), a test used to determine subgrade strength in pavement applications, greater than three or undrained shear strength greater than 90 kPa in the field.

Table 2. AASHTO M 288-00 Separation Geotextile Property Requirements.

	Test Method	Requirements
Geotextile Class		Class 2 from Table 1
Permittivity	ASTM D 4491	0.02/s (greater than soil)
AOS	ASTM D 4751	0.60 mm max
UV Stability	ASTM D 4355	50% strength retained after 500 hrs exposure

Table 3 shows MARVs for the stabilization function. In wet, saturated soil conditions the geosynthetic may be used to provide filtration, separation, and in some cases reinforcement. Applicable soils are those with CBR between one and three and undrained shear strength ranges from 30 to 90 kPa. It is explicitly stated in the standard that these properties are not appropriate for embankment or pavement reinforcement, which are site specific design issues. Note that, other than requiring the strength based on geotextile class 1, there are no guidelines for selecting which strain level dictates or whether a particular modulus is required.

Table 3. AASHTO M 288-00 Stabilization Geotextile Property Requirements.

	Test Method	Requirements
Geotextile Class		Class 1 from Table 1
Permittivity	ASTM D 4491	0.05/s (greater than soil)
AOS	ASTM D 4751	0.43 mm max
UV Stability	ASTM D 4355	50% strength retained after 500 hrs exposure

Table 4 defines MARVs for paving fabrics, which act as waterproofing and a stress relief layer within the pavement structure. Specifications in Table 4 do not cover reinforcement applications such as reflective cracking, pavement joints and local or spot repairs.

Table 4. AASHTO M 288-00 Paving Fabric Requirements.

	Test Method	Requirements
Grab Strength	ASTM D 4632	450 N
Ultimate elongation	ASTM D 4632	≥ 50%
Mass per unit area	ASTM D 5261	140 gm/m^2
Asphalt Retention	ASTM D 6140	Manufacturer (1/m^2)
Melting Point	ASTM D 276	150^{o}C

These specifications exist to satisfy minimum survivability concerns. Guidelines for secondary functions related to burst strength, impact strength, and fatigue were not included as part of these specifications. If a particular design resulted in one or more of these functions as being critical, the engineering judgment clause would then govern.

AASHTO PROVISIONAL STANDARDS

AASHTO PP 46-01, (AASHTO, 2001) "Geosynthetic Reinforcement of the Aggregate Base Course for Flexible Pavement Structures" summarizes design considerations laid out by the Geosynthetics Materials Association (Berg et al. 2000) and in the Geosynthetics Design and Construction Guidelines (Holtz et al. 1998). AASHTO PP 46-01 warns that the methods outlined in the two publications are very empirical and that the practitioner should make an effort to identify documented field tests that are similar to the situation for which the design is being developed. Since AASHTO M 288-00 covers separation and filtration functions, AASHTO PP 46-01 only considers reinforcement applications.

The geosynthetics used in this application are intended to improve or extend the service life under traffic loads or to reduce the thickness of the structural section. The provisional standard recommends repeatedly that the designer check the design through field verification to ensure the engineering and economic benefits expected are being realized. The standard lays out steps for design. The design methodologies in the white paper (Berg et al., 2000) and in Holtz et al. (1998) will be summarized in Chapter 6. The design methodology in AASHTO PP 46-01 also includes recommendations for monitoring long term performance and preparation of annual performance assessments.

AASHTO STANDARD SPECIFICATIONS FOR HIGHWAY BRIDGES

Allowable Stress Design (ASD) (17th Edition, 2002)

Section 5.8 of the AASHTO ASD Specifications includes methods for designing MSE walls. External stability of the wall is calculated using as a factor of safety against sliding, overturning, bearing capacity and global stability. Internal stability depends on the extensibility of the reinforcement, and considers potential for geosynthetic reinforcement rupture or pullout at the wall facing and point of maximum stress. The geosynthetic's long term tensile strength for the internal stability calculations is reduced by a factor of safety and by reduction factors to prevent creep, to consider installation damage, and to account for degradation due to chemical and biological agents when applicable. The design factors of safety in the specifications are included in Table 5.

Table 5. AASHTO ASD Specifications: Design Factors of Safety for MSE walls (AASHTO 2002).

Wall Stability Concern	Minimum AASHTO Factor of Safety
Overturning	2.0
Sliding	1.5
Bearing Capacity	2.0 (with geotechnical analysis)
Reinforcement Pullout	1.5
Reinforcement Rupture	1.5 (global), plus reduction factors

The extensibility of the reinforcement used in the MSE wall dictates the shape of the active zone for internal stability analyses in the AASHTO (2002) specifications. For inextensible reinforcing elements (e.g., steel strips), the active zone is trapezoidal, while for extensible reinforcement (e.g., geosynthetics), a Rankine failure surface (triangular) is assumed. The shape of the active zone then partly determines the tension experienced by the reinforcement.

A chart used to estimate the lateral displacement of an MSE wall during construction is also included in AASHTO (2002). Considerations are given to surcharge loads due to hydraulic, traffic, and concentrated dead loads. Similarly, minimum reinforcement lengths are specified.

Load Resistance Factor Design (LRFD) (3rd Edition, 2006)

In the 2006 LRFD specifications, MSE walls are covered in Section 11.10. The methods of analysis of MSE walls in the AASHTO LRFD are similar to those in ASD. The major differences are related to load and resistance factor selections. For the initial LRFD specifications, the resistance factors required in LRFD section 11 were selected by calibrating the LRFD method to the same factors of safety in the ASD method. This should result in similar or slightly more conservative designs compared to those produced by ASD design methodologies. Once a larger database of tests and walls is compiled to better determine resistance and load factors, these factors may change in the future.

Unlike ASD, factors of safety against overturning are no longer calculated, otherwise, for external stability, the LRFD codes are largely unchanged.

The LRFD resistance factors in Table 6 for MSE walls show different resistance factors for metallic and geosynthetic reinforcement. The differences between metallic and geosynthetic resistance factors are historical: in previous ASD versions, the factor of safety required for metallic strips was higher than for geosynthetic strips. The calibration of resistance factors to the previous factors of safety then reflects this trend.

Table 6. Resistance Factors for Permanent MSE Walls (AASHTO LRFD Table 11.5.6-1, 2004).

DESIGN CONDITION		RESISTANCE FACTOR
Bearing resistance		0.45 to 0.55
Sliding		0.8 to 0.9
Tensile resistance of metallic reinforcement and connectors	Strip reinforcement: • Static loading • Combined static/earthquake loading Grid reinforcement: • Static loading • Combined static/earthquake loading	 0.75 1.00 0.65 0.85
Tensile resistance of geosynthetic reinforcement and connectors	Static loading Combined static/earthquake loading	0.90 1.20
Pullout resistance of tensile reinforcement	Static loading Combined static/earthquake loading	0.90 1.20

Similarly, the load factors applied to the vertical earth pressure load, EV, were determined assuming no inclusions (e.g. reinforcement strips) in the soil. The specifications note that the EV load factors should be considered "interim" until further studies are completed.

FEDERAL LANDS HIGHWAY PROGRAM SPECIFICATIONS

The current geosynthetic guidelines used and developed by the FLHD come solely in standard specifications and special contract requirements. All other design guidance comes from other agencies, such as AASHTO or National Highway Institute courses. This section summarizes the specifications currently in use from the Federal Lands Highway Division.

FP-03: Standard Specifications Addressing Geosynthetics

In the FP-03 specifications (FHWA 2003), Section 714 governs geocomposite drains and other geotextiles. This document provides no design guidance; instead, after a design is completed, the designer goes to Section 714 to require minimum properties for a geosynthetic. The material selected by the contractor must then meet or exceed these properties. In most cases, MARVs shown in FP-03 are the same as those laid out by AASHTO M 288-00. The applications for geotextiles are the same: subsurface drainage, which again, is actually filtration (Type I), separation (Type II), stabilization (Type III), permanent erosion control (Type IV), silt fences (Type V), and paving fabric (Type VI). The major differences are related to how geotextiles are classified.

Subclasses of Type I through VI depend mainly on the strength of the geotextile, as laid out in Table 1, combined with the other MARVs as presented in Table 2 through Table 4 for each particular application. For separation and stabilization, information from Table 1, Table 2 and Table 3 are used, with allowances for all strength classes in separation and Classes 1 and 2 for stabilization. Type VI Paving Fabric MARVs are the same as in Table 4, except for grab strength, which is 500 N (112 lbs) instead of the 450 N (101 lbs) noted in Table 4.

In FHWA Standard Specs (FP-03) Section 415, Paving Geotextiles are allowed as an overlay between existing and new pavement layers to form stress relieving and waterproofing layers. First, asphalt sealer is laid down, then geotextile fabric is placed atop the seal. After a tack coat, the top asphalt concrete layer is placed. The minimum average properties in the weakest direction for paving fabrics are summarized in Table 7. Note these results are similar to those from the AASHTO specifications in Table 4.

The standards in FP-03 are thus derived from AASHTO M 288-00, with some slight modifications. Like AASHTO M 288-00, these are predominantly minimum survivability properties, with other functions designed based on the responsible engineer's judgment.

Table 7. FP-03 Standard Specifications: Minimum Properties for Paving Applications.

Property	Specified Requirement
Grab Strength	500 N
Ultimate elongation	50% at break
Asphalt retention	0.90 L/m^2
Mass per unit area	140 g/m^2
Melting Point	150^o C

Special Contract Requirements

In the Western Federal Lands office, special specifications for geogrids have been created and added to the existing FP-03 specifications on a project specific basis (Alzamora, 2006). Otherwise, there are no official geogrid material specifications in FP-03.

NHI/FHWA PUBLICATIONS

In the last twenty years, a number of design manuals and guidelines have been introduced by contractors for the FHWA, often to develop materials for National Highway Institute (NHI) Courses. These include entire manuals on geosynthetic usage in designs and on MSE and reinforced soil slopes, as well as portions of other manuals, such as the column supported embankment and stone column sections in the Ground Improvement manual. A brief summary of some of the topics covered in each course manual follows, highlighting design methodologies used and other guidance given.

Geosynthetics Manual

The geosynthetics manual was last revised in 1998 by Holtz, et al. An update to the manual, reportedly, is to be completed prior the end of 2006. This document provides guidance for geosynthetic inclusion in design of subsurface drainage systems, erosion control systems, roadways and pavement reinforcement, pavement overlays, embankments, slopes, MSE walls and barriers. Each of these are briefly described below.

Roadway and Pavement Reinforcement

This section describes the typical use of geosynthetics in roadways as a separator, reinforcement, or as a filtration and drainage medium. The design methods for temporary and unpaved roads in the geosynthetics manual consider only the separation and filtration functions, since these have the longest history of successful implementation. The analysis method in this case is based on the work of Steward, et al. (1977), who quantified the improved drainage and segregation effects of the geosynthetic separator by suggesting an increased bearing capacity factor. Based on AASHTO (1993) design curves, this increased bearing capacity may lead to a reduced thickness of aggregate base course compared to the case without geosynthetics.

For permanent pavements, the geosynthetics are assumed to not provide any structural support or improvement. Any savings in overall thickness comes from the reduction of non-structural stabilizing layers in weak soils. By the methods noted here, the thickness of additional subbase, for stabilization using geosynthetics, is calculated using the same procedure as temporary road design. Again, this, however, does not reduce the height of the *structural* pavement system that will be placed atop the stabilization layer.

Pavement Overlays

This section of the manual deals with geosynthetics placed in asphalt or concrete overlays, primarily to prevent infiltration of water into the subbase or to relieve stresses transferred into the overlay by underlying reflective cracking. The main purpose of any overlay is to extend the life of the pavement, not to prevent cracks or fatigue indefinitely. Pavement overlay design without geosynthetics is covered in AASHTO (1993, 2002).

Holtz et al. (1998) stress the importance of comprehensive field studies both before and after overlay installation. This includes surveys of crack widths, structural strength, locations of base failure prior to the remediation with overlay and by installing a control section without geotextile overlay to monitor the relative performance of the geotextile. They recommend following the AASHTO (1993) guidelines, designing the thickness of the overlay as if the geotextile was not present. A method to allow reduction in thickness of the overlay is suggested in Holtz et al. (1998) by changing drainage coefficients in the equation to determine structural thickness. However, this guidance is not explicit, and selection of particular coefficients is left up to individual user of the manual.

Because correctly selected and installed pavement overlay geosynthetics are thought to increase the life of a roadway, Holtz et al (1998) suggest pavement overlays benefits should be justified by lower costs in maintenance, longer times between rehabilitation, and possibly an increased structural capacity. Based on the work of Barksdale (1991), this economic analysis could include historical cost and performance data available either locally, regionally or nationally, as well as analyses into the probability of success. Doing so, however, requires carefully controlled and documented field studies, some of which will be briefly discussed in PAVED ROADS: BOUND LAYERS section of Chapter 6.

Embankments

Design and construction of geosynthetic reinforced embankments is also covered in Holtz et al. (1998). In this case, the design method considers the selected geosynthetic to primarily perform a reinforcement function, although separation could also be a secondary function to prevent mixing of embankment soils with the subgrade. The design method first checks the need for additional reinforcement. Next, the required reinforcement strength for rotational stability and lateral spreading type failures is calculated. The reinforcement mechanism has no benefit on consolidation or secondary settlement.

Once the required geosynthetic strength is determined, the reinforcement deformation requirements are calculated depending on strain limits specified as a function of soil type. The recommended modulus is a secant tensile modulus between the strain limit and zero strain. Thus, the main reinforcement characteristics required for this design methodology are strength at a particular level of strain, the equivalent secant modulus, and the angle of the reinforcement force with respect to the critical failure surface.

Slopes and MSE Walls

While there is extensive coverage of MSE wall design in the Geosynthetics Manual, the information it contains has been updated and published in the “MSE Wall and Reinforced Soil Slope Design and Construction Guidelines” by Elias et al. (2001) described later in this chapter.

Barriers

Holtz et al. (1998) deals with basic design, specification and selection issues involved with selecting geosynthetics as moisture barriers. There is some mention of geosynthetic clay liners, mainly for flow mitigation applications such as tunnel and wall waterproofing, canal lining, or secondary containment of sensitive sites. Design considerations noted include installation conditions, Geosynthetic Clay Liner (GCL) durability, economics, and in-service conditions and performance.

Ground Improvement Manual

This manual (Elias, et al., 2006) summarizes a number of soil improvement design, and construction methodologies. Most of the topics in the manual do not use geosynthetics; however, the stone column section and the column supported embankment section do include some geosynthetics discussions. Lightweight fill materials, including expanded polystyrene (EPS) – also referred to as "geofoam," are addressed in this manual, as well. Lightweight fills are not within the scope of this report, but it is noted that such materials are often used in conjunction with embankment reinforcement applications.

Geotextile Encased Columns

One of the improvement approaches mentioned in Elias et al. (2006) is geotextile encased columns (GEC), a patented method developed in Europe. GEC are installed by replacing or displacing the *in situ* soil, and filling the resulting space with a tube of high strength, seamless geosynthetic. The empty tubes are then filled with sand. One possible advantage of such a column technology is their applicability in very soft soils and the ability to design them for vertical drainage. Unfortunately, they are still relatively new and are proprietary. Use of these columns in the U.S. has been very limited to date and, therefore, they should be considered as experimental features.

Column Supported Embankments with Geosynthetic Load Transfer Platforms

Elias et al. (2006) also contains a technical summary chapter on design, cost estimating, specification, and construction of Column Supported Embankments (CSE). In the last two decades, a load transfer platform constructed from layers of geosynthetics and soils has been added to help reduce the number of columns required. Elias et al. (2006) note that the main advantage of this technology is the speed of construction and elimination of post construction settlement. A major disadvantage of CSE is often initial construction cost when compared to other solutions. However, if the time savings are included in the economic analysis when using CSE technology, the cost may be far less than other solutions.

Another major disadvantage is lack of a widely accepted design procedure. There are many different design approaches, and they all give different results. Without some standardization of the load transfer platform design, the technology will be limited in its use and acceptance.

Current design methods of the geosynthetic load transfer platforms treat the composite soil-geosynthetic section as either a catenary or a beam. Catenary theory assumes that a single layer of reinforcement is deformed and soil arches form in the embankment soil. Beam theory (the Collin Method), assumes three or more layers of reinforcement spaced vertically 200 to 450 mm (8 to 18 inches) apart, that arching develops in the load transfer platform soil only, and that the platform is at least ½ the thickness of the span between the columns. In both the beam and catenary theory, the geosynthetic layer(s) must develop tension to withstand the weight of the soil (either embankment fill or load transfer fill for catenary and beam formulations, respectively). Design considerations for column design, lateral spreading, and global stability are similar to those discussed elsewhere.

Mechanically Stabilized Earth Walls and Reinforced Soil Slopes Design & Construction Guidelines

The FHWA guidelines on MSE walls and reinforced soil slopes were written by Elias et al. and published in 2001. These guidelines are consistent with those in AASHTO (2002). Reinforced soil structures involve placement of reinforcing strips or sheets, placement and compaction of reinforced fill, and construction of a facing system. The manual includes recommended, step-by-step design, construction and installation guidelines for both walls and slopes, using both hand and computer analysis methods.

MSE Walls

Elias et al. (2001)'s MSE wall design methodology consists of three analyses: working stress, equilibrium, and deformation. The working stress analysis examines tension and resistance to pullout in the reinforcement, and the spacing of the reinforcement layers. The limit equilibrium analysis checks the overall stability of the wall against sliding, bearing capacity, global stability and internal stability failures. The deformation analysis determines horizontal and vertical movements under assumed loadings.

In the design methods for internal stability outlined in Elias et al. (2001), the determination of the horizontal forces acting on the wall (and thus the required tensile resistance of the wall's reinforcement layers) depends on the type of reinforcement used. Similarly, the potential failure surface is determined by the reinforcement's extensibility. These also affect the length, spacing and required strength of the geosynthetic reinforcement. Calibrating and verifying these parts of the working stress analysis have received the most attention over the past two decades, in field tests and numerical studies. The manual suggests specific software, MSEW (ADAMA Engineering, Inc. 2006) that follows the design methodology laid out in Elias et al. (2001).

Another widely used national guideline for MSE walls is the National Concrete Masonry Association's (NCMA) Design Manual for Segmental Retaining Walls (1997). These guidelines are specifically for modular block unit (MBW) faced walls. However, FHWA (Elias et al., 2001) and AASHTO (2002) procedures also address MBW faced walls, and are different than the NCMA procedure. The use of the FHWA/AASHTO procedure is recommended to maintain a consistency in design and equitable bidding environment.

Reinforced Soil Slopes (RSS)

The design method for RSS involves calculating a factor of safety for the unreinforced slope for a series of possible failure surfaces. The required tensile resistance is then calculated based on the unbalanced driving moment, followed by distribution, spacing and length of the reinforcing members. Once the factor of safety against rotational failure is complete, the external and seismic stability of the reinforced structure must be checked. The slope face treatment to prevent erosion and promote vegetative growth, surface runoff, and subsurface water infiltration must also be considered. Elias et al. (2001) also suggests specific software for RSS analysis (ADAMA Engineering, Inc. 2006). A version of this software has been licensed to the FHWA.

Federally Sponsored Durability Studies

The FHWA oversaw a sizable pooled-fund study to determine the effects of a number of degradation mechanisms on the performance of geosynthetics (and steel reinforcements) used in geotechnical applications (Elias et al., 1998a, b, and c; Elias, 2000 and Elias 2001). The main purpose of these studies on geosynthetics was to better understand and quantify the effects of potential degradation due to stress cracking (Elias 1998a), chemical oxidation (Elias 1998c), ultraviolet and biological processes (Elias 2000). Elias (2001), in his study of geosynthetic material exhumed from 12 sites up to 20 years old, concluded that observed rates of degradation were consistent with laboratory tests, and that, in the cases examined, only low levels of strength loss were observed.

Elias (2000) also summarizes the soil types and groundwater environments that can lead to accelerated degradation of geosynthetics manufactured from certain types of polymer materials. This report also compiles a range of reduction factors for geosynthetic tensile strengths that considers both the geosynthetic type and polymer for installation damage and durability. Methods to monitor and test installation damage are also suggested in this document.

Degradation mechanisms, environmental factors, and degradation rates of geosynthetics are well documented as a result of this study. Specific environmental limits and design property reduction values were defined, and can actively be used for design of geosynthetic structures.

Shallow Foundations Reference Manual

Munfakh et al. (2001) summarized guidelines for design of shallow foundations. The discussion includes a short section on reinforced soil foundations. Reinforced soil foundations involve placing one or more layers of geosynthetics beneath the shallow foundation to act as a stiffener. The design formulation for shallow foundations over geosynthetic reinforced soils is for settlement calculation only, and models the geosynthetics as a series of stiff layers using Westergaard's theory. The geosynthetic spacing, horizontal extent and total depth are recommended in these guidelines based on empirical small scale and field scale laboratory tests. The design method does not consider improvements to limit state bearing capacity calculations, nor does it discuss the geosynthetic properties such as tensile strength, stiffness or creep characteristics that should be considered when specifying a design. Use of geosynthetics for reinforcement beneath shallow foundations has been very limited to date and, therefore, such applications should considered experimental in nature.

OTHER RELATED PUBLICATIONS

In an attempt to speed acceptance of new earth retaining system technologies and to help reduce redundant system evaluations by multiple organizations (DOTs), a set of guidelines to evaluate proprietary earth retaining systems was developed in 1998 (HITEC, 1998). The evaluations are set in motion by the manufacturers of the retaining systems. The application process for evaluating a system includes summarizing the materials used, the suggested design procedures, the methods of construction, and documented performance histories. Once a manufacturer submits an application, an advisory panel then suggests further testing (if required) and creates a technical evaluation report for the product. The distributed reports are then used by DOTs as a tool for system evaluation. These guidelines spawned a series of other reports that evaluated various geosynthetic reinforced wall systems (for an example, HITEC, 2003).

Another noteworthy publication (relevant to FLHD mission) is the one by Fannin (2001b) in which he describes applications of geosynthetics specifically for forest engineering. In 2000, Fannin compiled a "best practices" document geared specifically toward projects that affected forestry projects. Describing Canadian practices, this document included a review of ten forestry projects in which geosynthetics were used.

A review of several international documents was also conducted .These were Queensland Department of Main Roads (2001), Queensland Department of Main Roads (1999), Vic Roads (Undated), Miki (2005), and Palmeira (2005) led to the conclusion that information related to international practice is rather similar to US literature with slight variation that are mainly in response to local issue

SUMMARY

When considering existing national design guidelines and specifications involving geosynthetics, it is clear that some applications have been studied and developed extensively, while others require more calibration and development. For example, MSE walls, reinforced soil slopes, and geosynthetic reinforced embankments have reached a level of acceptance in practice that is related to the completeness of their design methods. While these applications still have some outstanding development issues to consider, it is our assessment that these applications are relatively mature.

Pavement applications and ground improvement techniques (geosynthetic plus column supported embankments, for example) have some information on usable design methodologies but still require considerable calibration, additional validation and possibly some improvements through carefully designed and instrumented laboratory and field studies. While case studies exist, more are required before a design model is widely accepted.

Other applications have little or no coverage in the national or AASHTO design guidelines. Reinforced shallow footings and geosynthetic encased columns are mentioned, but the suggested design methods are either nonexistent or still largely based on a few empirical studies. Geosynthetics for bridging subsurface voids and for capillary barriers to control frost heave are not mentioned at all.

The existing specifications (FP-03 and AASHTO) are used to determine acceptability of a product suggested by a contractor and were written with roadway applications in mind. As such, geosynthetics are mainly grouped by their ability to provide filtration and separation when one type of soil material is placed adjacent to another. Both FP-03 and AASHTO M 288-00 do not include specifications for applications for reinforcement.

In the next chapter, the results of a survey of FLHD and U.S. Forest Service (USFS) engineers will be presented. The survey will provide information on types of applications in which the engineers are involved and the process and methods the engineers use to design projects that include geosynthetics. The perceived challenges, benefits and problems with geosynthetics will also be summarized.

CHAPTER 3 – SURVEY OF GEOSYNTHETICS USE

In tandem with the literature review, a survey was created to gauge the current level of geosynthetics usage in FLHD Projects. The survey included questions regarding the number of projects and types of applications in which geosynthetics were used, the specifications and types of geosynthetics used, and descriptions of the respondent's experiences with geosynthetics on projects, both positive and negative. Roadway applications listed in the survey included frost heave, separation, edge drains, rehabilitation and subgrade reinforcement of paved roads, new construction and rehabilitation of unpaved roads, and shoulder patches. Geotechnical/structural applications included conventional (i.e., unreinforced) retaining walls, MSE walls, soil and rock slopes, embankments, drainage, construction platforms and reinforced shallow foundations. A copy of the questionnaire is included in Appendix A.

The survey was initially sent to 18 individuals identified by FLHD, of which three had USFS e-mail addresses, and 15 had FHWA e-mail addresses. The individuals surveyed were selected by FLHD personnel to represent a cross section of FLHD practice across the three divisions, as well as a small sample of Forest Service practice. These individuals were geotechnical and pavement design, construction and field engineers. The response rate for the survey was 61% (11 returned surveys). Of these 11, one was from a USFS e-mail address.

A large majority of survey respondents (10 of 11) reported using geosynthetics in construction projects. Of these ten, four reported seeing projects with geosynthetics once a year or less, and four reported two to ten projects with geosynthetics per year. The remaining two respondents reported more than ten projects per year.

APPLICATIONS

Figure 1 and Figure 2 show pavement and geotechnical applications, respectively, in which the respondents were involved in the design or construction. In these figures, the hatched bars show the approximate number of projects that included geosynthetics. For example, for newly constructed unpaved roads, eight respondents reported being involved in such a project, while two of those eight respondents reported being involved in a new unpaved road project that included geosynthetics (Figure 1).

Roadway Applications

From Figure 1, the majority of the 11 respondents indicated being involved in the design of all the applications listed in the survey. The applications that respondents were most likely to be involved with the design were related to edge drains and separation (nine of 11), followed by subgrade reinforcement for paved roads, unpaved road rehabilitation and new unpaved road construction (nine of 11). Geosynthetic usage was most common for subgrade reinforcement of paved roads and deep patches for soft shoulders. In these two cases, all respondents who said they were involved with these applications also reported projects where geosynthetics were used.

The roadway applications on which respondents reported using geosynthetics least were new unpaved road construction (two of 11) and asphalt overlays for paved roads (two of 11). Frost heave mitigation also showed low reported usage of geosynthetics (three of 11).

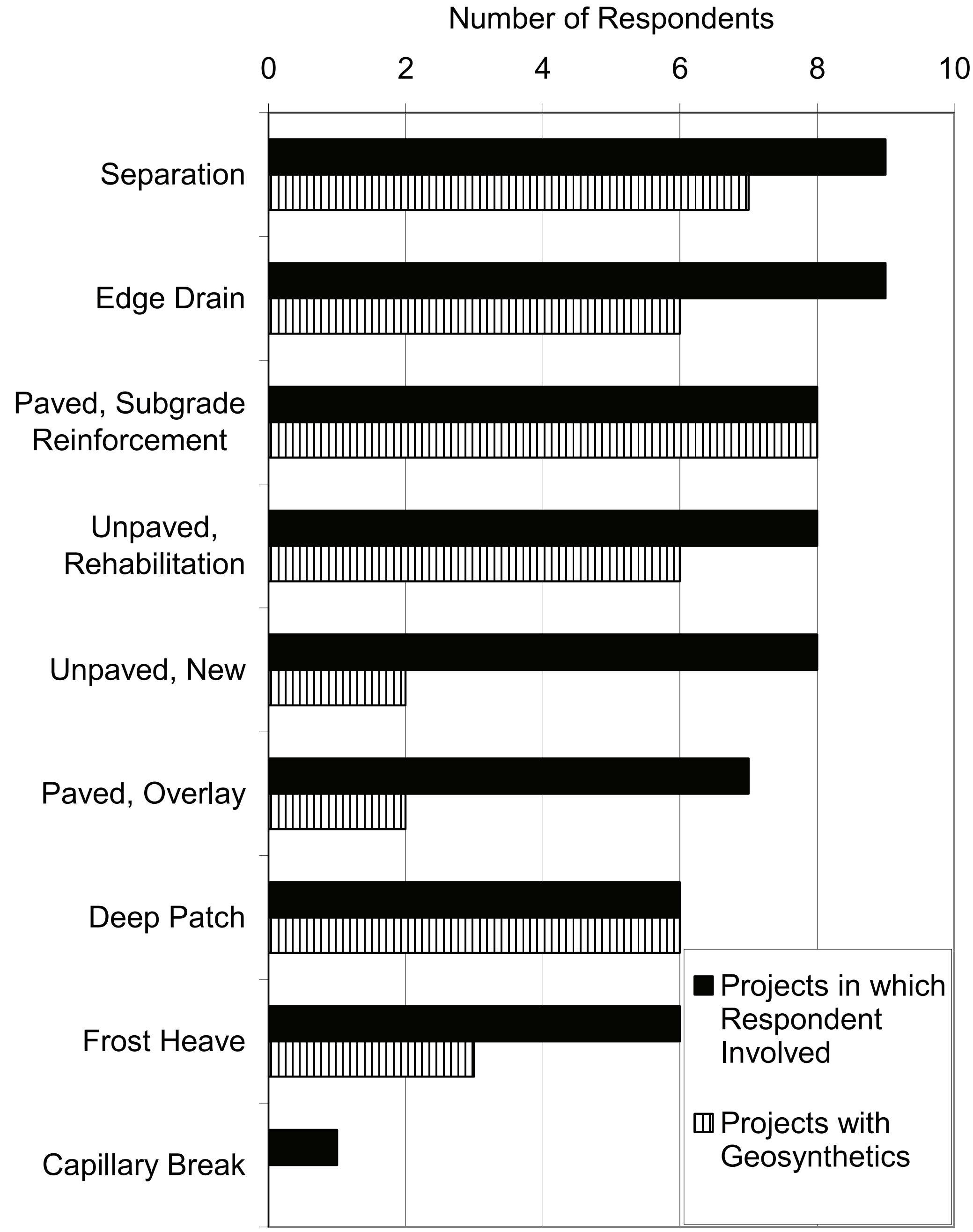

Figure 1. Graph. Roadway Applications.

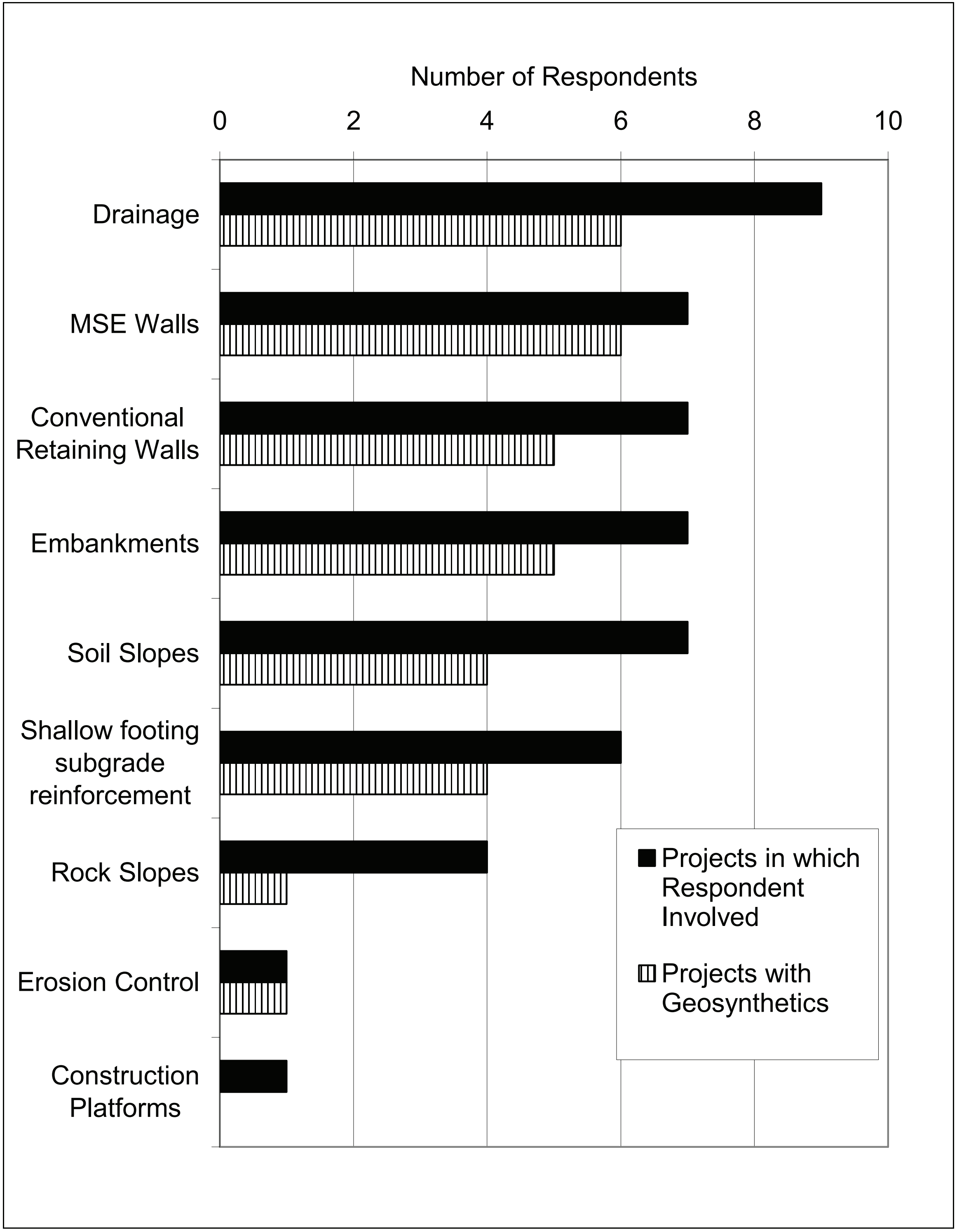

Figure 2. Graph. Geotechnical Applications.

Geotechnical Applications

In the geotechnical applications shown in Figure 2, the most reported application was drainage (nine of 11), followed by MSE walls, conventional retaining walls, embankments and soil slopes (seven of 11). Construction platforms (one of 11) received the smallest response. This may well be because reinforcement of construction access platforms is often left to contractors to implement and design (as mentioned in Perkins et al. 2005) or it may simply be a difference in terminology—to the respondents, a construction platform may be synonymous with subgrade reinforcement or new unpaved road construction.

Geosynthetic usage was most commonly reported for MSE walls (six of 11) and drainage applications (six of 11). Slopes (soil and rock) had the lowest number of respondents reporting geosynthetic usage. In absolute numbers, shallow foundation subgrade reinforcement also had four of 11 respondents reporting geosynthetic usage, but this represents 2/3 of the respondents who said they were involved with design of shallow foundations without reinforcement.

Most Common Types of Projects and Selecting When to Use Geosynthetics

When asked which of the applications in Figure 1 and Figure 2 were most commonly used by the respondent's agency, no single application was overwhelmingly reported. Five respondents reported drainage applications were most common. Retaining walls, MSE walls, slopes and separation were each noted by three respondents. A number of other applications listed in Figure 1 and Figure 2 were noted by one or two respondents only. Figure 3 summarizes the applications identified as most common.

When asked what leads to geosynthetic usage in a project, most respondents cited cost savings or improved performance for a specific application. Others noted improved constructability or specific site conditions, such as soft subgrade soils. Perhaps referring to the requirement in Holtz et al. 1998 that geosynthetic reinforcement in permanent (paved) roadways cannot reduce the base course thickness, only the stabilizing layer thickness, one respondent shed some light on why the use of geosynthetics may be hindered in permanent unpaved road construction applications:

> "During cost comparison, the paving options with geogrids generally lose out to more economical design. Only a couple of designs that were recommended have incorporated geogrids or separation fabrics. Geogrid still requires 6 inches of base on top of the geogrid, and height can be an issue on mountain roads."

Finally, all respondents reported using geosynthetics in permanent installations. Six of 11 respondents said their agency uses geosynthetics in temporary construction, or structures lasting up to three months. Five of 11 respondents reported geosynthetic usage in installations that would last up to two years. Thus, it would appear that concerns over geosynthetics long term performance have been at least partially satisfied, at least if all respondents are reporting geosynthetic usage in permanent structures.

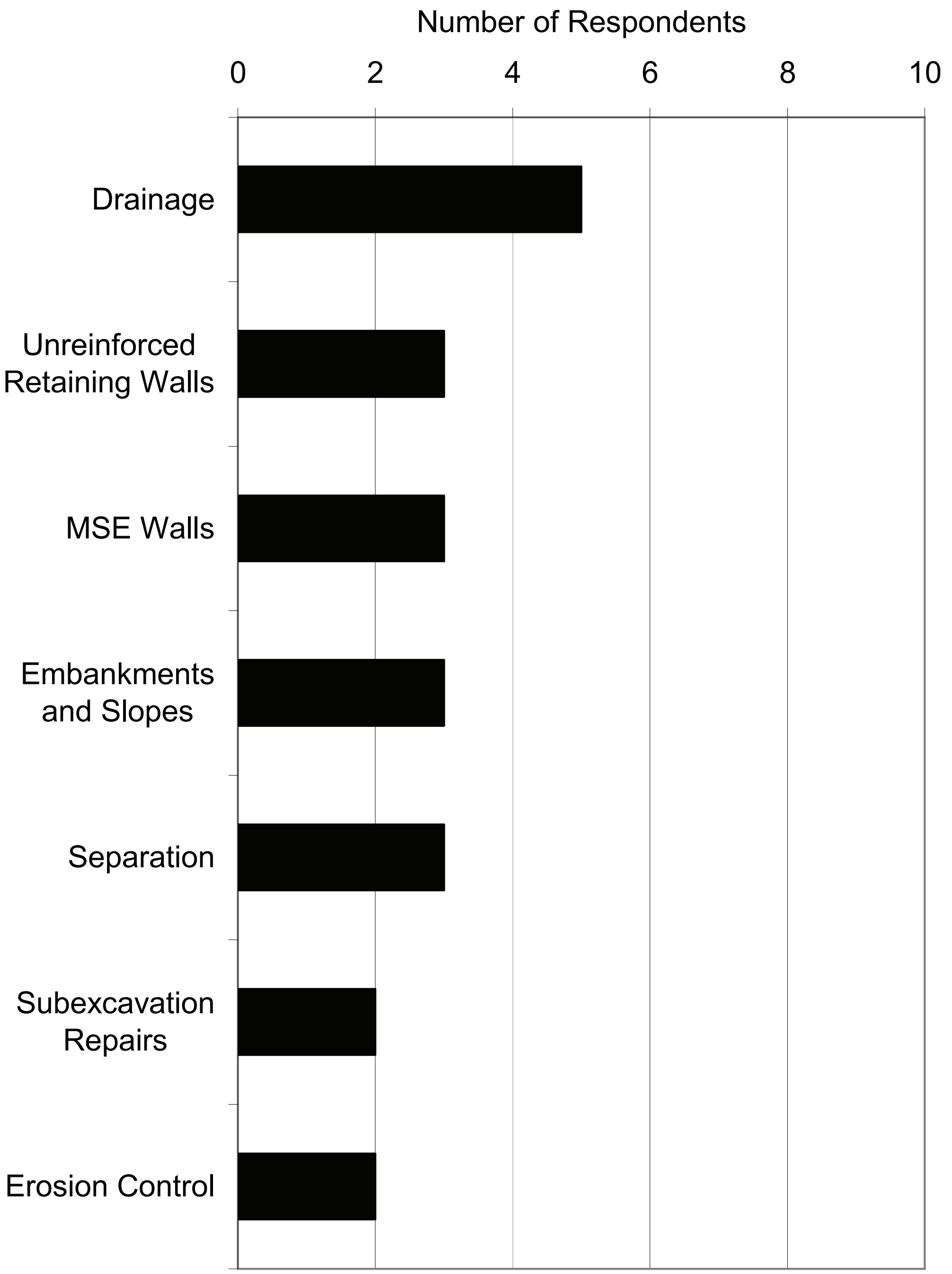

Figure 3. Graph. Reported Applications that Most Commonly Use Geosynthetics.

MATERIALS

After asking what types of projects the respondents usually encountered and whether geosynthetics are used regularly, the survey turned to the types of geosynthetics used. The survey asked about the major sub-types of geotextiles and geogrids as well as geonets, geomembranes, geocomposites, and geosynthetic clay liners. Information on the process for selecting and approving geosynthetics was also requested.

Geosynthetic Types Used

When asked if there were specifications or guidelines for selecting type of geosynthetics, nine of 11 survey respondents said yes. One said no, and one did not answer. When asked to list such guidelines, five respondents noted FP-03, four listed publications by FHWA or the National Highway Institute, and three did not answer. Two others listed special contract requirements (SCRs). Other publications listed only by one respondent were reference books by Koerner, Holtz, Christopher or Berg; manufacturer specific literature; the AASHTO manual; and details in project drawings.

The respondents were also asked to list all types of geosynthetics used by their agency. The responses to this question are shown in Figure 4.

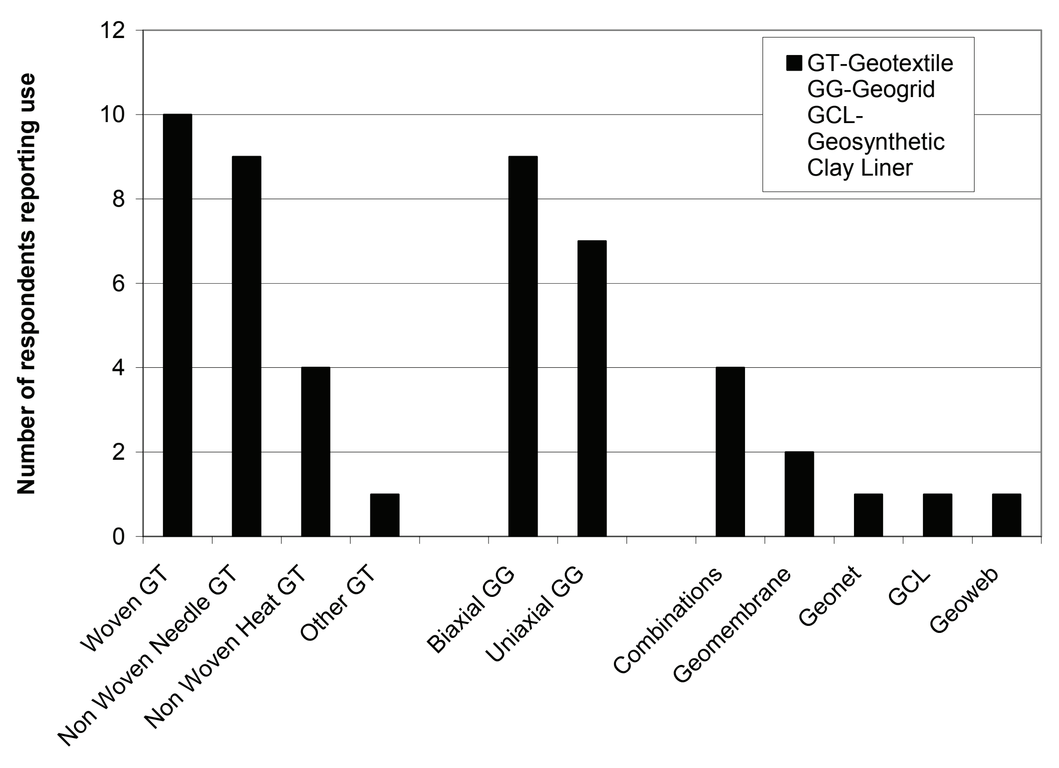

Figure 4. Graph. Types of Geosynthetics Used.

Geotextiles and geogrids are reportedly used by a majority of the respondents. Geogrid usage is a little surprising from a specifications standpoint, if not from the standpoint of available design guidelines, since these values are only covered by SCRs, and are not explicitly covered in FP-03. The "combinations" shown in Figure 4 are typically drainage geocomposites.

The majority of respondents (nine of 11) also noted that their agency does not have a pre-approved product list. A comment by one respondent noted that proprietary items are not specified unless a particular case justifies it, as is common for public agencies. One respondent thought that their agency did have such a list, however. The other respondent gave no answer.

Geosynthetic Approval and Selection

Figure 5 illustrates responses related to the product approval process. When asked how a product is approved, the majority (seven of 11) of respondents said certification letters by the manufacturer. Three respondents said research on products or methods eventually led to product approval. Interestingly, demonstration projects by the FHWA or a product's manufacturer were not cited as reasons for accepting a particular product. Likely, these types of projects are more instrumental in calibrating and developing design methodologies than directly affecting day-to-day design and construction practice.

When asked what information the respondents desire for selecting a particular geosynthetic, four indicated the need to be sure a particular geosynthetic was applicable to the required function. Two said more information on the geosynthetic's properties and cost. Three had no comment. One comment in particular captures one of the problems of using geosynthetics in practice:

> [I don't want to have] "…to provide a sales pitch to the project manager and construction people."

Thus, there appears to be either real or perceived resistance by construction personnel when it comes to using geosynthetics, which could be changed by additional education and training.

RESPONDENT EXPERIENCES IN PRACTICE

When asked if the available products and methods had yielded satisfactory results, six of 11 respondents gave their opinions. Some respondents noted good success with geosynthetics in deep patch, wall, separation and subgrade stabilization applications. Another reported construction cost and design savings. One respondent was more circumspect, saying:

"Assumed that in most cases geosynthetics are performing as required. Drainage problems, to my knowledge, have not been investigated sufficiently to determine if a geosynthetic application failed."

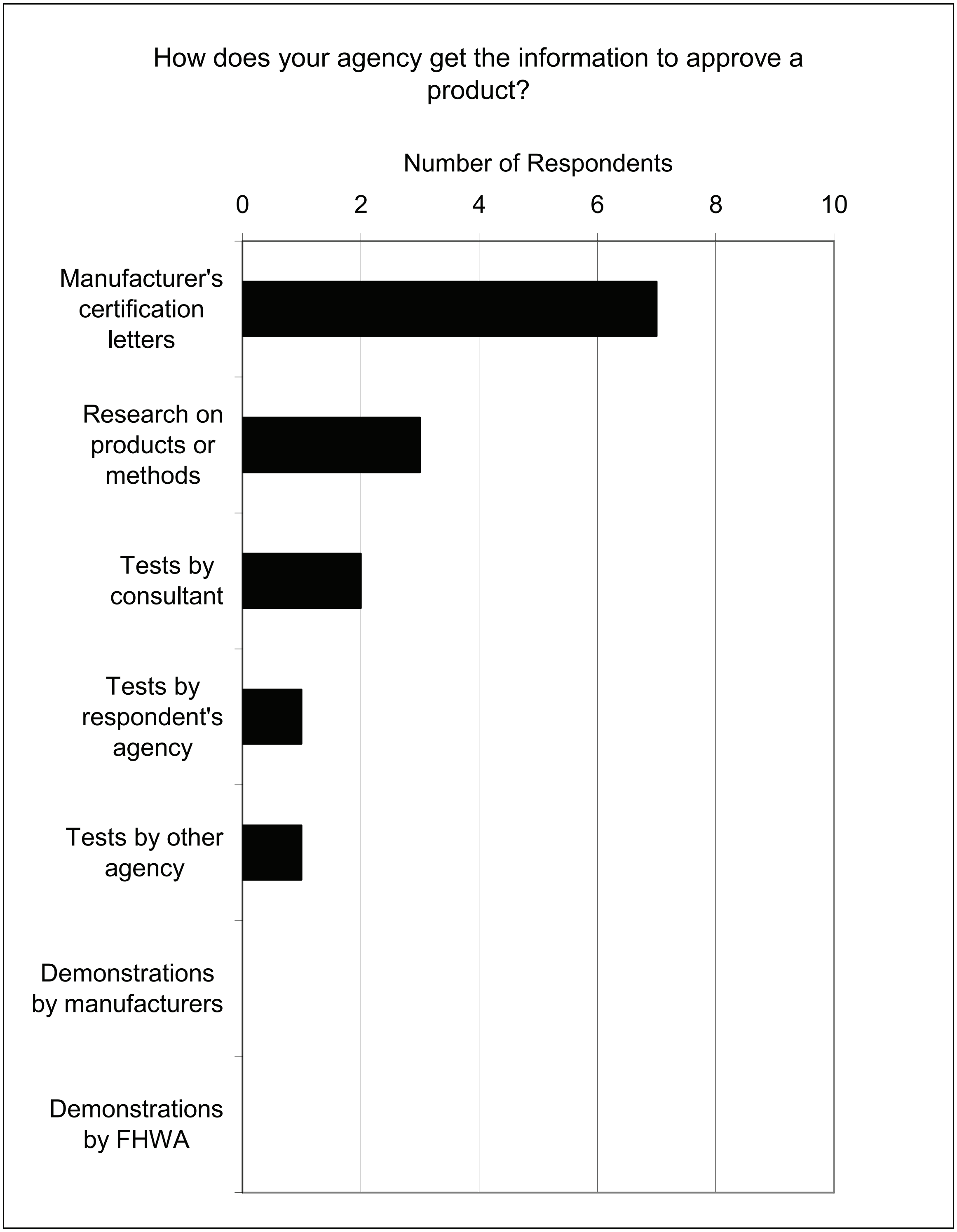

Figure 5. Graph. Information Sources for Product Approval.

When asked about unsuccessful experiences with geosynthetics, four respondents noted no problem, three had no comment and one had not had his geosynthetic projects constructed. One respondent reported unfavorable experiences for subgrade stabilization:

> "Using geosynthetics to bridge a poor soil has lead to poor results from my experience. The geosynthetic used did not bridge the poor soil, but instead, conformed to the poor soil and imbedded (sic) making the material useless."

Another respondent noted "limited results with paving geotextiles." However, in that case, the reasons for the problems were not known to the respondent. Another respondent described a project that began unsuccessfully because a contractor was not experienced installing a particular geosynthetic. Those problems were reportedly overcome, however.

CHALLENGES AND PERCEIVED BARRIERS

When asked what other challenges they felt their agency faced in using geosynthetics, respondents gave a variety of answers. One respondent felt having inspectors and contractors with enough experience to be comfortable using geosynthetics in the field was important. Another noted that knowing what products exist for application to a particularly difficult problem was a frustration, especially in erosion control applications. Some respondents also noted that the guidance for paved and unpaved roads is not consistent, and that the lack of understanding of geosynthetics function and lack of performance data are hindering further acceptance. Another noted that the height of the covering material for roadway applications and acceptance of project managers are also problems.

When asked to identify why geosynthetics are not used on a project, the most common response involved the lack of long term performance information. Figure 6 summarizes the other responses. A lack of design guidelines and a lack of awareness of applicability of geosynthetics to a particular situation were cited by five respondents as a hindrance. Surprisingly, not having prior experience with the materials and documentation in the standards was cited the least, with three respondents each.

In spite of these challenges, the respondents were still relatively optimistic about the future of geosynthetics. When asked if they thought geosynthetics had potential to offer substantial savings to the FLH Program, three of 11 strongly agreed, and five of 11 agreed. Three expressed neutral feelings.

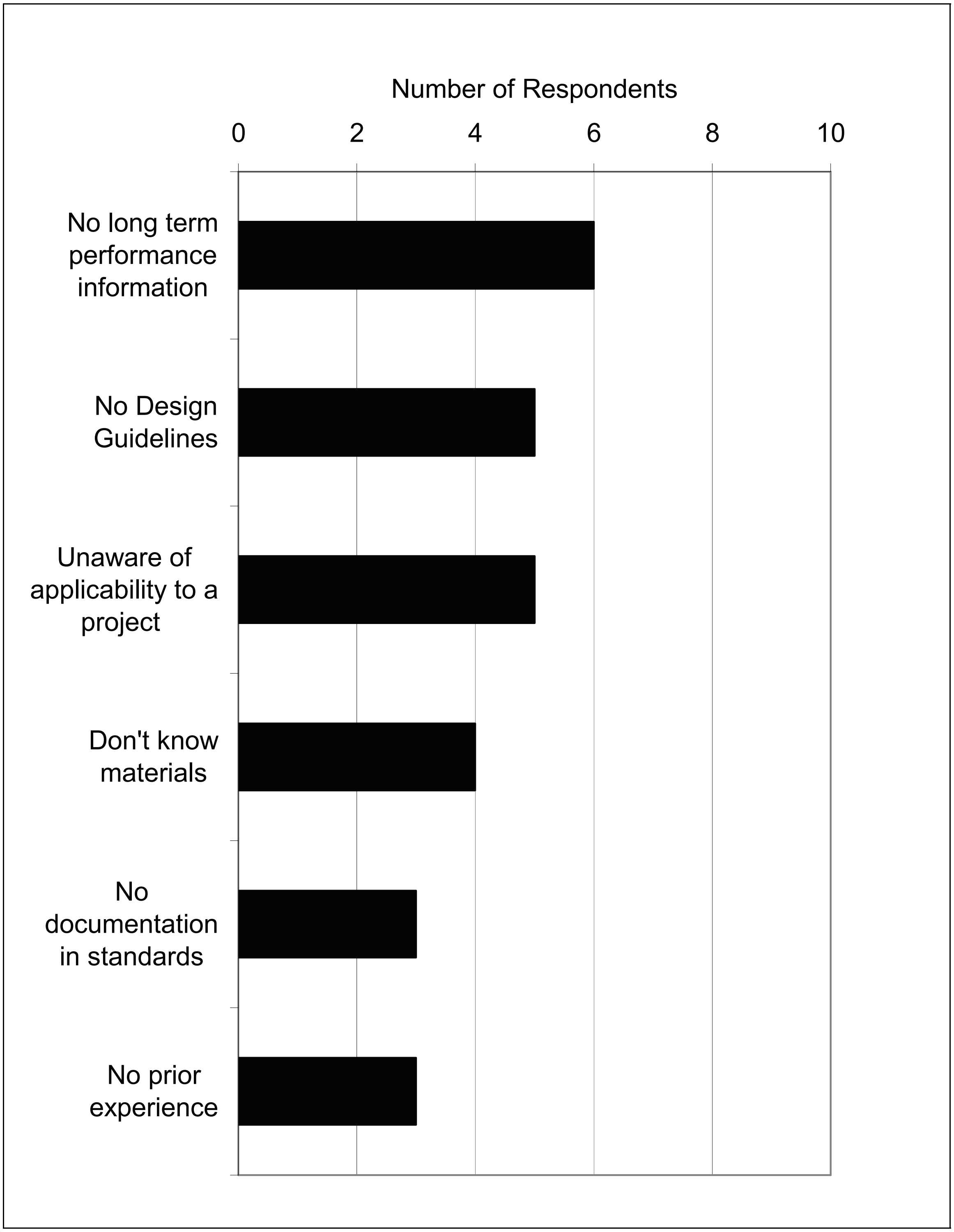

Figure 6. Graph. Reasons for Not Using Geosynthetics.

SUMMARY

In summary, it would appear the use of geosynthetics is gaining acceptance for FLHD applications and the implementation of geosynthetics in various projects is occurring. There are a number of applications where FHWA studies, publications and AASHTO guidelines have helped in this endeavor. These include MSE and reinforced earth structures, filtration applications and subgrade stabilization. Other applications seem to lag behind, due to the lack of well documented design approaches and field long term performance. These include frost heave mitigation, pavement overlays, and shallow foundation reinforcement.

In the next few chapters, each general application will be looked at in details, reviewing briefly the national guidelines identified in Chapter 2, assessing the level of maturity of an application and identifying emerging trends and recent advances in literature and practice. In addition suggestions as to where the gaps in knowledge and in practice may be for each application will be provided.

CHAPTER 4 – WALLS AND SLOPES

MSE WALLS

MSE walls have been used in public and private projects for at least three decades. Lateral stability and tensile capacity are added to compacted backfill soils by inclusions made of metallic or polymeric strips, grids, and sheets, as shown in Figure 7. MSE walls are more flexible than gravity walls, and they are often more cost effective if adequate space behind the wall is available for development of tensile reinforcement forces.

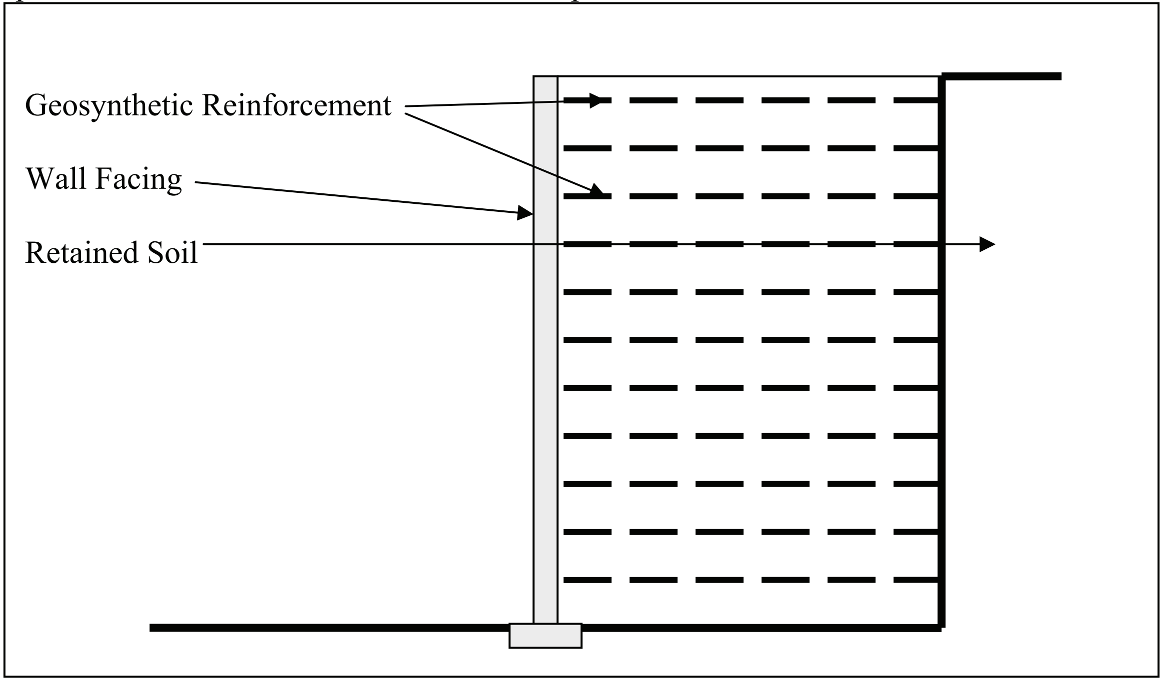

Figure 7. Diagram. Conceptual geometry for MSE wall (after Elias et al., 2001)

Summary of National Guidelines

Elias et al. (2001) summarized the FHWA's design methodology, considering three main analysis types for internal and external stability and an approach to estimate deformations. The methods outlined allow the user to determine length, spacing and required strength of the geosynthetic reinforcement, and assumes linear and bilinear failure surfaces to determine the required reinforcement tensile strength. The FHWA has sponsored development of specific software, MSEW, (ADAMA Engineering, Inc. 2006) that facilitates design. The FHWA design methodology is consistent with AASHTO (2002).

Seven of 11 survey respondents reported involvement in both unreinforced retaining walls and MSE walls. For unreinforced retaining walls, five of the seven respondents said they had considered or used geosynthetics, likely in drainage, filtration or separation applications. For MSE walls, six of the seven respondents noted geosynthetics were used.

Level of Maturity

Mature. The design and construction of MSE walls has become relatively common around the world. The national design procedures are quite robust, and commercial, FHWA-sponsored software is readily available.

Recent Advances

Design

Christopher et al. (2005) summarized MSE wall design and construction practice in the United States, reviewing the three main methods of analysis used in design: earth pressure, limit equilibrium and continuum mechanics. Earth pressure techniques are currently used in the FHWA design methods to calculate reinforcement tensile forces, while limit equilibrium methods address global stability. Christopher et al. (2005) note that the move to LRFD methods may push U.S. design practice toward more rigorous limit equilibrium methods that require more than moment equilibrium, and may also lead to acceptance of the K-stiffness method proposed by Bathurst et al. (2003).

Bathurst et al. (2003) concluded from a study of 20 geosynthetic MSE wall case histories reported in Allen et al. (2002) that AASHTO design methods result in between 1.5 and 4 times more geosynthetic reinforcement than needed. To reduce this conservatism, Bathurst et al. (2003) considered both failure of the geosynthetic reinforcement by rupture and by failure in the backfill soil, which led to the so-called K-stiffness method, an empirically-based design method that was calibrated using measured reinforcement strains from full scale walls. The method calculates the maximum working tensile load per length of reinforcement based on the shear strength and unit weight of the backfill soil, the area within the wall contributing to the force, and a series of empirical parameters calculated using methods developed by Bathurst et al. (2003).

Allen (2006) presented some results of a monitoring and construction project of an instrumented MSE wall designed using the K-stiffness method. The predicted strains in the reinforcement and resulting horizontal deformations of the wall were conservatively predicted by the K-stiffness method. Allen estimated that use of the K-stiffness method for this wall saved $62,000 in additional geogrid cost compared to an AASHTO design.

Backfill Material

Considering other advances, Christopher et al. (2005) also note the disconnect between public and private practice regarding backfill material. Most designs for public works restrict fines content in the backfill to less than 15%, while private MSE wall projects have seen fines content of 35% or higher. An ongoing NCHRP study, No. 24-22, is scheduled to be completed in 2007 and is investigating the applicability of current design methods to soils containing a higher fine content. This latter point is crucial, since most existing design methodologies, including the K-stiffness method described above, were calibrated using soils with low fines content.

Some geosynthetics manufacturers are also developing products that provide both reinforcement and drainage. Jones (2005) summarizes work in Europe to integrate reinforcement and drainage functions into a single geosynthetic product. Domestically, a similar product was installed at the Salmon/Lost Trail project site in Idaho (Barrows and Lofgren, 1993).

Multi-Tiered and Other Walls

A few researchers have considered design methods for multi-tiered MSE walls. The FHWA recommendations in Elias et al. (2001) include analysis methods for up to two tiers. Wright (2005) proposes a method of preliminary design for multiple tiers that considers the global stability of the entire wall system. Oversimplifying, Wright's process involves constructing a series of MSE walls on top of one another, rather than two independent wall systems as discussed in Elias et al. (2001). Wright (2005)'s observations resulted from analyses and construction methods in use by the Texas DOT.

Leshchinsky and Han (2004) performed a series of numerical studies, looking at whether existing software could adequately predict a factor of safety for multi-tiered walls. They used the limit equilibrium software program ReSSA (Adama Engineering, Inc. 2006) and compared it to the continuum mechanics-based numerical program FLAC (Itasca Consulting Group, 2005). They performed a parametric study considering a wide range of parameters, including water level, reinforcement length, quality of backfill and others, comparing calculated factors of safety and critical failure surfaces from both methods. They concluded the more user-friendly limit equilibrium methods provided similar results to the FLAC results in most cases.

MSE walls have also been combined with soil nail walls to widen and improve a roadway as well as control an area of landslides in Wyoming. Turner and Jensen (2005) describe the construction and monitoring efforts of a slide mitigation and roadway improvement plan that included stabilizing the existing roadway with tiered soil nail walls. The soil nail walls were instrumented to determine the loads carried during construction of the MSE wall, which was built to widen the road's shoulder. The Turner and Jensen (2005)'s main focus was on the performance of the upper soil nail wall, which had a temporary facing that would ultimately be covered by the reinforced earth.

FLHD sponsored a study by Morrison et al. (2006) to develop a design procedure for shored mechanically stabilized earth (SMSE) wall systems. The system considered in this study incorporates contributions from both a soil nail wall for shoring a cut slope and an MSE wall and is shown conceptually in Figure 8. The shoring system in these cases should be designed as a permanent structure, such that lateral forces applied to the MSE wall system are reduced. The study looked at centrifuge and numerical models, as well as an instrumented field test to develop the recommendations. The report suggested a design procedure for the MSE wall component, with design and construction considerations for the shoring system also included.

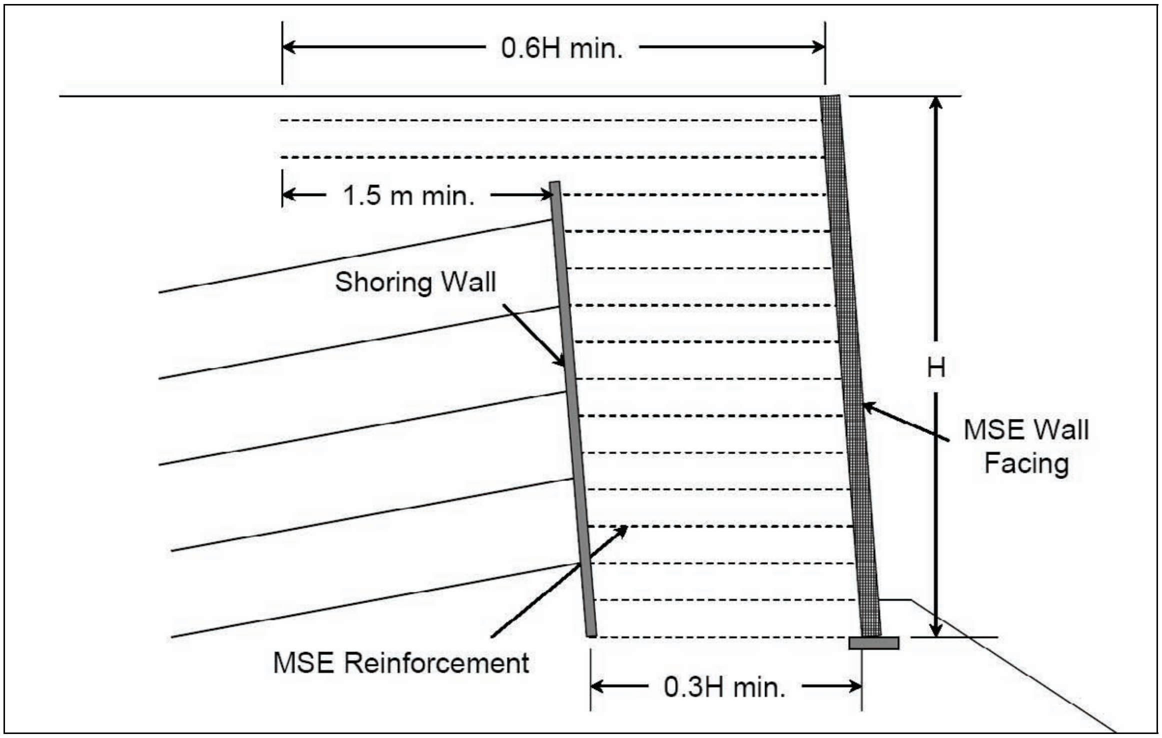

Figure 8. Diagram. Conceptual geometry for SMSE wall (Morrison et al. 2006).

FHWA Durability Studies

Creep deformations have also received attention in the literature. Bueno et al. (2005) review the effects of confinement on the amount of creep experienced by non-woven geotextiles, as well as providing plots of creep vs. log time. Crouse and Wu (2003) also provide a survey of seven monitored MSE wall sites. They observed that the rate of creep in these walls tended to decrease with time, and that deformations due to creep in a wall should therefore slow or diminish with the decreasing creep rate. Allen and Bathurst (2002) make similar observations in their work, also noting that stress relaxation will tend to increase with time.

Gaps in Our Knowledge

Further development of the K-stiffness method and some work towards its validation is already underway in a National Cooperative Highway Research Program (NCHRP) study scheduled to be completed in 2007 (TRB, 2005). This study is focused on application of the method to lower quality backfills (silts and silty sands), as well as building field scale walls for more verification studies. These objectives are necessary for implementation into the AASHTO LRFD Bridge design specifications.

Because the current load and resistance factors for AASHTO LRFD Bridge design specifications (AASHTO 2006) are calibrated to match the factors of safety used in the previous ASD specifications (AASHTO 2002), there are significant gaps in the knowledge of resistance factors for geosynthetic and steel reinforcement. These resistance factor values can only be refined through a statistically significant number of carefully observed case studies, comparing calculated loads to actual measured loads. The vertical earth pressure load factor for MSE walls was developed assuming no inclusions were present. This value, too, should be refined specifically for MSE walls.

Deformation analysis of MSE walls is still quite difficult to perform, and is often assumed to be adequate if specified factors of safety are met (Elias et al., 2001). Vertical deformations are currently based on foundation or embankment settlement methods. An improved method to estimate deformations (either numerically or empirically) would be useful.

The AASHTO LRFD design specifications (AASHTO 2006) note one deficiency in MSE wall design: erosion control. Walls designed near areas where high stream velocities or high piping or seepage forces could occur may be susceptible to damage. In these cases, the soils behind the wall can migrate out into the stream, reducing the soil available to hold up the wall and possibly causing large deformations or collapse. Use of MSE walls in this environment is not recommended.

Currently, design of more complex, multi-tiered wall systems has been largely numerical. Very few published studies have looked at the applicability and safety margins involved in the numerical and theoretical studies proposed in the previous section. As walls get taller and larger, such design methodologies may become more necessary.

SLOPES

Reinforced soil slopes (RSS) are most often specified when highway construction requires a fill slope to be steeper than 1V:2H. In these cases, the new slope is constructed with lifts of compacted backfill and geosynthetic reinforcement. In many ways, RSS are similar to MSE walls, although traditionally MSE walls are defined as having face angles of 0 to 20 degrees from the vertical; slopes tend to have an angle greater than 20 degrees (typical slope angles 45-60 degrees). A conceptual drawing of a reinforced slope is shown in Figure 9.

Short Review of National Guidelines

Elias et al. (2001) discussed design and construction considerations for steepened, reinforced soil slopes. The design method for RSS involves calculating a minimum factor of safety for the slope, with and without reinforcement, for a series of possible failure surfaces. Once reinforcement tensile strength, layer spacing, external and internal stability have been calculated, the engineer must also consider the effects of water infiltration and hydrostatic forces from groundwater, the interaction between the *in situ* and backfill soil, and stabilization of the outer face with either vegetation or something stiffer.

The FHWA has sponsored development of specific software, *ReSSA*, (ADAMA Engineering, Inc. 2006) following FHWA guidelines (Elias et al., 2001) that facilitates design. Other reinforced slope stability programs are commercially available. However, the assumptions used within these other programs may vary from those recommended by FHWA and/or used in the ReSSA program. The use of the ReSSA program is recommended to maintain a consistency in design and equitable bidding environment.

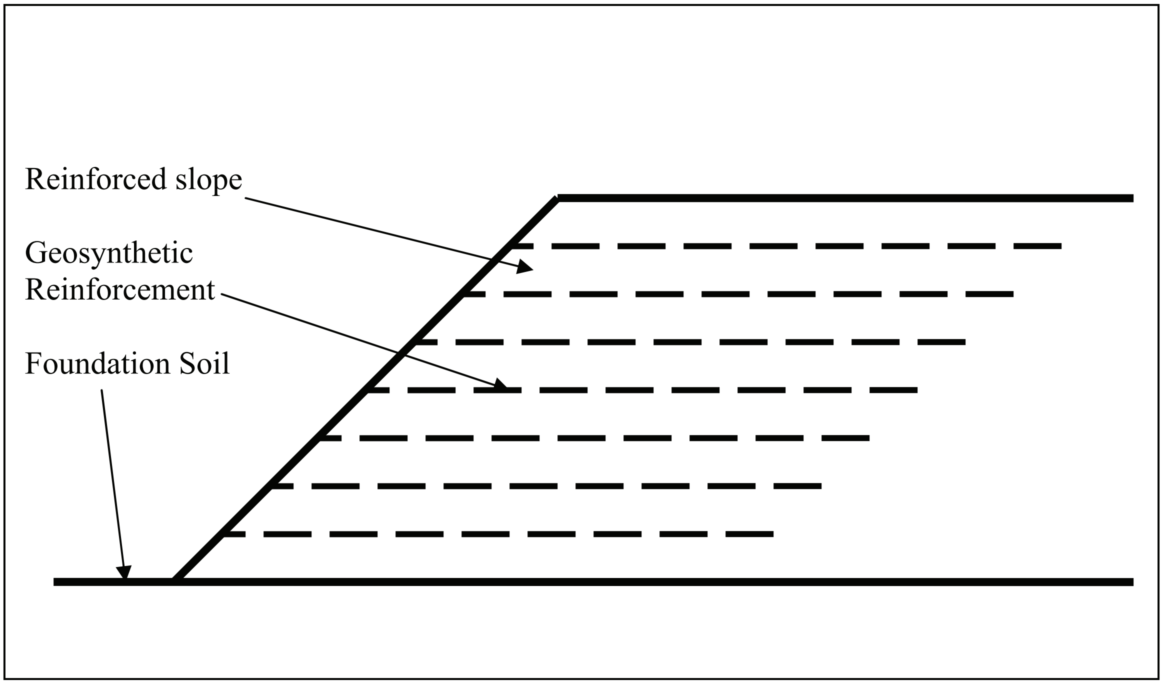

Figure 9. Schematic. Conceptual Reinforced Soil Slope (after Elias et al., 2001 and Koerner, 1998)

One decision the designer must make is the angle at which the reinforcement will deform at the failure surface. The angle of the reinforcement at the failure surface may vary from horizontal to tangent to the failure surface. The most conservative solution occurs when the reinforcement is assumed to be horizontal. Recommendations for selecting an angle to use in the design are not explicitly available.

Level of Maturity

Mature. In many ways, the distinction between constructed slopes and walls is largely a matter of face steepness. That said, reinforced soil slopes and design methods have been in use for many years. However, the maturity of face treatment (a critical element in performance/maintenance) is more localized and varies.

Recent Advances

Recent advances in reinforced soil slopes can be divided into two categories. First, are constructed or steepened slopes, which are the most common type of reinforced slopes. Second, are stabilized natural slopes, where minimal change is made to the face of the slope, but other actions are taken to keep the slope from deteriorating.

Steepened or Constructed Slopes

Christopher et al. (2005) notes the increase in continuum mechanics type analyses for slopes, and the infiltration of these methods into practice. Finite element and finite difference analyses are not limited in the shapes of failure surfaces they can analyze; the plane of lowest shear strength develops "naturally" under a particular loading condition. The problem with these types of analysis is the extent of soil properties required to create the model—while these values can be obtained, they typically are not regularly measured in current practice.

Jones (2005) reports on usage of different design methodologies in Europe. Instead of a method looking at equilibrium of vertical slices, the method presented by Shahgholi et al. (2001) considers horizontal slices. This method, however, is still under development.

Seismic design and performance of reinforced soil slopes has received some attention over the past decade (Ling et al. (1996), Ling et al. (1997), Ausilio et al. (2000), Lo Grasso et al. (2005).). Some methods are highly mathematical, while others are empirical. Nova-Roessig and Sitar (2006) performed centrifuge studies to investigate the seismic response of reinforced soil slopes. They observed that as the intensity of the simulated seismic event is increased, or as the density of the backfill is decreased, or as the stiffness of the reinforcement is decreased, deformations of the slope tended to increase.

Recent field performance and construction studies are described in Fannin (2001a) and Mendoca et al. (2003). In the former case, strains in the reinforcement and temperature in the backfill soils were monitored for three years, and a nonlinear change in force with time was observed. In the latter case, vertical and horizontal deformations, as well as reinforcement strain and earth pressure were measured at a number of points on the wall. Mendoca et al. (2003) observed that horizontal displacements stabilized rather quickly, and that the location along the length of an individual reinforcing layer and the magnitude of maximum strain in the reinforcement changed with time.

Zhang et al. (2003) performed a series of field tests on highway embankment slopes in Louisiana that exhibited signs of failure due to infiltration of water into tension cracks and subsequent saturation of the embankment soils. The slopes were constructed from high plasticity clays, and were rehabilitated using nonwoven geotextiles. They concluded that the nonwoven geotextile used in the study effectively repaired the failing slopes. The repairs were made by excavating a stepped surface for repair, then building the slope back up in lifts of approximately 250 to 300 mm (10 to 12 inches) in height. Based on this study, a very simple slope repair method (presumably using nonwoven geotextiles of similar properties) was suggested.

Finally, FHWA is reportedly developing an updated Slope Maintenance & Slide Restoration Workshop that will incorporate current geosynthetic stabilization techniques. This work is scheduled to be completed in 2007.

Stabilizing Existing Slopes

Anchored geosynthetic slopes are described as a stabilization method for existing saturated sand slopes by Ghiassian et al. (1997). In this case, an existing slope prone to erosion by wind or water is held into place by a geosynthetic that is tensioned by attachment to driven anchors. Depending on the type of geosynthetic chosen, there may be spaces for vegetation to grow, further reducing erosion potential. Mulch mats are described for slope stabilization by Ahn et al. (2002). These multilayered systems consist of a sandwich of seed and fertilizers between geotextiles and a layer of netting. The system reduces erosion and run-off and promotes plant growth over an exposed slope.

Vegetation plays a significant roll in the stability of the face of RSS systems. However, for very steep slopes, greater than 50 degrees; for clean sands and rounded gravel fills; and for silts and sandy silts, other facing systems may be required to provide stability at the face of the slope and protection from erosion. Some of the facing systems that may be considered when secondary reinforcement and vegetation alone are not sufficient are: gabions; geocells; geogrid wrapped face; soil-cement, bioreinforcement; wire baskets; stone and shotcrete. Table 8 (Collin, 1996) provides guidelines for selecting the facing system for various slope angles with different soil types. This table may be used during the preliminary design phase of an RSS system.

Gaps in Our Knowledge

National guidelines do not explicitly cover stabilization of natural slopes, or improvement of rock slopes. In these cases, where future landslides are likely, geosynthetic usage could still have some opportunity for growth. Geosynthetics in tandem with anchor bolts or rock bolts should continue to be considered.

Limit equilibrium methods are well established, although as Christopher et al. (2005) note, the movement toward LRFD may lead to greater usage of methods that satisfy all limit equilibria, not just moment equilibrium. Design schemes based on the results of rigorous finite element or finite difference methods are likely to also be proposed. In these cases, proven models for geosynthetic reinforcement materials and their interaction with the surrounding soils will be required.

DEEP PATCHES FOR SOFT SHOULDERS

This application was developed in the early 1990’s as a repair for USFS roads that had shown signs of cracking in the roadway or on the shoulder (see Powell et al., 1999). The cracks were most often noticed on older roads with lower traffic volume, particularly those constructed using a so-called sidecast method. In this method, a natural slope is cut to make the roadway, as shown conceptually in Figure 10. The cut material was then often placed uncompacted on the side of the slope to complete the full shoulder. Over time, water infiltration and other drainage issues led to slope stability problems, as shown by cracks and subsidence in the roadway, and the sidecast section sliding down the original slope.

Table 8. RSS Slope Facing Options (Collin, 1996).

Slope Face Angle and Soil Type	Type of Facing			
	Face not wrapped with geosynthetic		Face wrapped with geosynthetic	
	Vegetated Face	Hard Facing	Vegetated Face	Hard Facing
>50° All Soil Types	Not Recommended	Gabions	Sod Permanent Erosion Blanket w/ seed	Wire baskets Stone Shotcrete
35° to 50° Clean Sands Rounded Gravel	Not Recommended	Gabions Soil-Cement	Sod Permanent Erosion Blanket w/ seed	Wire baskets Stone Shotcrete
35° to 50° Silts Sandy Silts	Bioreinforcement	Gabions Soil-Cement Stone veneer	Sod Permanent Erosion Blanket w/ seed	Wire baskets Stone Shotcrete
35° to 50° Silty Sands Clayey Sands	Temporary or Permanent Erosion Blanket w/ seed or sod	Hard Facing not needed	Geosynthetic wrap not needed	Geosynthetic wrap not needed
25° to 35° All Soil Types	Temporary or Permanent Erosion Blanket w/ seed or sod	Hard Facing not needed	Geosynthetic wrap not needed	Geosynthetic wrap not needed

As a fix, a shallow excavation of a few feet deep is made in the roadway, and replaced by a compacted fill reinforced with one or more layers of geogrid, also shown in Figure 10. The geogrid must be embedded into the area within the natural slope to provide tensile resistance against the slopes movement. Often, a more robust drainage system and a waterproofing geosynthetic in the overlay layer are also added to prevent further water infiltration and slope stability issues (Musser and Denning, 2005). As of 2005, this application has been used in about 100 areas where roadways are failing, predominantly in the west coast states and Colorado.

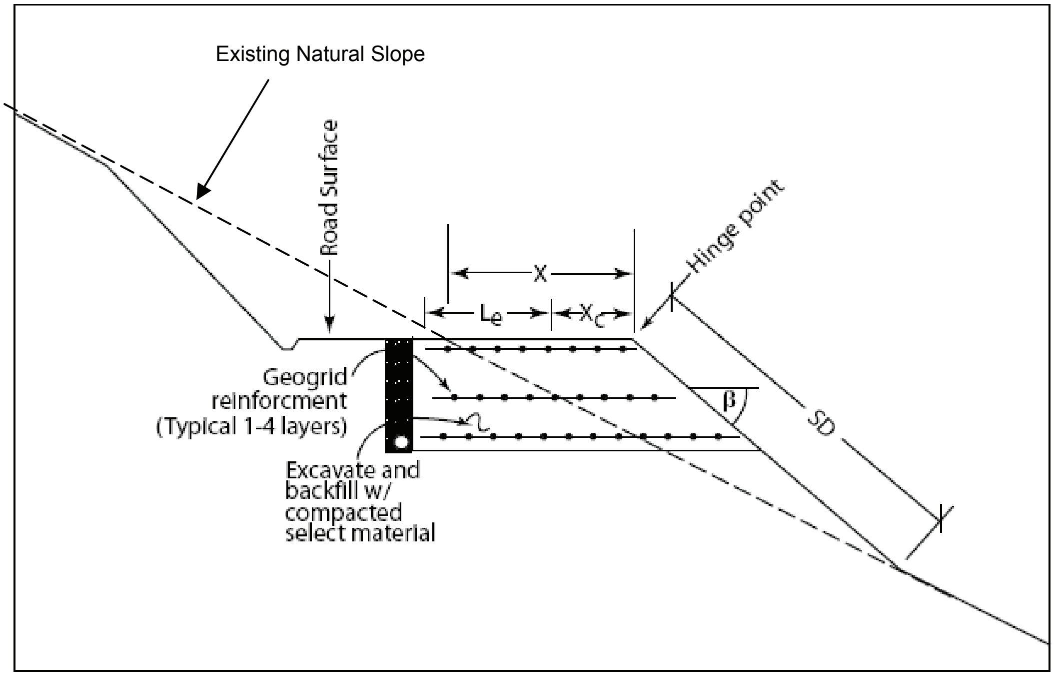

Figure 10. Diagram. Conceptual Geometry of Deep Patch Stabilized Shoulder (modified slightly from Musser and Denning, 2005).

Summary of National Guidelines

There is some documentation from the USFS governing the design of deep patches. The USFS has two design procedures available. The first was described in the FLHD's *Retaining Wall Design Guide* (Mohney, 1994). This method included a 0.9 m (3 ft) deep excavation stabilized with a single layer of geogrid. The geogrid's required strength was not specified, and the required embedment length (L_e in Figure 10) was set equal to the distance from the shoulder edge to the crack furthest from the edge (X_c in Figure 10).

Mohney's 1994 procedure was recently updated by Musser and Denning (2005) based apparently on a series of slope stability analyses. The results were a design method that included a partially solved slope stability problem that could be finished using a series of on-site soil parameters and problem geometry observations in tandem with a series of charts. The results of the analysis determine the required depth of the excavation and the allowable tension in the geogrid for a 1.5 m (5 ft) geogrid embedment length. Once the allowable tension is determined, the total number, depth, and spacing of geogrid layers are calculated. Musser and Denning (2005) also provide construction guidelines.

Based solely on Musser and Denning's guide, it is unclear how much verification using field observations was performed. That said, the method does appear to be a technical improvement over Mahoney's 1994 procedure, if only because it is more flexible concerning depth and geogrid selection.

Six of eleven survey respondents said they were both involved in a deep patch project and used geosynthetics. This would appear to indicate that there has been some penetration of the Mohney's methods described above.

Level of Maturity

Undeveloped to Developing. While a design method is available, there is still some need to standardize and validate the models for deeper patches. This application still requires monitoring of the long term efficacy of the repair and standardizing the design method for more complicated situations.

Recent Advances

Wu and Helwany (2001) created a "deep-patch test apparatus" to test the effects of the reinforcement used in the deep patch technique. This device allowed more or less full scale, plane strain tests. The apparatus allowed reinforced depth of over 2.1 m (7 ft) and a slope of approximately 1.2 to 1. The slope failure was modeled by creating a movable section that would drop out, mimicking movement of the soil below a portion of the patch due to a slide.

Wu and Helwany (2001) monitored the strain in the five embedded geotextile layers (geogrids are more typically used in practice). The benefits of the reinforced section were clear: in the reinforced section, minor localized cracking near the slope face was observed, while the unreinforced section showed near vertical cracks in the modeled shoulder. Other than Wu and Helwany's (2001) work, most of the advances in deep patch design and implementation appear to be occurring in the field but remain undocumented.

Gaps in Our Knowledge

Musser and Denning's (2005) design methodology does not include observed field comparison cases. Similarly, it does not include recommendations for steps to take or analysis procedures to use for more complicated situations. Thus, a wider scale search of past and present deep patch projects, with some possible instrumentation or long term monitoring are advisable. Reportedly, one project is already underway that looks at the history of deep patch repairs and monitors 10-15 existing and new deep patch sites for two years. These observations focus on rates of movement of the failing slope and propagation of cracks (FLHD CTIP, 2006).

SUMMARY

The use of geosynthetics in slopes and wall reinforcement has received considerable attention over the last few decades. The design methods are quite mature, and a number of successful case histories are available. MSE walls and reinforced soil slopes have become standard construction tools throughout the country, in both private and public projects. The deep patch method is also gaining acceptance, although the design methods in practice could use additional refinement and verification.

CHAPTER 5 – REINFORCED SOIL FOUNDATIONS

Base reinforcement of soils is the addition of one or more layers of geosynthetic underneath structures constructed on soft and/or yielding soil. Typical reinforcement projects include stabilizing embankments over soft soils, column supported embankments, shallow foundations constructed over reinforced soil, and bridging voids in the subsurface or roadway shoulders. The mechanism for soil improvement can be as simple as separating native soils from fills, or can include tension membrane, soil arching, and alteration of failure mechanisms.

EMBANKMENTS OVER SOFT SOILS

When geosynthetics are used to reinforce embankments to be constructed over soft soils, one or more layers of geotextiles or geogrids are placed between the native soil and the embankment fill, while additional layers may be placed within the embankment to provide separation and reinforcement. A conceptual drawing is shown in Figure 11. Properly designed geosynthetics then reduce the tendency of certain failure mechanisms to develop, including foundation instability and lateral sliding. Ultimately, the geosynthetics are in place to speed construction (i.e., eliminating staged construction) of the embankment and to allow greater embankment heights than would be possible in an unreinforced case.

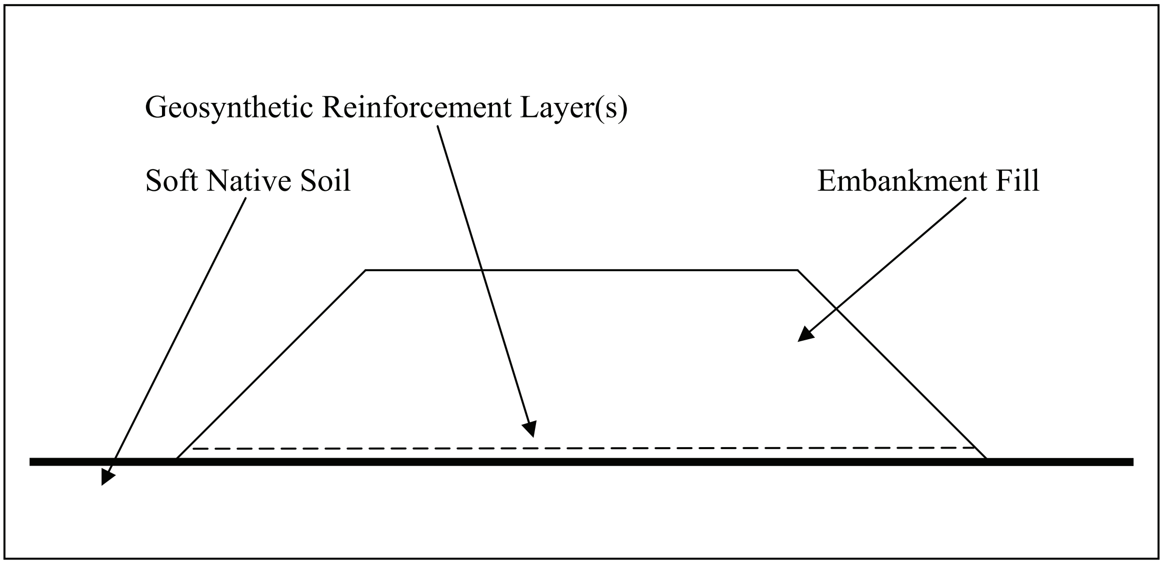

Figure 11. Diagram. Conceptual Geometry of Reinforced Embankments over Soft Soils (after Koerner 1998).

Summary of National Guidelines

Geosynthetics are used primarily for separation and reinforcement in this application. The national design guidelines in Holtz et al. (1998) provide methods to calculate required geosynthetic and fill thickness to create a stable working platform, which is often necessary to get construction equipment out onto the soft soil. The guidelines also provide a design methodology to evaluate the improvement to rotational stability and resistance to lateral spreading due to the presence of one or more geosynthetic layers. The overall bearing capacity of the foundation soil is not affected by the presence of reinforcement in this design methodology. However, the demand bearing capacity is reduced due to the distribution of the embankment load across the full width of the embankment. Lateral deformations are affected by the geosynthetic modulus; stiffer geosynthetics lead to less deformation due to lateral spreading. Rotational stability is improved through the tensile strength of the geosynthetic that adds to the resisting moment, in a manner similar to that described in Chapter 4 for reinforced soil slopes.

Seven of 11 respondents reported being involved in embankment design projects. Of those seven, five reported considering or using geosynthetics in an embankment project. As such, there appears to be some penetration of geosynthetics into an application in which a majority of respondents are involved.

Level of Maturity

Mature. These methods have been applied, with various extents,- to several embankments over nearly three decades.

Recent Advances

Gabr and Han (2005) summarized the current state of practice and suggested future enhancements to embankment design. Design methods commonly in use today were presented nearly 20 years ago, as for example the approach by Bonaparte and Christopher (1987). These limit equilibrium methods typically consider bearing capacity failure, lateral spread and deep seated, slope failures. A number of finite element studies have been performed to better understand reductions in deformation of the embankment with reinforcement (e.g. Varadarajan et al., 1999) and stresses in the underlying soil (e.g. Forsman et al., 1999). More recent studies (for example, Li and Rowe, 2001 and Sharma and Bolton, 2001) have looked at the combined effect of prefabricated vertical drains (PVDs) and geosynthetic reinforcement to expediently stabilize the embankment foundation.

Gaps in Our Knowledge

There are no prohibitive gaps perceived for this technology. Geosynthetics in separation and reinforcement functions have been used in embankment construction for more than two decades. The methods to estimate resistance to lateral spreading, overall global stability, and applied stresses as compared to the underlying soil's bearing capacity are well documented and accepted in practice. FLHP should not hesitate to implement and use this technology where economical.

COLUMN SUPPORTED EMBANKMENTS

Column supported embankments are usually constructed when a very soft soil overlies a significantly more competent one, such as a soft clay over dense sand. In these cases, driven piles, drilled piles or other soil improvement methods (vibrated concrete columns, rammed aggregate piers and deep mixed columns, for example) are used to transfer embankment loads to the more competent soil or rock layer, as schematically illustrated in Figure 12. Before the embankment is constructed, one or more layers of geosynthetics (perhaps embedded in a sand or aggregate backfill) are placed to create a load transfer platform (LTP). The LTP acts as a "beam" to transfer the embankment load away from the soft native soil, into the stiffer piles and into the more competent, deeper bearing layer.

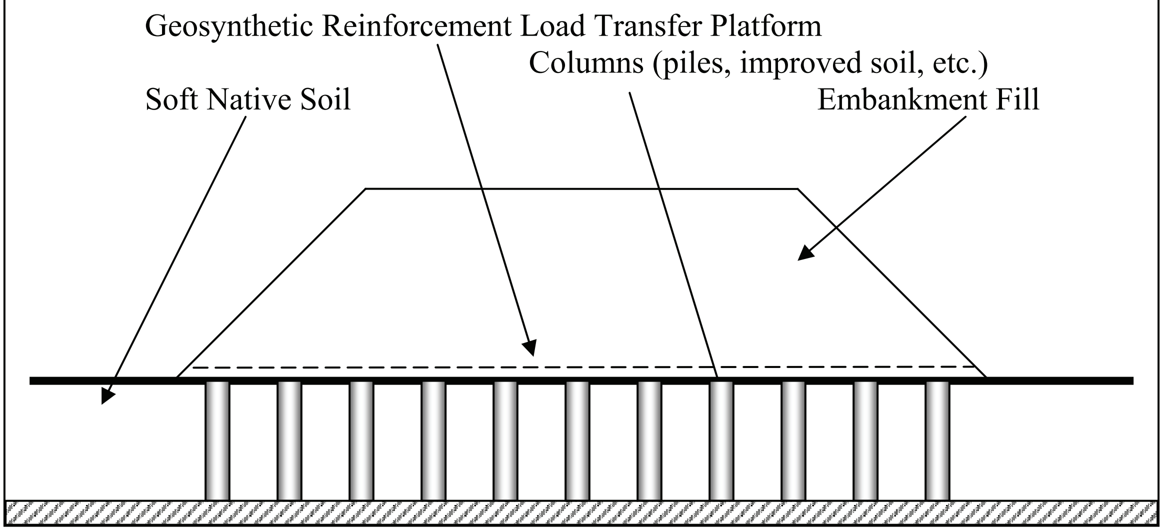

Figure 12. Diagram. Conceptual geometry for column supported embankment (after Elias et al., 2004)

Summary of National Guidelines

The national design guidelines provided in Elias et al. (2004) reviews various techniques to account for the geosynthetic reinforcement between the column-improved native soil and the embankment fill. Current design methods of the geosynthetic load transfer platforms treat the composite soil-geosynthetic section as either a catenary or a beam. Catenary theory assumes that a single layer of reinforcement is deformed and soil arches form in the embankment soil. Beam theory (the Collin Method), assumes three or more layers of reinforcement spaced vertically 0.2 to 0.45 m (8 to 18 in) apart and that the platform is at least ½ the thickness of the span between the columns. The arching that develops in the load transfer platform (beam method) is a function of the strength and confining behavior of the geosynthetic. In both the beam and catenary theory, the geosynthetic layer(s) must develop tension to withstand the weight of the soil (either embankment fill or load transfer fill for catenary and beam formulations, respectively). Design considerations for column design, lateral spreading, and global stability are similar to those discussed elsewhere.

Level of Maturity

Developing. To some extent, this is an extension of reinforced embankments over soft soils, but recent and ongoing studies are attempting to calibrate and improve the methods outlined in Elias et al. (2004).

Recent Advances

Gabr and Han (2005) surveyed the state of column-supported embankment design. They noted that geosynthetics used in the single or lowest layer of the platform are typically high-strength geotextiles or geogrids, which allows the geosynthetics to be considered as a tensioned membrane. Multiple layers embedded in the earth platform can be of lower strength, such that the resulting system can be considered as if it were a beam (Collin, 2003). As the distributed embankment load is applied on top, the bottom of the beam can have some tensile resistance that will lead to redistribution and attenuation of the applied stresses.

Design models currently attempt to estimate the stresses applied to the geosynthetic layers based on a soil arching mechanism, then estimate the required tensile resistance in the geosynthetic layers based on tensile strain properties and membrane theory. Gabr and Han (2005) summarized the available approaches for both single- and multi-layer geosynthetic systems, as does Munfakh et al. (2001) in a manner similar to shallow foundations overlying geosynthetic reinforced soils.

A number of two and three dimensional numerical models have also been developed to determine the stresses and required tensile properties of the geosynthetics (Huang et al., 2005, Han and Gabr, 2002 and Pham et al., 2004). For single layer systems, the maximum tensile stresses in the geosynthetic are predicted at the edge of the columns, which is unexpected based on tension membrane theory alone. Han and Gabr (2002) also noted that stress concentration and maximum tensile stresses are affected by the stiffness of the geosynthetic in tension and the stiffness of the column material. For multiple layered systems, the maximum tensile stresses occur near the center of the span in the bottom layer, but closer to the edges of the columns in the top layer.

Column-supported embankments for roadway applications have been constructed and reported in other recent literature. These include Mankbadi et al. (2004), Stewart et al. (2004), and Collin et al. (2005). Whyte (2005) also summarizes a number of European roadway embankment projects. A number of full scale projects have been funded or built in recent years by the FHWA and other organizations, such as Stewart et al. (2004) and “Geosynthetic Reinforced Column Supported Embankments” which began as an FHWA

Pooled Fund project in September 2003 and was scheduled to be complete in the summer of 2006.

Gaps in Our Knowledge

There is no current guidance or overwhelming field verification regarding which of the four design methods to use when designing the load transfer platform. All four methods consider the geosynthetic's strength only. The confinement benefit from the geosynthetic on the granular LTP material (if applicable for a particular grid or textile product) are not addressed in the design method. Similarly, a geosynthetic's confinement properties are not currently defined by a measurable, accepted quantity.

Gabr and Han (2005) suggest some directions for further study. The current design methods should be validated by full scale, well instrumented field measurements investigating strains in the geosynthetic, deformation characteristics, and stress distribution between column and native soil. Han et al. (2005) is an example of such field testing, combined with calibration of a numerical model. This type of validation may also be partly satisfied by ongoing studies.

Soil arching models currently employed assume rigid supports at the columns. The mechanism of load transfer from the LTP to the columns is not well understood when non-rigid columns are used. This is an area that requires further study. Similarly, the current design methods do not allow the designer to estimate total and differential settlements. Finally, the effect of soil resistance between the native soil and the geosynthetics layer and the effect of geosynthetics creep within the formed earth beam are also poorly understood.

To properly apply tensioned membrane theory, enough strain must develop in the geosynthetic to result in some tension. As a result, there will be some displacement that occurs to generate this strain. This deformation typically occurs during placement and compaction of the embankment fill.

SHALLOW FOUNDATIONS

Shallow foundations can be constructed on soils that have been replaced and reinforced with one or more layers of geosynthetics with the objective of reducing the size of over-excavation, as shown conceptually in Figure 13. When built atop reinforced soils, the bearing capacity or stiffness of the new system is expected to be greater than the unreinforced case.

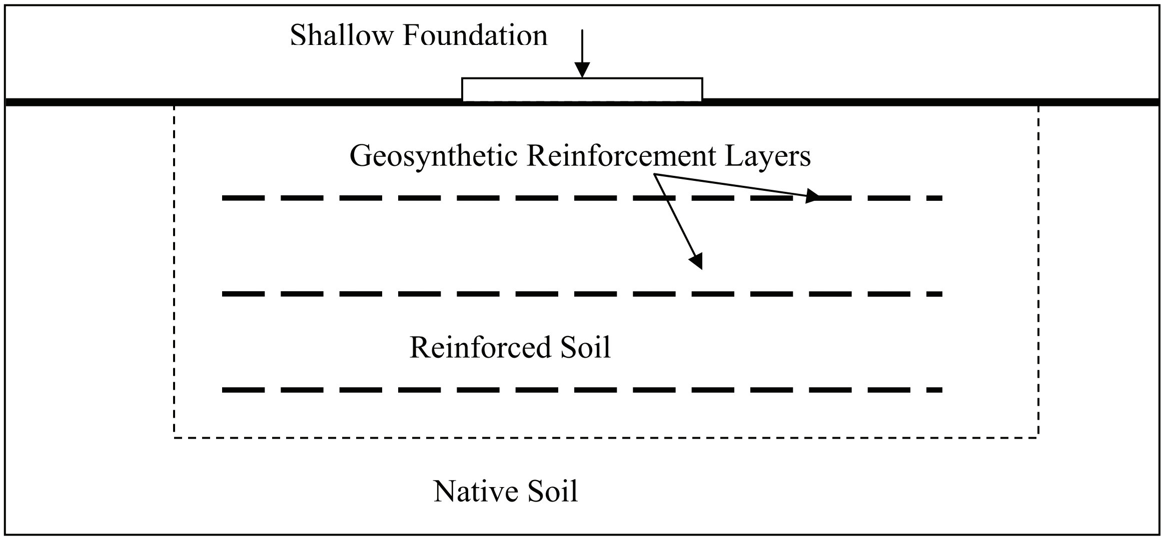

Figure 13. Diagram. Conceptual Geometry for Reinforced Shallow Foundation (after Das, 1995 and Munfakh et al., 2001).

Summary of National Guidelines

Munfakh et al. (2001) briefly discusses base reinforcement with multiple layers of geosynthetic. The manual generally recommends maximum spacing between reinforcement layers, maximum depth of the first layer of reinforcement below the footing, and the minimum width of the reinforcement relative to the width of the footing. The recommendations presented by Munfakh et al. are based on the work by Adams and Collin (1997). The Westergaard method, using a ratio of reinforced to unreinforced elastic soil modulus of 10 is recommended to estimate the reduced vertical stress distribution that is used to calculate settlement of the reinforced section.

Despite a relative lack of guidance on how to determine the amount and spacing of reinforcement in this application, four of eleven survey respondents said they had designed shallow foundations over reinforced soil. This may be a shallow foundation over an existing MSE wall or other improved wall technology.

Level of Maturity

Undeveloped. There are the beginnings of design methods that can be applied in practice for both bearing capacity and settlement, but these are largely uncalibrated.

Recent Advances

Reinforcement of fill or natural soils with geosynthetics beneath shallow foundations has been explored for nearly two decades, after the pioneering soil reinforcement work of Binquet and Lee (1975a and 1975b). Das (1995) summarized results of predominantly small model strip or square footings in test boxes filled with sand or clay. This work has identified, for the situations tested, a series of bounds on reinforcement spacing, number of reinforcing layers, total reinforced depth and reinforcement width. That is, they have identified dimensions relative to the width of the footing where no additional benefit is gained. These tests seem to suffer from unknown scale effects, as explained in Michalowski (2004), and it is unclear whether the findings are general enough to apply to other soils.

Adams and Collin (1997) performed the first (and to this date only) prototype scale tests on square footings. This work was sponsored by the FHWA, and was performed at Turner-Fairbank Highway Research Center in a large test pit filled with sands reinforced with geogrids and geocells. Their results seemed to confirm some of the relationships noted by Das and his colleagues, and showed an increase in bearing capacity could be obtained using reinforced soils.

In general, few design methods are available for determining the bearing capacity of shallow foundations. Huang and Menq (1997) suggested an empirical formula for reinforced soils after Schlosser et al.'s (1983) "deep footing" effect, where the reinforcement spreads the load with depth, such that the system can be modeled as a wider footing acting at the depth of the last reinforcement layer. The increase in footing width, ΔB, is estimated by Huang and Menq's method using Binquet and Lee's (1975a and b) lab scale testing results of soils reinforced with geosynthetics, fibers, aluminum strips, etc. The same criticism of Das's work can be applied to this analysis.

Michalowski (2004) suggested a method to estimate the upper bound of bearing capacity for a reinforced soil mass based on failure surfaces determined by plasticity theory. His results were for strip footings only, and take a form similar to a typical bearing capacity equation. This method is promising, but still requires considerable calibration and refinement before it can be adopted for use in practice.

Gaps in Our Knowledge

Clearly, the development of a relatively simple design methodology for a shallow foundation on a reinforced soil mass is important for state-of-practice implementation. Testing on a wider range of soils with either geogrids or geotextiles seems imperative, as do a wider range of instrumented full scale tests on different footing shapes. Current methods also do not quantify how to determine the optimum size and spacing of geosynthetic reinforcement.

In most cases, bearing capacity does not control shallow foundation design. Some work has been done to calibrate measured strains in large scale laboratory tests to existing settlement calculations. This must be considered for a wider range of geosynthetics to verify the assumptions of the elastic modulus increase, and for a variety of spacings.

Finally, the economics of reinforced soils should be addressed. Unless the footing is being placed over a soil reinforced for an MSE wall or other RSS structure (another possible avenue of inquiry), the construction of the reinforcement zone requires excavation of an area to a depth where the attenuated stresses do not exceed the subgrade strength. When adding in the cost of geosynthetics and backfilling with competent material, the cost of simply constructing a larger traditional footing must be considered. If the depth of excavation can be reduced, however, the shallow foundation on reinforced soils may be economical from a health and safety standpoint—shallower excavation could mean less bracing or excavation support required.

BRIDGING SUBSURFACE VOIDS

Geosynthetics have also been considered to mitigate possible settlement due to geologic discontinuities. In these cases, high strength geosynthetics are placed in areas where development of voids are feared, such as regions prone to sinkholes or where significant mining activities have occurred, as shown in Figure 14. The reinforcement is placed to bridge small and moderate sized voids by maintaining soil arching and to slow deformations to prevent collapse until the problem can be fixed for larger voids.

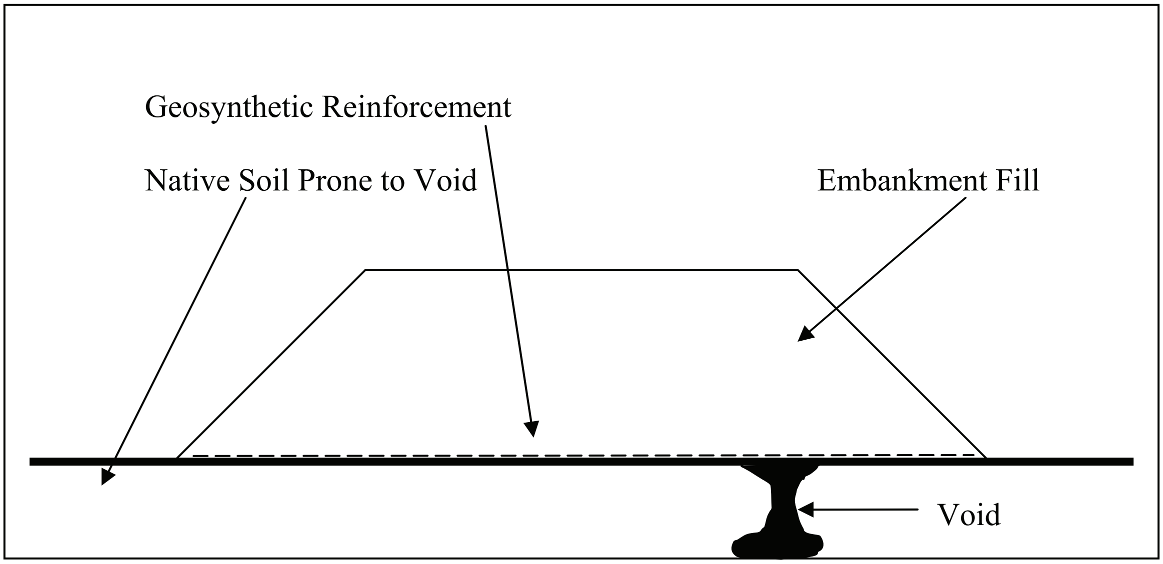

Figure 14. Diagram. Conceptual Geometry for Bridging Subsurface Voids

Summary of National Guidelines

Subsurface voids are mentioned tangentially in Holtz et al. (1998) during the embankment support section. No design method was found that addressed bridging of voids explicitly.

Level of Maturity

Undeveloped. On the national design level, no methods are currently recommended for bridging possible voids under roadways. While methods are in practice by other agencies globally, they have not been codified by AASHTO or FHWA. There may, however, be some implementation of this technology by state DOTs on a case by case basis.

Recent Advances

Recent developments for bridging subsurface voids, which could include geosynthetic reinforcement overlying a developing sinkhole, are summarized in Gabr and Han (2005). Giroud et al. (1990) suggested a model that includes pressure over an infinitely long or circular void due to arching followed by calculation of the required tension force using tensioned membrane theory. Giroud et al.'s (1990) method assumes the geosynthetic is located directly above the cavity, that the geosynthetic material's tension-strain behavior is isotropic, and that the approximation used to calculate strain in the geosynthetic over circular voids is acceptable. Drumm et al. (1990) suggested an empirical model to estimate the surface deformation due to deeper bedrock cavities such as mine voids.

Jones and Cooper (2005) reviewed the current British practice of roadway design over karst voids, which is codified in the British Standard 8006 (BSI 1995) and uses tensioned membrane theory without the addition of soil arching to determine the tension developed in the reinforcing geosynthetic. Jones and Cooper noted that this assumption results in a conservative, lower bound solution. Their parametric numerical model study concluded that differential deformation was most affected by the ratio of cover thickness to void diameter, followed by reinforcement stiffness. The numerical model indicated that reinforcement stiffness must be increased significantly to have any affect on surface deformation, and that multiple layers of geosynthetic ultimately have the same effect as a single layer of equivalent stiffness. However, these results could be a manifestation of how the reinforcement was modeled.

Gabr and Han (2005) noted that much of the work for spanning subsurface voids in the last five years has come out of Europe, where the interest is predominantly in the High Speed Rail industry. Villard et al (2000) performed a numerical and experimental study focusing on evaluating the contribution of arching and allowing the geosynthetic to reduce the vertical displacement over the void. For the high speed rail industry, the main purpose of geosynthetic reinforcement is to prevent catastrophic failure and to allow reduced speed service while construction repair activities are undertaken. In this regard, "smart geosynthetic" emerged as reinforcement layers with strain gage instrumentation. The strain in the reinforcement layers are monitored continuously to warn of impending sinkhole collapse or excessive settlement.

Gaps in Our Knowledge

No design or analysis method is available that adequately takes into account subsurface geologic discontinuities with various configurations. In this case, developing numerical models with robust representation of reinforcement to investigate anticipated deformation and efficacy of remedial measures, including geosynthetic mats, is needed. Similarly, advances in strain gage technology allow for real time monitoring of sinkhole prone areas—if an abrupt increase in geosynthetic strain is detected, a sinkhole may be forming and immediate remedial measures should be taken. For this to be the case, however, strain gage technology would have to be relatively inexpensive for wide coverage of suspect areas. This approach calls for installation of geosynthetic reinforcement over wide areas, since exact location of "future" geologic discontinuities is normally not known in advance. If FLHD were to consider this application, the geosynthetics should be considered a temporary reinforcement and warning system, not a permanent reinforcement solution.

SUMMARY

Reinforced soil foundations include embankments overlying soft soils, column supported embankments, reinforcement of soils beneath shallow foundations, and bridging subsurface voids. The use of geosynthetics in embankments overlying soft soils has been successful for many decades, and is a mature approach. Similarly, column supported embankments that include a geosynthetic reinforced load transfer platform are rapidly developing and have been field verified in both demonstration and actual projects. There is still significant work to be done before applications such as reinforcement of soils beneath shallow foundations and bridging subsurface voids can be recommended for widespread use. While some field scale projects have been completed, proven design methodologies are still needed before these two technologies can be widely used.

CHAPTER 6 – PAVED AND UNPAVED ROAD SECTIONS

This chapter summarizes the following applications in roadways:

- i. Reinforcement
  - a. Paved Roads: Unbound Layers and Subgrade
  - b. Paved Roads: Bound Layers
  - c. Permanent Unpaved Roads
  - d. Construction Platforms (Temporary Unpaved Roads)
- ii. Moisture Barriers
  - a. Frost Heave
  - b. Expansive Soils
- iii. Geosynthetic Clay Liners for Lining Drainage Channels

Perkins *et al.* (2005a) recently reviewed the state of practice in the United States (U.S.) regarding geosynthetic use in paving systems. Perkins *et al.* (2005a) summarized the current practices, recent developments and ongoing studies, then identified future needs for acceptance by the wider community. They divided their paper into three parts: reflective cracking, base reinforcement, and subgrade reinforcement.

Similarly, Watn *et al* (2005) reviewed the state of European practice. They looked at geosynthetics reinforcement usage in unbound and bound paving systems, then summarized recommendations and field studies. Both Perkins et al. (2005) and Watn et al. (2005) roughly separated their discussions into two categories: geosynthetics use in bound pavement layers and geosynthetics use in unbound pavement layers. Figure 15 graphically depicts where these layers are defined and the terminology used to define them.

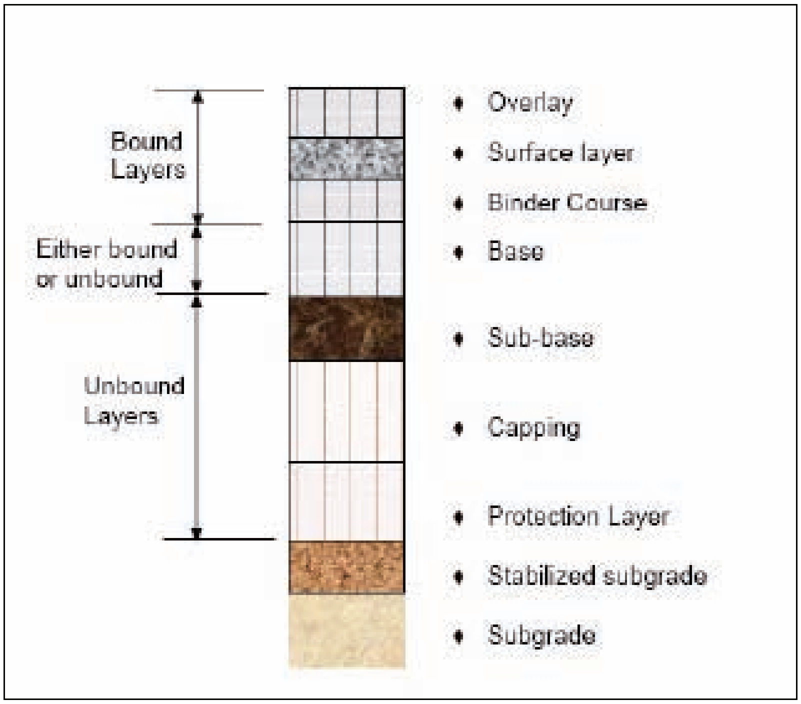

Figure 15. Schematic. Pavement Structure Terminology (after Watn *et al.,* 2005).

PAVED ROADS: UNBOUND LAYERS AND SUBGRADE

Summary of National Guidelines

AASHTO PP 46-01 (AASHTO 2001) provides guidelines for base course reinforcement by geosynthetics. It recommends following the procedures specified in Holtz et al. (1998) or the procedures from the GMA White Paper II (Berg et al., 2000). A brief description of both approaches follows.

Holtz et al. (1998) consider design methods for two types of roadways: temporary and permanent. In temporary roadway design (i.e. construction access roads, etc.), the engineer may assume the geosynthetic improves the drainage and keeps the subbase separated from the weaker native soil. This improvement is modeled by assuming an increased bearing capacity factor, which in turn reduces the required calculated thickness of the roadway. The increased bearing capacity necessitates that the assumed rut depth be large enough to mobilize this additional bearing capacity. In permanent applications, the above method can be used to reduce the thickness of any stabilizing layers, but it is assumed the reinforcement will not improve the bearing capacity of the structural layers, so no reduction in the design base course thickness is allowed. However, economies may be realized by reducing the aggregate required for stabilization and construction.

The U.S. Army Corps of Engineers (Tingle and Webster, 2003) specifies a method of design for subgrade and unpaved road reinforcement similar to that described in Holtz (1998). The bulk of these recommendations are based on the effect of geotextile separation and filtration on subgrade strength by Steward et al. (1977), although the design methodology has been expanded to include geogrids based on engineering judgment.

Berg et al. (2000) proposed a method for design of base course and subbase reinforcement based on the results of a number of field studies from literature. Base course reinforcement is quantified using three different factors: Base Course Reduction (BCR) to reduce the thickness of base courses, Traffic Benefit Ratio (TBR) to extend the life of the pavement and Layer Coefficient Ratio (LCR), which is used in some methods to match reinforced to unreinforced cross section performance by modifying the base course portion of the AASHTO structural number equation. Each factor depends on the type of reinforcement, aggregate, and design cross section for which it was calculated. Currently, however, the design approach has no mechanistic basis and the method suggests obtaining one of these ratios on the basis of lab tests that have been correlated to a field section for a particular reinforcement.

For subgrade restraint in permanent paved roads, Berg et al. (2000) recommend procedures outlined by other researchers to estimate subgrade thicknesses required to support construction activities. In these cases, the geosynthetic layer may act in one or more of the following functions: separation, filtration or reinforcement. Nine different possible design methods are listed, including the method described by Holtz et al. (1998). Seven of the remaining eight methods are for specific products calibrated by the product's manufacturer.

Berg et al. (2000) also discuss the separation and stabilization function of geotextiles in temporary and permanent roads. The geotextile acts to maintain distinct layers of base coarse and subbase materials. This prevents mixing, and at a minimum helps to ensure the designed layer thicknesses are maintained throughout the pavement's (unreinforced) design life. In many cases, the stabilization function is often primary for roadways with CBR greater than two or three.

The survey results in Chapter 3 showed that eight of 11 respondents had been involved in projects requiring subgrade reinforcement in paved roads, and that all eight also reported considering geosynthetic for these applications. Thus, there appears to be relatively strong interest in this application.

Level of Maturity

Developing. A number of studies have been performed, but a mechanistic, generic, design approach that includes geosynthetic layers has not been developed. The methods suggested by Berg et al. (2000) still require calibration through laboratory and field studies, combined with local experiences. The development should be with the framework of Mechanistic-Empirical methods advocated in the NCHRP project 1-37A, revised in 1-40A-D and implemented by the FHWA. There is however a gap in the pavement design guide on how to model the use of geosynthetics in pavement structural layers.

Most of the work regarding geosynthetics in a mechanistic-empirical approach is based on finite element results. There is a need however to systematically evaluate factors controlling the pavement response when geosynthetics reinforcement is used. Such approach should include the effects of key factors such as the optimum placement of geosynthetics, the impact of reinforcement grade and types of interfaces, and the thickness of pavement layers. A possible approach to such evaluation is to use the discrete element method (DEM). The DEM can be used to characterize pavement cracking due to strain localization, and plastic strain accumulation under cyclic loading.

Recent Advances

Unbound layers include both subgrade reinforcement and base or subbase reinforcement. The European practice described by Watn *et al.* (2005) mainly focused on the subgrade stabilization aspects, where geotextiles, geogrids and geocomposites are used to increase the bearing capacity of very soft soils. The thrust of the application is that the use of these geosynthetics reduces the pressure on the soft subgrade, and also tends to reduce deformation due to traffic or construction loading. Watn et al. (2005) observe the benefit of geosynthetic reinforcement tends to increase as the quality of the subgrade decreases or as the number of traffic loadings increase.

Perkins *et al.* (2005) also noted geosynthetics usage in the subbase to reduce deterioration and fatigue cracking due to dynamic loading. Perkins et al. (2005) stressed the importance of geosynthetics in subgrade reinforcement. This usage appears to be in practice in at least some USFS roadways, as discussed by Vischer (2003). In this case, geogrid reinforcement with a geotextile separator was used to rehabilitate a paved road over a soft subgrade. Al-Qadi and Appea (2003) also reported on an eight year study investigating the effects of geogrid and geotextile reinforcement placed between the base course and subgrade. They investigated three different base course thicknesses, and realized a measurable increase in service life and pavement quality only on the thinnest, 100 mm thick base course.

Al-Qadi's other work consisted of laboratory tests of pavement sections, some with geotextile or geogrid placed as reinforcement or as a separator over subbases with CBR ranging from two to six. (Al-Qadi et al. 1997). From this study and the ensuing field studies (Al-Qadi et al. 1998; Al-Qadi and Appea, 2003), with similar geotextile and subgrade soils, a curve was developed for design that showed the extension of service life in terms of Equivalent Single axle loads (ESALs) for a section with and without geotextile reinforcement (see also Al-Qadi, 2002). While the study did show the effectiveness of the geosynthetic in prolonging the life of a pavement before significant rutting occurred, clearly the relationship developed is dependent on the conditions represented in the field test section and the laboratory.

For subgrade stabilization, the Illinois DOT (IDOT, 2005) includes a short section on geosynthetic reinforcement of subgrade and base reinforcement. It includes a table suggesting reduced aggregate thicknesses for geotextile and geogrid -stabilized subgrade. This table should be used with caution (as is alluded to in the manual) as specific geosynthetic properties are not included with the recommendation. The manual also notes that combined separation-reinforcement action of geotextiles and geogrids have been investigated, but have generally not been cost effective in IDOT's experience.

The Washington State DOT is also currently involved in an ongoing monitoring effort for a number of roadways (Perkins *et al.*, 2005) where geosynthetics were used for subgrade stabilization. Similarly, the Wisconsin DOT has sponsored studies examining geosynthetics reinforcement of soft subgrades (Maxwell et al., 2005). From that study, it was concluded that platforms with geosynthetic reinforcement showed lower accumulated deformations than unreinforced platforms. Total deflections were always smaller for the reinforced sections compared to the unreinforced sections.

A finite element model including geosynthetics at the bottom of the unbound layer was described in Perkins and Edens (2002). The finite element mesh included models for the asphalt concrete layer, the unbound aggregate layer, the subgrade and a biaxial geosynthetic layer. This finite element model was then used in Perkins and Edens (2003), where a parametric study was performed to arrive at a set of simple design equations for flexible pavements with reinforcement between the subgrade and the unbound layer. The outcome of this design method is the calculation of ratios to estimate the increase in service life or the reduction of base course due to the inclusion of the geosynthetic. These design equations were thought to be conservative, at least within the assumptions used to develop the finite element model. Perkins and Edens (2003) also recommended further calibration as new test section results became available.

From a cost standpoint, Perkins *et al.* (2005a) observed that geosynthetics are sometimes used as a cost reduction measure, mainly by reducing the thickness of aggregate required for a project. Presumably, there is a point where the cost of aggregate saved exceeds the additional cost of the geosynthetics. Perkins *et al.* (2005a) noted a number of ongoing or past projects that have explored the benefits of geosynthetics. The U.S. Army Corps of Engineers Cold Regions Research and Engineering Lab (CRREL, 2004) was seeking funding through a pooled study to build multiple field test sections of pavement, some of which included base layer reinforcement. As of this writing (2006), the study was still awaiting funding.

Gaps in Our Knowledge

Watn *et al.* (2005) noted that problems associated with selecting geosynthetics for use in unbound layers include:

1. Usage in this application is largely based on an agency's prior experience or on a particular producer's recommended empirical method.
2. Existing numerical models were largely developed to replicate field observations. Thus, key parameters for a more generally usable design methodology may be neglected simply because they are not measured or not an issue in a particular study.
3. Numerical models for pavement modeling are complicated, even without considering geosynthetics usage.
4. Modeling assumptions that will require further study include that geosynthetics a) decrease elastic deformation by increasing horizontal stresses in a soil layer, b) increase the bearing capacity of the subgrade by increasing the area influenced by the pavement, c) decrease shear stresses in the subgrade and d) reduce the deformation of the granular subbase material by confinement mechanisms.
5. The challenge of determining properties of a particular geosynthetics for a particular application that can be generalized and measured in a lab. Then, further used in a design method that properly considers the mechanism of reinforcement and the interaction between the geosynthetics and the aggregates.

Watn *et al.* (2005) concluded that the European community appears most hindered by a lack of a technically sound model for design, a lack of knowledge about the reinforcement characteristics by specifying agencies, and a lack of detailed guidance from national specifications on the subject. They note ongoing studies may help bridge the gap, but certainly more needs to be done in these areas.

Perkins *et al* (2005a) identified several issues that prevent the wider implementation of geosynthetics in pavement designs in the United States, not least of which is a rational method for cost-benefit analysis. For subgrade reinforcement, the main barriers are whether design methodologies should be formalized such that it becomes part of pavement design and just how much improvement of the subgrade affects pavement performance over the long term.

For base reinforcement, Perkins *et al.* (2005a) suggested a number of possible areas for future work. These include determining the required geosynthetics material properties and geosynthetics interaction with base aggregate, the importance of the thickness of asphalt concrete and base layer thickness for a particular reinforcement scheme, and the optimal placement of reinforcement in the base course. Other areas include interaction of geosynthetics with poor subgrades or base course aggregates, and the applicability of the design methods to rehabilitation projects.

PAVED ROADS: BOUND LAYERS

European use of geosynthetics in bound layers is mainly limited to rehabilitation projects, according to Watn *et al.* (2005). This includes upgrading degraded gravel roads to paved roads and repaving cracked overlays. The latter appears to be the most commonly used, where the geosynthetics reduce tensile strain in the system by mobilizing tension in the geosynthetics. The use of geosynthetics also helps to minimize transfer of tension into the lower layers, which in turn retards further weakening of the previous structure.

Usage of paving fabrics in the United States is similar to European practice. Perkins *et al.* (2005a) noted that 20% of geotextiles sold are applied as an interlayer between an asphalt overlay and the original pavement surface. Both Perkins et al. (2005a) and Watn et al. (2005) note geosynthetics in the bound layers partially address problems such as frost heave, rutting and reflective cracking due to high traffic volume, cracks due to temperature variation and deformation due to soil movement. They are also sometimes used as moisture barriers or as reinforcement.

Summary of National Guidelines

Minimum material properties for pavement overlays are discussed in both AASHTO M 288-00 and FP-03 Section 415. Design guidelines are covered by Holtz et al. (1998), which, similar to the recommendations for unbound layer reinforcement reviewed in Section 6.1.1, strongly recommend detailed pre- and post-construction field studies to determine the efficacy of the pavement overlay. Holtz et al. (1998) also suggest justifying the use of pavement overlays by considering the cost savings associated with long term maintenance, or by possible overlay thickness reduction by considering the improvement in drainage. Like bound layers, no mechanistic design methodology is covered in the national design documents.

A majority of survey respondents (seven of 11) reported being involved in overlay projects on paved roads. Of these seven, only two reported considering geosynthetics in one or more of such projects. Other respondents may have included pavement overlays in their experience of rehabilitating unpaved roads (eight of 11 respondents, six of which reported considering geosynthetics).

Level of Maturity

Developing. While pavement overlays have been in use for decades, their use, or lack of use, is largely based on local experiences. The mechanisms for improvement of a pavement section with geosynthetic reinforcement are qualitatively described, but are not captured in a generally accepted design methodology.

Recent Advances

Perkins et al.(2005a) focused on two main benefits of geosynthetics in bound layers: i) to reduce the thickness of the asphalt layer or ii) to provide a longer life compared to unreinforced asphalt overlays of the same thickness. Both Perkins et al. (2005a) and Watn et al. (2005) noted that selection of pavement overlays is largely based on local experience. Design methods are either developed by manufacturers or as empirical methods to try to quantify its function as moisture barrier or stress relief benefits.

Amini (2005) surveyed a number of field reports that described the performance of geosynthetic overlays meant to reduce reflective cracking. He concluded that, unless the asphalt overlay was very thin (on the order of 25 to 37 mm or 1 to 1.5 in thick), overlays were “very effective” at reducing reflective cracks. Amini (2005) also looked at cost effectiveness surveys in literature, noting the difficulty in identifying and assigning a cost to the benefits that may be had. He also noted that overlays tended to perform better in warmer climates, perhaps due to freeze-thaw cyclic stresses occurring in colder climates between the overlay fabric and the new pavement (instead of cracks developing from the base and reflecting into the new asphalt).

Similarly, Cleveland et al. (2002) presented the results of laboratory testing on a range of six geosynthetics used in overlays and summarized several decades of overlay research, frequently citing Barksdale (1991). Cleveland et al. (2002) describes pavement test sections that were designed, but not fully constructed or implemented by the publication date. From the lab tests, the authors observed that the inclusion of geosynthetics increased the number of cycles required before failure was reached. However, they also noted that the cost effectiveness of the fabric samples tested “appears to be marginal,” based on a survey of a number of other studies.

Considering the life cycle costs of paving fabrics, Sprague (2005) developed a technique to compare the relative costs of fabrics with overlays, overlays only, and full recycling. By comparing South Carolina road records, some over the course of twenty years, Sprague (2005) concluded the cost-effectiveness of a particular application depended largely on the initial conditions of the roadway prior to application of the overlay. The roadway condition was defined by a “Pavement Condition Index,” a method that is likely not measured in the same way from state to state.

Brown (2003) demonstrated that fabric and chip seal improved service life, as well as reduced the cost compared to traditional overlays with fabric only. Similarly, Davis

(2005) described the practice of combining a paving fabric with chip seal. This approach resulted in good performance in desert conditions where temperature changes can be quite large and cracking can be a concern. The first application of fabric with chip seal reported in that study was in 1987, a section that was still performing adequately when the paper was written in 2005.

Conversely, in a study for the South Dakota DOT, Storsteen and Rumpka (2000) saw no significant improvement in reflective crack occurrence or movement when either a geomembrane seal or geogrid was used between asphalt overlays and joints in existing concrete pavements. This study looked at 120 rehabilitated joints and included the approximate costs of each measure. Based on five years of observations, it was concluded that the geogrid used reflected more cracks than the sections with a geomembrane seal or no geosynthetic at all. Storsteen and Rumpka (2000)'s final recommendations included a sealed saw cut above the joints without using either geosynthetic overlay or extensive rehabilitation at the joint level.

Gaps in Our Knowledge

From a design standpoint, both Watn *et al.* (2005) and Perkins *et al.* (2005a) noted that no model currently used for design takes into account the wide range of factors that affect the performance of asphalt pavements. Lytton (1989) proposed a model that included 13 different parameters. From Perkins *et al.*'s (2005a) perspective, the sheer number of model parameters, with their magnitudes likely changing over the length of a road project, seems to hinder implementation.

Maxim (1997) looked at 200 reports that used geosynthetics in asphalt overlays and suggested a model for design. Maxim (1997) suggested that the inclusion of a geosynthetics layer corresponded to a reduction in asphalt thickness that ranged from 25 to 45 mm (1 to 1-3/4 in). This equivalence has also been reported by Carmichael and Marienfeld (1999) and a 15 mm (0.6 in) equivalence by cost was reported by Marienfeld and Smiley (1994). The biggest challenge with citing equivalent thicknesses is that the design properties of the geosynthetics, asphalt concrete, the base course, and the subgrade are often not reported alongside the resulting equivalent thickness.

While a number of projects are ongoing (for example, NCHRP, 2005), the biggest barriers to widespread implementation comes mainly from understanding the mechanisms of the composite pavement overlay systems. Perkins *et al.* (2005a) noted that the causes of success and failure in projects with and without geosynthetics are still largely unknown. To that end, they suggested the following: i) determining the geosynthetic's primary function for a particular project, ii) understanding and modeling the entire pavement system with geosynthetics included, iii) creating a user friendly design model and, iv) developing a cost analysis to determine whether geosynthetics will be cost effective over the life cycle of a particular project. It is also imperative to address the dire need for systematic field studies to verify the design approaches and modeling results.

PERMANENT UNPAVED ROADS

In some ways, use of geosynthetics to extend the life and improve the performance of unpaved roadway sections is similar to the unbound section of the paved roads described earlier. However, current practice tends to treat reinforcement of unpaved roads as a separate topic from paved road. This primarily comes from the lower traffic volume and acceptance of larger ruts that can develop in unpaved road applications.

Summary of National Guidelines

AASHTO PP 46-01 (AASHTO 2001) provides guidelines for base course reinforcement by geosynthetics. It recommends following the procedures laid out in Holtz et al. (1998) or the procedures from the GMA White Paper II (Berg et al., 2000). A brief description of both approaches follows.

Holtz et al. (1998) consider design methods for permanent applications, where the bearing capacity factor, N_c, can be increased to reduce the thickness of any stabilizing layers, but it is assumed the reinforcement will not improve the structural layers (aggregate base course). No reduction in aggregate base course thickness is allowed. Berg et al. (2000)'s methods are not explicitly applicable to permanent unpaved roads. The methods may eventually be applied if enough field or laboratory data are collected for calibration.

In the survey, eight of 11 respondents reported being involved in unpaved roadway design, either new construction or rehabilitating of existing roads. When rehabilitating roadways, six of the eight respondents said they had been involved in a project that also used geosynthetics. New construction lagged here, with only two of eight respondents reporting geosynthetic usage. It would appear then, that unpaved road construction is a common part of the FLHD work, and that if geosynthetics use in practice can be improved or updated, potential benefits could be achieved.

Level of Maturity

Developing. While the national design methods do not allow for reduced sections, geosynthetics in unpaved roads are often used in separation and filtration applications to prevent mixing of the base courses with the native soils. In the past two decades, a number of numerical studies and proposed design methods have been suggested in the literature for reinforcement applications such that smaller base course layers can be specified.

Recent Advances

Permanent unpaved road design has appeared often in literature. Early work by Giroud and Noiray (1981) and Steward *et al.* (1977) proposed design methods that required deep and large rutting magnitudes to mobilize a tensioned membrane effect in the geotextile layer. Recently, Giroud and Han (2004a and 2004b) proposed a new empirical design model for geogrid reinforced unpaved roads, based in part on lab model tests that were reported by Gabr (2001). This model accounts for aggregate base course deterioration as the number of traffic loading cycles increase, and, while developed for a rut depth of 75 mm (3 in), allows for the input of different rut depth values, and is calibrated for a geogrid's aperture stability modulus (ASM). In their closure to the paper (Giroud and Han, 2006), defended the use of ASM, comparing traffic benefit ratios of reinforced unpaved roads measured by Watts et al. (2004) to 5% secant moduli for the geogrids used. Based on those measurements, it was noted that there was no correlation, that the average strains mobilized in the geogrids ranged from 0.1 to 1.2% and ASM is a better indicator to use in this case.

Tingle and Webster (2003) back-calculated bearing capacity factors using results from four test sections subjected to simulated traffic loading, observing rut depths up to three inches. Finite element analysis of unpaved road sections were performed by Perkins et al. (2005b) and Leng and Gabr (2002) and attempted to explain the contribution of geosynthetics to increasing the service life of the unpaved section. Leng and Gabr (2005) also presented a design model that estimates the benefits realized in an unpaved section with inclusion of reinforcement. The model includes effect of level of mobilization of subgrade bearing capacity as a function of rutting as well as relative aggregate base course to subgrade modulus ratio.

Gaps in Our Knowledge

The recent methods proposed by Giroud and Han (2004a and 2004b) are largely uncalibrated. In their closure (2006) the authors mention that more than 20 paved road designs have since been implemented using their methods. Such database needs to be considerably increased, with long term monitoring and model verification for wide acceptance of the proposed approach.

The numerical finite element studies reported in literature may be a first step toward a more mechanistic-based design model. These methods, however, are unlikely to make their way into common practice unless (i) the interface between user and finite element model are more stream lined and user friendly, (ii) interface and material models are accepted and (iii) the results are well correlated to measured behavior. So far, the finite element studies have provided design charts that are dependent on the type of reinforcement modeled and the initial boundary conditions assumed.

CONSTRUCTION PLATFORMS (TEMPORARY UNPAVED ROADS)

Temporary unpaved roads have different design requirements than permanent ones. Often times, they are placed simply for construction access, so the rut depths can be larger under lower number of passes by traffic (albeit heavier load). From a FLHD standpoint, these projects may also be considered within the realm of contractor design-build arrangement.

Summary of National Guidelines

Construction platforms are not specifically covered in any national design manual. However, since they are similar to unpaved, temporary roadway reinforcement, AASHTO PP46-01, which references the GMA White Paper II (Berg et al., 2000) and Holtz et al. 1998's methods may also be used. In the latter, the geosynthetic selected is assumed to allow for reduced thickness of aggregate by improving the drainage and separation of the soil from the subbase. The model quantifies this effect by allowing a higher bearing capacity factor, N_c. The U.S. Army Corps of Engineers (2003) also addresses unpaved roads in a manner similar to Holtz et al. (1998).

Level of Maturity

Developing. Typically, construction platforms are left to contractors to design. This would partially explain the lack of coverage in the national literature, and the low number (one) of survey respondents who said they were involved in construction platform design or construction.

Recent Advances

Temporary work platforms are sometimes constructed over soft or very wet soils using granular fills and geosynthetics to avoid rutting and mud waves due to construction traffic. Currently, design of these platforms is based on local bearing capacity considerations, where geosynthetics tend to increase the bearing capacity factor and also attenuate the stresses transferred to the subgrade. The configuration may call for a 3D stability solution but is normally treated with a 2D plane strain model for simplicity. Often only one layer of geosynthetics is used. Perkins *et al.* (2005a) noted subgrade reinforcement for construction platforms is quite common, and usually implemented by a construction team.

The methods used to design unpaved roads can also be used for construction platforms. In this case, geosynthetics are used at an interface between soft soils and an aggregate subbase (or other granular fill). Giroud and Noiray (1981) and Steward *et al.* (1977) proposed design methods for these situations that assume the rut depth is deep enough for a tensioned membrane effect to develop in the reinforcement layer. Similarly, Leong *et al.*(2000) performed bench scale models of roadways using anchored and pretensioned geotextiles and reported the response of the composite section.

Giroud and Han (2004a and 2004b)'s empirical design model for geogrid reinforced roadways could also be used for construction platforms. In this application, the allowable rut depth should perhaps be larger and number of traffic passes should be decreased, but with heavier truck load, to account for the temporary nature of construction loading.

Gaps in Our Knowledge

Future design methodologies should consider multiple layers of geosynthetics and their impact on reducing the thickness of the aggregate base course (ABC)m as well as limiting it deterioration with cyclic loading. Similarly, development of 3-D models such as those described by Perkins et al. (2005b) may lead to more refined results, particularly if very heavy construction loads are involved.

A wider survey of methods used by contractors on federal lands projects may also lead to a better understanding of their practice and the ability t o suggest improvements. Alternatively, more careful monitoring of the performance of temporary roadways and platforms on new projects could lead to a larger data and experience base. This could improve the confidence of construction, inspection and design personnel, and lead to improving current design methods and avoiding experiences like that reported by a survey respondent's in Chapter 3.

MOISTURE BARRIERS

The use of geotextiles (typically thick nonwoven needle-punched) as a capillary break is summarized by Koerner (1998). The fabric's in-plane drainage capacity acts to cut down on the tendency of water to rise above the water table due to capillary action. If the size of the pore spaces are abruptly increased, the pore water will then tend to flow in-plane, and can be removed by underdrains. This behavior is helpful for mitigating volume changes due to ice lenses in cold weather and for stopping salt water rise in very arid regions.

Another commonly used moisture barrier, primarily in Texas and throughout the west, are geomembranes to prevent water infiltration. In these cases, water from roadways comes in contact with layers of expansive soils in the subgrade. This causes roadway heave and significantly degrades the pavement structure.

Summary of National Guidelines

There are currently no existing national guidelines for design of capillary barriers to mitigate frost heave. The Geosynthetics manual (Holtz, 1998) does not mention their use. In the survey of FLHD and USFS engineers, one noted capillary barrier projects, and six noted they were involved in frost heave projects. Three of the six reported involvement with geosynthetics. Based on that small sample, there appears to be some demand for frost heave mitigation, and some interest in geosynthetics usage as moisture or capillary barriers. For prevention of water infiltration into expansive soils, few national guidelines are included. However, the Geosynthetics Manual (Holtz, 1998) does consider geomembranes in other barrier applications, such as landfills and containment units.

Level of Maturity

Undeveloped. Some initial lab and field work has been conducted and reported in literature. Koerner (1998) recommended a design method that considers the transmissivity of the geotextiles; in fine grained soils, a secondary filtration function would also have to be considered to prevent clogging.

Recent Advances—Frost Heave

Laboratory

In their survey of European paving technology, Watn *et al.* (2005) mentioned use of geosynthetics in frost susceptible subgrades or where old gravel roads are used as subgrade for new paved roads. In these cases, a geotextile is used to separate the frost susceptible materials from the paving layers, while geogrids are used as reinforcement. One problem, at least from the European perspective, is that it is not possible to define the benefits of using geosynthetics by performing simple tests in the laboratory.

Henry and Holtz (2001) investigated frost heave in laboratory scale test cylinders. The authors noted a few limitations to their study, including the modeled 1-D water flow, and freezing behavior, and scale effects. Nonetheless, they concluded the geotextiles used were only effective capillary barriers until moistened, particularly if soil fines had infiltrated the geotextile.

On the other hand, Henry and Holtz (2001) noted geocomposites, that is, a geonet drainage layer separated from the soil by geotextile on either side of the geonet, tended to reduce frost heave, but only when the top geotextile (between the modeled roadway and the geonet) dried out between cycles. They identify the difficulty in measuring or predicting unsaturated flow in geotextiles and the likelihood that only a portion of the geocomposite was allowing in-plane water migration.

Field Studies

Evans et al. (2002) reported the results of full scale installations of geocomposite drainage layer in roadways in Maine. The data from the study were decidedly mixed, with the authors concluding that the geocomposite was “somewhat effective in mitigating frost heave” in one of three test sections. They attributed the failure in the other two sections to the location of the water table, which during certain parts of the winter was apparently at or above the level of the geocomposite, thus circumventing the system’s function as a capillary barrier. They also noted that areas where soils were removed prior to road construction tended to heave more than areas where soils were added.

Henry et al. (2005) created test sections in two unpaved roadways in Vermont and monitored their performance over two winters. The researchers installed geotextile separators, geogrid reinforcement, capillary barriers, and geocells (a honeycomb geosynthetic that is filled with aggregate) 0.3 m (1 ft) below the cement pavement surfaces in different sections. Other methods used included edge drains or geotextile-wrapped gravel layers 0.3 m (1 ft) beneath the pavement surface to improve drainage during thaws. Henry et al. (2005) concluded that performance of the roadways were best in the sections that either provided additional strength throughout the profile (the Geocell and the cement sections), or that provided better vertical drainage and moisture control prior to freezing (the capillary barriers or the geotextile-wrapped gravel layers). The edge drains were thought to not be effective due to the relatively slow lateral drainage of water from the center of the roadway to the edges. It was also concluded that the geotextile separator and geogrid reinforcement did little to improve the upper 75 to 300 mm (3 to 12 in) of the roadway, which was saturated during the spring thaw and then most susceptible to deep rutting failures.

Other studies have investigated the use of polystyrene sheets as insulators (Kestler and Berg, 1995 and Konrad et al., 1996*)***.** In this case, the polystyrene inclusion acts to interrupt the formation of ice, reducing the zone where heave can occur. Similarly, Leu and Tasa (2001) discuss practices in Minnesota, where geotextiles have been used primarily for their ability to separate sections damaged by frost boil (where fine subbase material is pushed up into the aggregate base course during thaws) from the newly placed subgrade.

Recent Advances—Barriers for Expansive Soils

Steinberg (1998) describes in detail a number of highway and structural case studies from the American West and around the world that have used Geosynthetics to mitigate expansive soil problems. A discussion of testing, design and material costs is also presented. Basically, the geomembrane is installed as a barrier against vertical water infiltration, against horizontal water infiltration from road shoulders or other flowing ground water, or against both. The geomembrane placed has very low hydraulic conductivity, which essentially keeps the initial moisture in the expansive soil unchanged. These horizontal and vertical barriers are usually installed in tandem with drainage structures, to prevent water from ponding on the road surface and to reduce hydraulic heads leading to water infiltration.

Gaps in Our Knowledge

The largest gaps in frost heave mitigation practice involve applying the results of the relatively few laboratory and field tests to model development and practice. There is ongoing work as to the best methods to mitigate frost heave. While geosynthetic capillary barriers are gaining some ground as a new application, specific design methods and field performance data have yet to be developed.

More controlled field testing will be required to fully quantify whether certain frost heave mitigation techniques, either as moisture barrier, capillary barrier, or both, are useful. These types of studies, however, require multi-year commitments to monitoring over a series of freeze-thaw seasonal cycles. A viable design method is also required, as are methods that will allow the costs of various possible solutions to be compared. In expansive soils, most solutions appear to be regional or on a state-by-state basis. A more systematic national effort and design methodologies is needed for wider application of this technology.

GEOSYNTHETIC CLAY LINERS

Geocomposite Clay Liners (GCLs) are manufactured by sandwiching or embedding bentonite clay in geotextiles or attaching a layer of bentonite to geomembranes. As water comes in contact with the bentonite, the bentonite expands, effectively reducing the hydraulic conductivity and creating a barrier to flow. For drainage ditches, the GCL could be used to minimize seepage into the surrounding ground, and channeling the water to a sump area for routing to storm water facilities. GCLs can also be a key component in reducing contaminant transport from roadways into the surrounding environment, allowing non-point source contaminated run-off to be sent to a particular location for treatment instead of making its way directly into sensitive areas.

Summary of National Guidelines

GCLs are mentioned briefly in the “barriers” section of the NHI Geosynthetics manual (Holtz et al. 1998). In that section, their usage was described as waterproofing layers in tunnels walls or bridge abutments, storm water retention pond or canal liners, and secondary containment for underground storage tanks. It is also mentioned that overlapping is generally required to create a water-tight seal.

Level of Maturity

Underdeveloped. While GCLs for environmental applications (such as landfills) are well developed, the application to prevent seepage from ditches are virtually unused by the FLH. Only one of eleven respondents in the survey in Chapter 3 reported using geosynthetic clay liners in any application. This may be partly due to unfamiliarity with the material, concerns about long term performance, or a lack of more explicit guidance in design documents.

Recent Advances

Boardman and Daniel (1996) investigated the ability of clay liners to “self heal” over many wetting and drying cycles in two geotextile-bentonite (GT-B) composites. They noted that one GT-B system developed large cracks in the bentonite when desiccated, which significantly increased hydraulic conductivity (from 10^{-9} to 10^{-3} cm/s or from approximately 10^{-10} to 10^{-4} in/s in this study) until the bentonite was rehydrated. In this test, hydration took a little over an hour. The other GT-B system did not develop such cracks during desiccation, an observation attributed to the higher reinforcement given by the particular geotextile used in the product. Lin and Benson (2000) performed a similar test, adding a calcium chloride solution and more wetting-drying cycles. They, too observed significant cracking and loss of self-healing due to the chemical change in the bentonite and the loss of its ability to self heal.

Egloffstein (2001) noted that hydraulic conductivity of GCL liners tends to increase over the first three years of the liners' life, as sodium ions in the bentonite are replaced by calcium ions in the seepage liquid. This ion replacement can increase the hydraulic conductivity by as much as one order of magnitude. In ditches near roadways or other structures to which deicing salts, such as calcium chloride, are applied this ion exchange could be of concern and would have to be considered in design. Jo et al. (2005) further observed the stronger the salt solution, the more likely an increase in hydraulic conductivity. Jo also noted the amount of time it took for GCLs exposed to salt solutions to reach a stable, higher conductivity. For weak salt solutions (< 50 mM calcium ion), an increase of around one order of magnitude in hydraulic conductivity occurred over a time period of about 0.2 years. For stronger solutions, Jo et al. (2005) observed a nearly immediate 3 order of magnitude increase in hydraulic conductivity that stayed constant thereafter.

GCL liners for canal rehabilitation in Germany were reported by Heerten and List (1990). Side slopes varied from 5 to 30 degrees, and the measured shear strength was 34 degrees, which was in part dictated by the nonwoven needling process. In this case, a soil cover was used over the GCL. Crouse et al. (2000) described procedures used to install GCL's at a mine site. The GCL was covered with rock using a scraper and belly dump. After installation and removal of the rock, visual inspection showed no observable damage to the GCL by either the rocks or the scraper.

The required overlap of GCL to overcome possible shrinkage and separation between adjoining layers was discussed by Thiel et al. (2005). They measured shrinkage due to cyclic wetting and drying and recommended overlap amounts to overcome the change in GCL panel spacing. On a related material note, Zornberg et al. (2005) compiled a database of direct shear tests on GCL to measure the GCL's internal friction angle. They determined the internal friction shear strength of a GCL varies considerably between manufacturers and the date of manufacture, and includes variability in the type of geosynthetic used and the bentonite used.

Gaps in Our Knowledge

The research above identifies a few areas of inquiries, mainly considering the behavior of the GCLs. First, the change in hydraulic conductivity over time due to wetting and drying cycles, desiccation and salt infiltration should be better quantified. The hydraulic conductivity value will determine how much water seeps from the ditch. Second, shear strength and overlap considerations will determine survivability and constructability of the GCL liner system. These values will have to be combined with other studies of soil-GCL interface friction studies, either on the manufacturer level or on a project basis. Third is the behavior of GCL under relatively thin cover thickness as would be the case for lining ditches.

The biggest barrier however to wider GCL implementation is the increase in hydraulic conductivity that appears to occur when the bentonite comes in contact with salt solutions, resulting in cracks that will not fully self heal after desiccation due to the loss of swelling. Unless the GCL can survive such environmental hazards or the location is chosen such that the GCL remains at least partially wet or away from road or natural salt infiltration, increases in seepage will occur.

Part of the problem may be solved by using expansive clays with more calcium than sodium. While this would decrease some of the swell potential, it would reduce the ion exchange that occurs when sodium-rich bentonite is exposed to high concentrations of calcium in solution. Lee and Shackelford (2005) observed similar behavior in their work, where bentonite with higher calcium content did not show increases in hydraulic conductivity as large as higher sodium content bentonite when exposed to calcium chloride solution.

SUMMARY

This chapter reviewed the progress of geosynthetics as applied to pavements, including reinforcement applications, moisture barriers and geosynthetic clay liners for lining ditches. In spite of the length of time geosynthetics have been used in pavement applications, there is still a lack of consensus as to their benefits. There is, however, a tremendous opportunity for future development and optimization of usage to determine the cost-effectiveness of geosynthetic in new and rehabilitation applications as described in this chapter. In the meantime, it seems the most benefit can be derived by FLHD from systematic and careful application of geosynthetics to particular projects, monitoring performance, and focusing not only on the benefits realized but also understanding the likely reasons for those benefits. These calibration efforts should be a part of the larger efforts underway by NCHRP and FHWA to develop new and refine existing design methods.

Reinforcement applications are by far the most common use of geosynthetics in paved roads, unpaved roads or construction platforms. Despite decades of laboratory and field scale testing, the available design procedures (particularly for unpaved roadways) still recommend significant field verification efforts if geosynthetics are used as part of a design. Mechanistic-empirical design methods are currently being developed for paved roadway design, as are comparative ways to determine the cost effectiveness of roadway profiles containing geosynthetics. These continuing developments should be monitored in coming few years to see if wider implementation is possible.

Moisture and capillary barriers have been implemented and studied more frequently, and are a developing technology. The use of geosynthetics to control expansive soils has mainly focused on encapsulation of the soils beneath the roadway with geosynthetics, while control of frost heave has focused on adding drainage layers or capillary barriers to prevent water from freezing in the roadway profile. On the other hand, geosynthetic clay liners run-off control are largely undeveloped for roadway applications. Further studies of their survivability and effectiveness on a field scale must be performed before they could be widely implemented and accepted in practice.

CHAPTER 7 – RECOMMENDATIONS

Work presented in this report is aimed at providing guidance and recommendations on systematically including geosynthetics in highway construction projects by Federal Lands Highway Divisions (FLHD). The recommendations are based on information from the review of the current state-of-the-art and state-of-practice literature in several target areas using geosynthetics. In addition, input from a survey collecting information on current approaches and practices of various engineers in agencies related to FLHD was considered. Target technical areas included the following:

i. Walls
ii. Slopes
iii. Deep patches for soft shoulders
iv. Reinforced soil foundations (embankments, shallow foundations)
v. Unbound pavement layers
vi. Bound pavement layers
vii. Moisture barriers
viii. Liners to control/prevent seepage

Erosion control and drainage applications of geosynthetics were mentioned within the report but not emphasized as these applications are at present considered to be sufficiently used by FLHD. Table 9 summarizes the current state of general practice within the industry and the status of the respective FLHD specifications. Table 10 summarizes the types of geosynthetics that can be used in the applications covered in this report. The proposed recommendations establish actionable items for a wider implementation of geosynthetics in construction projects by FLHD and their stakeholders. The recommendations are classified into three categories: i) Broad guidelines for specifications updating, ii) Adaptation of specific design approaches for expedient implementation of best practice technologies, and iii) System-level recommendations for further development prior to wide acceptance for a particular application.

BROAD GUIDELINES FOR SPECIFICATIONS UPDATING

It is recommended to technically update the geosynthetics guidelines used by FLHD to include design guidelines, and, in addition, update the standard specifications in light of these design guidelines. To aid in material selection beyond filtration, drainage and separation functions using geotextiles, the portions of the FP-03 "Standard Specifications" addressing geosynthetics should be updated to include a wider range of materials, including geogrids, geonets and geomembranes. The updated specifications could take a form similar to those currently in place in sections 714 and 415, where geosynthetics are categorized based on certain property types. As is currently done in overlay and separation projects, this type of upgrade would allow designers to specify required material properties for reinforcement and drainage without specifying a particular manufacturer's product. This upgrade could be achieved by surveying a wide range of available geogrid, geonets and geotextile products for each application and determining typical ranges of material properties available on the market. An update of the standard specifications should be a **Very High** priority.

Table 9. Industry Wide Progress Toward Implementation of Projects in which Geosynthetics are Used.

Application	Level of progress/implementation					
	Technical awareness	Number of constructed projects	Existing FHWA material specifications	Standard design methods	Performance monitoring methods	Possible Implementation by FLHD
Separation	Very High	Very High	Could be improved	Mature	Mature	Should be in common use
Drainage	Very High	High	Could be improved (only textiles currently)	Mature	Mature	Should be in common use
Walls	Very High	Very High	Reinforcement needed	Mature	Mature	Should be in common use
Slopes	Very High	Very High	Reinforcement needed	Mature	Mature	Should be in common use
Deep patches	Emerging	Few	Reinforcement needed	Emerging	Improving	Proceed carefully
Embankments over soft soils	Very High	High	Could be improved	Mature	Improving	Should be in common use
Column Supported Embankments	Emerging	Moderate	None	None standard	Improving	Should be considered more often
Shallow Foundation	Low	Low	None	None	Lab scale tests	Research required

Table 9 (continued). Industry Wide Progress Toward Implementation of Projects in which Geosynthetics are Used.

Application	Technical awareness	Number of constructed projects	Existing FHWA material specifications	Standard design methods	Performance monitoring methods	Possible Implementation by FLHD
Paved Roads: Unbound Layers and Subgrade	Moderate	Moderate to High	Reinforcement specifications needed; separation OK.	Suggested, but not finalized	Multiple field tests, varying results	Implement with careful monitoring
Paved Roads: Bound Layers	Low-Moderate	High	Existing, Could be Improved	None finalized, broad rules	Variable in different areas	Implement with careful monitoring
Permanent Unpaved Roads	Moderate	Uncertain	Reinforcement specifications needed; separation OK.	Suggested, not yet finalized	Variable in different areas	Implement with careful monitoring
Temporary Unpaved Roads (Construction Platforms)	Moderate	Uncertain	Reinforcement specifications needed; separation OK.	Same as unpaved roads above	Very few projects	Implement if project falls under FLHD responsibility
Moisture Barriers	Low	Low	None	None	Very few projects	Research required
Liners to Control/Prevent Seepage	Low	Low	None	None	Very few projects	Consider for sensitive environmental issues

Table 10. Types of Geosynthetics Used in the Applications Covered in this Report.

Application	Geocomposite	Geogrid	Geomembrane	Geonet	Geosynthetic Clay Liner	Geotextile
Walls	X	X		X		X
Slopes	X	X		X		X
Deep patches for soft shoulders	X	X		X		
Embankments over soft soils	X	X		X		X
Column Supported Embankments		X				X
Shallow Foundation		X				X
Paved Roads: Unbound Layers and Subgrade	X	X		X		X
Paved Roads: Bound Layers	X	X		X		X
Permanent Unpaved Roads	X	X		X		X
Temporary Unpaved Roads (Construction Platforms)	X	X		X		X
Moisture Barriers	X		X	X	X	
Liners to Control/Prevent Seepage	X		X		X	

In addition to updating the current specifications, it seems imperative to include information on design guidance using both geotextile and geogrids in reinforcement applications. This will likely not be a part of an updated FP-03, but at least should be a recognized set of documents that will guide and standardize relatively simple designs. While design guidelines are not a complete substitute for engineering experience and judgment, they should serve as a catalyst to facilitate the implementation of geosynthetics especially in applications that are generally accepted as being state-of-practice by the profession. These include MSE walls, reinforced embankment slopes, and embankments on reinforced soil foundations. Once design guidelines are accepted and distributed to the FLHD design community, wider specifications can be written to complement the design guidelines. Development of design guidelines for applications that are considered state of practice should be a **High** priority, although it could be implemented in a piece-wise approach.

It is also recommended to consider adopting guidelines similar to those developed by HITEC (1998) to evaluate and speed acceptance of proprietary earth retaining systems. This may be as simple as using the existing HITEC reports if particular wall systems are considered. Such evaluation guidelines should include suggested design procedures and methods of construction. No such guidelines are currently available for reinforced embankment slopes or embankments on reinforced soil foundations; the development of a process similar to that adopted for reinforced walls should be considered, either in-house or as a part of a larger effort in collaboration with other agencies. Indeed, many state DOTs have lists of "approved" products for particular applications. Washington State DOT, for example, maintains a list of reinforcement geosynthetics that can quickly be approved for use in relatively simple slopes and walls in "non-aggressive" soils. The development of this type of list could be gradual as projects are approved and successful, thus the priority is **Moderate to Low**.

IMPLEMENTATION OF STATE OF PRACTICE DESIGN APPROACHES

The purpose of developing application-specific design recommendations is to assist FLHD professionals with the design of geosynthetics structures that have been repeatedly constructed over the past two decades. There are well documented design approaches for MSE walls, reinforced soil slopes, and embankments on reinforced soil foundations. The standardization of the design process of these applications will encourage FLHD professionals to perform the design and accumulate experience with the analytical approaches. In support of such effort, we recommend the following:

i. The development of charts that standardize the design of reinforced walls or slopes for configurations describing low, medium, and high categories while taking into account different backfill and foundation soil types. These charts should provide baseline design information including, for example, length of reinforcement, number of reinforcement layers, and strength of reinforcement materials, but at the same time should afford flexibility to economize a given design. It is our understanding that the FLHD does not often design (but does approve) MSE walls. As such, the priority for this project could be considered **Moderate**.

ii. The development of simple computer modules within the framework of MathCAD or Excel to aid FLHD engineers or geologists in expediently performing design and in investigating the sensitivity of the design configurations to key input parameters. While there is a computer program by FHWA for design of slopes/walls, programs for other applications are missing. For example, several modules can be developed for design of reinforced paved and unpaved roads, embankments on soft foundations, moisture barriers, frost heave mitigation, pavement overlays, shallow foundation reinforcement, and edge drainage. Providing these analysis tools to allow a degree of automation will facilitate the design and empower the designers with the flexibility of expediently discerning the best option(s) for a given project, while simultaneously allowing comparison of "traditional" design solutions. To implement geosynthetic technologies more uniformly and hopefully more easily, the priority of this recommendation could be considered **Moderate**.

iii. FLHD should adopt a series of short courses with a logical sequence to specifically emphasize applications of interest to them. Design issues of relevance to FLHD can be covered with detailed examples and case histories to empower FLHD engineers with tools to broadly use geosynthetics when appropriate. This series of educational efforts should be specifically designed and targeted toward FLHD professionals, and should be digitally recorded and distributed agency wide. While development of new courses could be given **Low** priority, in the shorter term, **Very High** priority should be given to using existing NHI courses or presentations by manufacturer's engineers and representatives on topics of particular interest to FLHD personnel. In addition a **Very High** priority should be given to the development of installation pocket guides for geosynthetics-related construction inspection to assist field personnel.

iv. FLHD should also consider an aggressive education program for construction managers, engineers, and technicians who inspect MSE walls, reinforced soil slopes and other projects in which geosynthetics are used. Many wall failures are often attributed to poor construction control, and to some extent the success of geosynthetic implementation is dependent on knowledgeable field staff who can identify improperly installed or damaged geosynthetic materials. This could be in part accomplished through continued use of NHI courses. Priority: **Very High.**

SYSTEM-LEVEL RECOMMENDATIONS FOR FURTHER DEVELOPMENT

There are several applications that are important to the practice of FLHD but are either not well developed or their design process and implementation are not well documented in literature. Recommendations regarding each of these applications are as follows:

Deep Patches for Soft Shoulders

There are some limited cases presented in literature on the use of soft deep patches as a rehabilitation measure but work was performed mainly for the USFS. It is recommended that a comprehensive technical review of the USFS's experience be performed to determine the likely need for further improvement or development; this step may already be underway in a forthcoming report in which the history and performance of several deep patch projects are investigated (FLHD CTIP, 2006). It is also recommended that the design approach presented by Musser and Denning (2005) should be implemented at a number of possible sites that can be instrumented or visually monitored. Once additional field data are obtained, the adequacy of this design process could be assessed and revised if needed. Thus, depending on the demand from FLHD clients and considering the activities currently underway, the priority for deployment of this technology following Musser and Denning's guidelines could be **Very High.** Once well developed and established as successful, design guidelines and personnel development should be incorporated as outlined in parts I and II of this chapter.

Column Supported Embankments

There are some prior documented examples implementing column supported embankments in the field. In addition, design guidelines are available in literature. FLHD should be implementing this technology but with the effort of monitoring and documenting the structures' performance. Key components to be developed for a wider acceptance of this technology include the following:

i. Develop guidelines for determining when the faster construction times allowed by column supported embankments are economically attractive. This could be considered to be of **Low** priority.
ii. Develop guidelines for selection of proper geosynthetics to be used in the "beam method" of design based on strength and confinement conditions. The priority here is **Low**,
iii. Review recent field studies and attempt to investigate whether a tensioned membrane or soil arching is developed and its percent contribution to the overall support mechanism. This priority is probably **Low** to FLHD, but could significantly improve the design methods currently in use.
iv. Verify numerical and analytical approaches with data from field studies to discern the differences in performance between the rigid and more flexible type of columns, and the resulting stress transfer between support columns and native soil. The priority here is also **Low,** although could be quickly implemented as a part of planned field construction.
v. Develop analytical approaches to better predict deformation (horizontal and vertical) of these systems. This priority is also probably **Low** to FLHD, but could significantly improve the design methods currently in use.

Shallow Foundations

In the case of shallow foundations on soft soils, the major advantage of using soil reinforcement is the ability to use smaller and shallower excavations. A reduction in the excavation size provides for significant cost savings and substantial health and safety benefits due to the shortening of construction and labor time, the excavation of shallower and smaller foundation pits, and the use of less natural fill material. However, there is a lack of data on the fundamental mechanics associated with the attenuation of stresses and deformation modes of geosynthetics-reinforced mats supporting shallow foundations over soft soils. It is recommended that FLHD use reinforced shallow foundations on a case by case basis. Widespread use should not be pursued at this time as there is a need for documented case studies and accumulated experience before a threshold is met for acceptance in practice. The following information is required for standardized design:

i. The definition of capacity improvement factor (CIF) as a function of deformation level due to the incorporation of reinforcement and its dependency on reinforcement type. While laboratory-generated values exist, field verification is needed before wide adoption is recommended.
ii. The definition of the stress-strain distribution within and below the reinforced soil mass for the design of the system and the evaluation of settlement (similar to methods for un-reinforced soils),
iii. The mechanics of load transfer as a function of deformation level where anisotropic material properties and membrane action of the reinforcement may play different roles, and,
iv. Life cycle cost analysis to demonstrate the advantage of using geosynthetics reinforcement versus the traditional “excavate and replace” approach in cases where both options can be employed.

Reinforcement of soil beneath shallow foundations is an emerging technology. As there are other technologies that can be adopted more immediately, the priority of this research effort is probably **Low**.

Subsurface Voids

In theory, geosynthetics reinforcement can be used to bridge geologic discontinuities including sinkholes and old mine subsidence areas. It may not, however, be sufficient to use such an approach as the sole technology in this situation, especially if future enlargement of the subsurface voids is expected (as in sinkholes for example). It is recommended to identify locations under the jurisdiction of the FLHD that could benefit from the use of reinforcement to bridge over subsurface voids. In such cases, the use of geosynthetics, in addition to other options such as grouting, should be considered. It is also highly recommended to always instrument the reinforcement geosynthetics with strain gages and other sensors to determine if failure is in progress and take additional precautions, particularly in areas where such subsidence would pose a major hazard to the public (or in high visibility areas). This approach has been used successfully in Germany for high speed rail corridors. For a wider acceptance of use of geosynthetics for bridging over subsurface voids, the following developments are needed:

i. Identification of areas under FLHD’s jurisdiction that may be subject to subsurface voids, and determine if such a mitigation approach can be economical or worthwhile. Priority: **Low.**
ii. Although not directly related to geosynthetics, establishment of methods to improve the ability to predict where voids may occur, so that geosynthetics can be properly deployed. Priority: **Low.**
iii. Study of characteristics of large and small voids and the underlying geologic processes. Accordingly, the applicability of the current design methods to each should be undertaken before wide deployment of this technology is implemented. Priority: **Low.**

Unbound Road Sections

The FLHD may consider eliminating the difference in design approaches between permanent and temporary unpaved roads and consider integrating the two using the same design approach. This recommendation is based on the notion that the difference between "temporary and permanent" is inherently recognized in terms of magnitude of the rut depth, design life, and the number of traffic passes. The priority of this is probably **High.**

From a design perspective, there are analytical approaches for design of reinforced unpaved roads. There is, however, a need to build up a database of experience on the field performance of reinforced versus unreinforced sections. This can be achieved by either actively constructing or monitoring reinforced unpaved road sections as well as funding or otherwise supporting (through access to projects, for example) systematic research projects that will provide such data with analyses. Accordingly, the following recommendations are advanced:

i. Consider limited application of the Berg et al. (2000), Giroud and Han (2004) and/or Leng and Gabr (2006) methodology to one or more road sections that can be instrumented and monitored to calibrate the methods for Federal Lands' applications. After calibration is complete and some confidence in the methods established, wholesale adoption may be considered. Priority: **High.**

ii. Monitor and construct unpaved road projects so that a database of successful and unsuccessful projects can be developed and analyzed. By determining where problem areas are on a particular roadway, targeted use of geosynthetics or other technology can be more effective. The focus should then be on determining "why" a particular measure worked or did not work, not simply on "if" it produced the desire outcome. Priority: **High.**

iii. The two recommendations above will take considerable time if implemented on traditional projects. An alternative that will save time but require more of a mainstream research effort would be to use accelerated testing facilities or test tracks to get results faster. Priority: **Moderate.**

iv. Perform life cycle cost analysis to discern the impact of using geosynthetics taking into account materials and transportation cost. Priority: **High**, if sufficient data are available.

The efforts described in i through iv above will be extensive and beyond the mandate of FLHD alone. As such, FLHD should consider supporting and assisting pooled funds or other studies to help validate design approaches and move forward with wide adoption.

Paved Roads

Geosynthetics can potentially be used to enhance the performance of the pavement sections by increasing its service life, reducing rutting, and minimizing reflection cracking. The use of geosynthetics in paved roads, however, has been mainly limited to rehabilitation projects involving asphalt overlays for repair of reflective cracking and in research projects. As resurfacing work is commonly employed for the maintenance of roads, geosynthetics can be used to reduce the thickness of the resurfacing bituminous layer or to increase the life cycle of the overlay (if the same thickness is maintained.) While pavement overlays have been in use for decades, geosynthetics use in this application has largely been based on local experiences. Minimum material properties for pavement overlays are discussed in both AASHTO M 288-00 and FP-03 Section 415 but FP-03 does not include recommended design guidelines. Generally, no mechanistic design methodology is covered in the national documents. Existing methods are empirical in nature and are usually developed by manufacturers for specific products.

The mechanisms for improvement of a pavement section with geosynthetics reinforcement are qualitatively, and at times quantitatively, described in literature, but a generally accepted design methodology is not yet available. In addition, the cost effectiveness of incorporating geosynthetics in paved sections is generally unknown over the life cycle of a particular project. Accordingly, it is recommended that the following be considered:

i. Methods to quantify pre and post overlay performance should be standardized such that the results of various projects can be better compared. Priority, **Moderate** if an overlay development program is initiated and funded
ii. Mechanistic models for incorporating geosynthetics at various locations within the pavement section are needed. These models will account for the effects of different types of geosynthetics, subgrade condition, Asphalt Concrete (AC) and Aggregate Base Course (ABC) layer thicknesses, and location of the geosynthetics. Priority: **Moderate.** Other researchers are pursuing this option numerically; it may be best, therefore, to adopt a “wait and see” approach for this item.
iii. Similar to applications of geosynthetics to unbound layers, rigorous field testing and aggressive monitoring programs should be developed. This could be implemented on existing projects or through research projects at accelerated testing facilities. Priority: **Moderate**.
iv. Methods to determine economic benefit of reinforcement are needed with quantification of the overlay’s impact on life cycle, short and long term savings in reconstruction, and upfront materials cost. Priority: **Moderate**, if significant overlay programs are implemented.
v. Identification of geographic locations where the use of geosynthetics in pavement application will be the most beneficial considering environmental potential and life cycle cost. Priority: **Moderate.**

The efforts described in i through v above will also be extensive and beyond the mandate of FLHD alone. As such, FLHD should consider supporting and assisting pooled funds or other studies to help realize the proposed recommendations.

Moisture Barriers (Frost Heave/Expansive Soils)

Moisture and capillary barriers are two applications that mainly aim at reducing frost heave and shrink/swell adverse impacts on paved and unpaved roads. No federal guidelines are currently available for design of capillary barriers to mitigate heave, while some state DOTs have experience using geomembranes as barriers to mitigate shrink/swell potential. While initial lab and field studies have been conducted and reported in literature, the following is recommended before wide adoption by FLHD:

i. Document the cost effective measures (including geosynthetics as moisture barriers) to address the shrink/swell and frost heave problems. In addition to moisture and capillary barriers (in which geonet/geotextile composite seems to be the most promising product), the use of underdrains, or additional stiffening (thicker section, geocells, cement) can also serve to address frost heave. Geomembranes and ponding to initially saturate a soil appear to show promise by reducing water infiltration in shrink/swell soils. Priority: **Low** unless a specific project arises.

ii. Use principles of unsaturated flow in geosynthetics and soils to develop analytical model for the design of these systems. Priority: **Low.**

iii. Continue to support instrumented programs in a variety of soil profiles. In this case, moisture/capillary barriers can be installed in pavement sections and the structure performance of the enhanced section is compared to control sections. Data from such comparison can be used to develop the best design approach. Priority: **Low** in new projects**, High** in existing projects.

GCLs for Seepage Ditches

Only one of eleven respondents in the survey in Chapter 3 reported using geosynthetics clay liners in any application. The use of GCLs for lining seepage ditches is, however, a novel application and should be considered as an option, particularly to address non-point source pollution in environmentally sensitive areas. Areas to be developed include quantifying the change in the GCL's hydraulic conductivity over time due to wetting and drying cycles, desiccation and salt infiltration. Unless the GCL can survive such environmental hazards, or the location is chosen such that the GCL remains at least partially wet or away from natural salt infiltration, increase in seepage flow will occur due to increase in the materials' hydraulic conductivity. For a wider implementation of this technology, the following is recommended:

i. Work is needed to determine the "strength" of salt solutions typically experienced in run-off during winter or in water infiltration in arid climates where salts leach from the soils.

ii. Accordingly, further studies are needed to determine long term hydraulic conductivity of GCLs under conditions similar to those encountered in roadway ditches. Performance data are needed under various environmental conditions (such salt spraying) in order to render such an approach viable as a ditch lining material.

iii. Effects of roots and plant growth on GCL hydraulic conductivity and integrity can be an issue that needs further investigation.

As in the case of reinforcement of soils beneath shallow foundation, this is an emerging technology. If there is an interest in pursuing it, considerable research and practical projects will be required. The priority, then, in absence of strong need driving the development, is likely **Low**.

Overall Implementation

The recommendations in the nine areas considered in this study are ambitious, and, if all or even some are implemented it would require significant human and financial resources. One recommendation that applies to all technical areas covered in this report is the return to the built structure and the collection of data on its performance (in a non-destructive or destructive manner as circumstances allow). Such performance data should be presented in context of the as-built design and lessons learned documented.

For the implementation of the recommendations put forward in this report, funding could come from a number of sources, not limited to FLHD and its client organizations. State DOTs, the FHWA, geosynthetic manufacturers, or contractors/installers could all benefit from the system level recommendations in this report, and should be approached when a promising project arises.

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APPENDIX A – SURVEY FORM

Geosynthetics Utilization in Federal Lands Programs

(Please return survey by mail to Brent Robinson, Dept of CE, CB 7908, Raleigh, NC 27695-7908, or fax to (919) 515-7904, or e-mail to brrobins@ncsu.edu)

Agency________________________________
Name ________________________________
Title ________________________________
Address________________________________
City__________________State________ Zip__________
Phone No.________________Fax No.________________
Email address________________________________

<u>Please answer the following questions. Mark answers with a check; more than one may apply. Attach additional sheets, if necessary.</u>

1. Have you ever used Geosynthetics in construction projects?
   [ ] No (Go to question 2)
   [ ] Yes
   If yes: About how many projects per year?

[ ] Less than one	[ ] one
[ ] 2 to 5	[ ] 6 to 10
[ ] 11 to 20	[ ] more than 20

2. Mark the applications that you were involved **(I)** in the design or construction (with or without geosynthetics); then mark **(G)** for projects that also used geosynthetics.

<u>ROADS</u>

<u>(I)</u> <u>(G)</u>	<u>(I)</u> <u>(G)</u>
[ ] { } Unpaved, Rehabilitation	[ ] { } Unpaved, New Construction
[ ] { } Paved, Asphalt Overlays	[ ] { } Paved, Subgrade Reinforcement
[ ] { } Frost heave	[ ] { } Deep Patches for Soft Shoulders
[ ] { } Edge Drains	[ ] { } Separation (base course from soil)

[ ] { } Other ________________________________

<u>GEOTECHNICAL</u>

<u>(I)</u> <u>(G)</u>	<u>(I)</u> <u>(G)</u>
[ ] { } Retaining Walls	[ ] { } Mechanically Stabilized Earth Walls
[ ] { } Embankments (Reinf., soft soil)	[ ] { } Construction Platforms
[ ] { } Rock Slopes	[ ] { } Soil Slopes
[ ] { } Shallow footing subgrade reinf.	[ ] { } Drainage

[ ] { } Other ________________________________

Of the above, which applications are most commonly used by, or for, your agency?

____
____

3. State the reasons that led to the use of geosynthetics over other materials in projects identified in Question 2.____
____
____

4. Do you have specifications, policy manuals and/or design guidelines for use of geosynthetics in any of the applications listed above?

Yes ____ No ____ if yes, please list and attach a copy to this survey, if possible.
1.________________________________
2.________________________________
3.________________________________

5. Do you have performance data of geosynthetics in any of your projects?

Yes ____ No ____ if yes, please attach a copy to this survey, if possible.

6. For what type of projects does your agency use geosynthetics?
(Check all that apply.)
[ ] Temporary construction measure - 0 to 3 months
[ ] Semi- permanent measure – up to 2 years
[ ] Permanent Installation- over 2 years

7. Indicate all of the types of geosynthetics that your agency uses or has used.
a. Geotextiles
    [ ] Woven ____
    [ ] Non-woven needle punched ______________________________
    [ ] Non-woven heat bonded _________________________________
    [ ] Other (state type) _____________________________________
b. Geogrids
    [ ] Uniaxial ____
    [ ] Biaxial ____
c. Geonets
    [ ] Description____
d. Gemembranes
    [ ] Description____
e. GCL (Geosynthetics Clay Liners)
    [ ] Description ____
f. Combination(s) of the above (such as Drainage Geocomposites) (state) ________
    ____
g. Other (state)____

8. Does your agency have a pre-approved product list? Yes________ No__________
If yes, please attach a copy of your pre-approved list.

9. How does your agency obtain the information necessary to approve a product? Check all that apply.

[ ] Tests by this agency
[ ] Demonstrations by the manufacturer
[ ] Tests conducted by an independent consultant
[ ] Research conducted on various products and methods
[ ] Manufacturer's certification letters
[ ] Tests by other FHWA agency
[ ] Demonstrations by FHWA

10. Have the available products and methods produced satisfactory results? Describe successful projects using geosynthetics:______________________________

11. Have you had unsuccessful experiences with geosynthetics? Describe. What do you believe was the source of the problems?______________________________

13. What information would you like to have when selecting geosynthetics for a project?

14. Comment on your agency's other challenges in using geosynthetics

15. Geosynthetics has the potential to offer substantial cost saving in Federal Land Projects if properly designed and installed

__Strongly Agree __Agree __Neutral __Disagree __Strongly Disagree

16. Reason for not using Geosynthetics includes:

[ ] No design guidelines
[ ] No documentation in standards
[ ] Do not know about the materials
[ ] Unaware of geosynthetics applicability to an application
[ ] No prior experience with the materials
[ ] No information on long term performance of the material

17. May we contact you with questions or for clarifications? Yes________ No_________

Other Comments:____

Thank you for your time and effort.