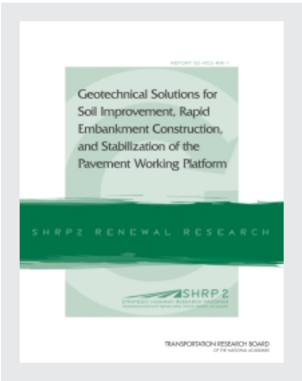

Geotechnical Solutions for Soil Improvement, Rapid Embankment Construction, and Stabilization of the Pavement Working Platform

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The Second
STRATEGIC HIGHWAY RESEARCH PROGRAM

SHRP 2 REPORT S2-R02-RW-1

Geotechnical Solutions for Soil Improvement, Rapid Embankment Construction, and Stabilization of the Pavement Working Platform

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The Second Strategic Highway Research Program

America's highway system is critical to meeting the mobility and economic needs of local communities, regions, and the nation. Developments in research and technology—such as advanced materials, communications technology, new data collection technologies, and human factors science—offer a new opportunity to improve the safety and reliability of this important national resource. Breakthrough resolution of significant transportation problems, however, requires concentrated resources over a short time frame. Reflecting this need, the second Strategic Highway Research Program (SHRP 2) has an intense, large-scale focus, integrates multiple fields of research and technology, and is fundamentally different from the broad, mission-oriented, discipline-based research programs that have been the mainstay of the highway research industry for half a century.

The need for SHRP 2 was identified in *TRB Special Report 260: Strategic Highway Research: Saving Lives, Reducing Congestion, Improving Quality of Life,* published in 2001 and based on a study sponsored by Congress through the Transportation Equity Act for the 21st Century (TEA-21). SHRP 2, modeled after the first Strategic Highway Research Program, is a focused, time-constrained, management-driven program designed to complement existing highway research programs. SHRP 2 focuses on applied research in four areas: Safety, to prevent or reduce the severity of highway crashes by understanding driver behavior; Renewal, to address the aging infrastructure through rapid design and construction methods that cause minimal disruptions and produce lasting facilities; Reliability, to reduce congestion through incident reduction, management, response, and mitigation; and Capacity, to integrate mobility, economic, environmental, and community needs in the planning and designing of new transportation capacity.

SHRP 2 was authorized in August 2005 as part of the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU). The program is managed by the Transportation Research Board (TRB) on behalf of the National Research Council (NRC). SHRP 2 is conducted under a memorandum of understanding among the American Association of State Highway and Transportation Officials (AASHTO), the Federal Highway Administration (FHWA), and the National Academy of Sciences, parent organization of TRB and NRC. The program provides for competitive, merit-based selection of research contractors; independent research project oversight; and dissemination of research results.

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Notice

The project that is the subject of this report was a part of the second Strategic Highway Research Program, conducted by the Transportation Research Board with the approval of the Governing Board of the National Research Council.

The members of the technical committee selected to monitor this project and to review this report were chosen for their special competencies and with regard for appropriate balance. The report was reviewed by the technical committee and accepted for publication according to procedures established and overseen by the Transportation Research Board and approved by the Governing Board of the National Research Council.

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SHRP 2 STAFF

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The research reported on herein was performed by Iowa State University, supported by Virginia Polytechnic Institute and State University, University of Kansas, Geosystems L.P., Ryan R. Berg & Associates Inc., The Collin Group, Trinity Construction Management Services, Barry Christopher, and Dennis Turner. Authors of this report are Vernon R. Schaefer of Iowa State University and Ryan R. Berg of Ryan R. Berg & Associates. The other principal investigators of this project are Barry Christopher; James Collin of The Collin Group; Donald Bruce of Geosystems; David White of Iowa State University; Jie Han of University of Kansas; Gary Fick of Trinity Construction Management Services; and George Filz, James Mitchell, and Linbing Wang of Virginia Polytechnic Institute and State University.

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FOREWORD

Jerry A. DiMaggio, D.GE, PE, *SHRP 2 Senior Program Officer, Renewal*

This report describes the work, results, and products of Phase 2 of SHRP 2 Project R02, Geotechnical Solutions for Soil Improvement, Rapid Embankment Construction, and Stabilization of the Pavement Working Platform. The selection of an appropriate geoconstruction technology to use in transportation systems is a complex undertaking that depends on the integration of available knowledge and a number of problem-specific and site-specific factors. A web-based information and guidance system, Geotechnical Solutions for Transportation Infrastructure, was developed to provide access to critical information on geoconstruction technologies and to provide a tool to assist in deciding which technologies are potentially applicable to site-specific conditions. Forty-six ground improvement and geoconstruction technologies and processes are included in the system. The system contains a technology catalog and a technology selection assistance tool, as well as sections on design philosophy and a glossary. User products for each technology include technology fact sheets, photographs, case histories, design procedures, quality control/quality assurance procedures, cost estimating tools, specification guidance, and a bibliography. This web-based system collects, synthesizes, integrates, and organizes a vast amount of important information in a system that makes the information readily accessible.

Problematic soil and rock conditions routinely have significant negative cost and schedule effects on transportation infrastructure projects. Many geoconstruction solutions to these problems face obstacles that prevent broader and effective utilization. SHRP 2 Project R02 investigated the state of practices of transportation project engineering, geotechnical engineering, and earthwork construction and identified and assessed methods to advance the use of these technologies. Several of the identified technologies, although underused, offer significant potential to achieve one or more SHRP 2 Renewal objectives: (1) rapid renewal of transportation facilities, (2) minimal disruption of traffic, and (3) production of long-lived facilities. Project R02 encompasses a broad spectrum of materials, processes, and technologies that are applicable to (1) new embankment and roadway construction over unstable ground, (2) roadway and embankment widening, and (3) stabilization of pavement working platforms.

CONTENTS

Executive Summary

Many geoconstruction technologies, some in existence for several decades and others recently developed, face both technical and nontechnical obstacles preventing broader and effective use in transportation infrastructure projects. The second Strategic Highway Research Program Renewal Project R02 (SHRP 2 R02), Geotechnical Solutions for Soil Improvement, Rapid Embankment Construction, and Stabilization of the Pavement Working Platform, investigated the state of practices of transportation project engineering, geotechnical engineering, and earthwork construction and identified and assessed methods to advance the use of these geoconstruction technologies. Several of the identified technologies are underused in current practice, yet they offer significant potential to achieve SHRP 2 Renewal objectives (rapid renewal of transportation facilities, minimal disruption of traffic, and production of long-lived facilities). Project R02 encompasses a broad spectrum of materials, processes, and technologies within geotechnical engineering and geoconstruction that are applicable to one or more of the following elements of construction: new embankment and roadway construction over unstable soils, roadway and embankment widening, and stabilization of pavement working platforms.

Transportation engineers, planners, and officials lack a readily available, comprehensive system to access critical information for geoconstruction technologies and lack a tool to assist in deciding which technologies may be applicable to their projects. Phase 2 of the R02 project focused on those geotechnical materials, systems, and technologies, as identified in Phase 1, that possess the most promise for achieving SHRP 2 Renewal objectives. The tasks in Phase 2 were devised to catalog the technologies and to develop design, quality control and quality assurance (QC/QA) guidance procedures, cost estimating tools, and sample guide specifications, all geared toward mitigating obstacles that prevent widespread use of these technologies. The main end user umbrella product is a web-based information and guidance system for geotechnical solutions for transportation infrastructure. The system provides the information necessary for determining the applicability of specific technologies for specific situations and then directs the user to supporting information needed to apply the selected technologies. The website contains a technology catalog and selection system, a geotechnical glossary, and sections on geotechnical design philosophy. Eight end user products are available for each of the geoconstruction technologies in the catalog: technology fact sheets, photographs, case histories, design procedures, QC/QA procedures, cost estimating, specifications, and a bibliography.

The web-based system was developed specifically for local, state, and federal transportation agency personnel and for consultants providing engineering services to transportation agencies. Geotechnical engineers comprise the primary audience for this system; however, the products are useful to various personnel, including civil and structural design and construction engineers, pavement design and construction engineers, project managers, and district engineers, as well as to procurement, research, and maintenance specialists. Nonpublic groups, such as general contractors, consultants, architects, engineers, academics, and students, will also find the system useful. In addition, the international community can use the system, and this will spur technology exchange and advancements here in the United States.

The principal value of the web-based information and guidance system is that it collects, synthesizes, integrates, and organizes a vast amount of important information about geotechnical solutions in a framework that makes the information readily accessible to state transportation agency (STA) personnel for rapid renewal and improvement of the transportation infrastructure. The system saves users time and makes users more efficient in selecting and designing geoconstruction systems for transportation infrastructure. Each of the technology products provides value by concisely summarizing information organized by technology. Furthermore, the system is readily updatable. There is nothing else like it currently available.

The R02 products and tools are organized and presented in a website in lieu of printed reports because of the advantages that a web-based system provides to users. These advantages will significantly improve achievement of SHRP 2 Renewal objectives throughout the United States. Key advantages of the web-based system include the following:

- It is a living system that can be updated and expanded.
- It is readily accessible.
- It provides a means for technology use exchange among state transportation agencies.

There are several work products that compile and document information, data, references, technology assessments, and website development completed in Phase 2. The main end user product is the information and guidance system for the Geotechnical Solutions for Transportation Infrastructure website, which includes more than 400 individual products and tools.

The R02 project developed and produced a platform for delivering the project products, tools, and reports via a website. However, the current project website requires additional development to become a fully functional website open to the general transportation professional.

CHAPTER 1

Introduction

This report describes the work efforts, results, and products of Phase 2 of the second Strategic Highway Research Program Renewal Project R02 (SHRP 2 R02), Geotechnical Solutions for Soil Improvement, Rapid Embankment Construction, and Stabilization of the Pavement Working Platform. Although in existence for several decades, many geoconstruction technologies face both technical and nontechnical obstacles preventing broader and effective use in geotechnical engineering for transportation infrastructure projects. The SHRP 2 R02 project investigated the state of practices of transportation project engineering, geotechnical engineering, and earthwork construction to identify and assess methods to advance the use of these technologies. Several of the identified technologies are underused in current practice, yet they offer significant potential to achieve one or more of the following SHRP 2 Renewal objectives:

- Rapid renewal of transportation facilities
- Minimal disruption of traffic
- Production of long-lived facilities

This SHRP 2 R02 project focused on investigating various geoconstruction technologies that are applicable to one or more of the following elements of construction:

Element 1: New embankment and roadway construction over unstable soils.
Element 2: Roadway and embankment widening.
Element 3: Stabilization of pavement working platforms.

Project R02 encompasses a broad spectrum of materials, processes, and technologies within geotechnical engineering to help transportation agencies achieve SHRP 2 Renewal strategic objectives. A total of 47 geoconstruction technologies potentially applicable to the R02 project were identified and assessed in the Phase 1 work, and a total of 40 were carried forward for Phase 2 work. During the course of the Phase 2 work, some technologies were added and some were subdivided. End user products and tools were produced for a total of 46 technologies.

The SHRP 2 R02 project research team consisted of private engineering consultants and university researchers having broad-based practice and research experience in geotechnical engineering, pavement engineering, and transportation applications. In the proposal, the research team presented a business plan approach to the research, beginning with a project vision to guide our efforts:

> To make geotechnical solutions more accessible to public agencies in the United States for rapid renewal and improvement of the transportation infrastructure.

Today, numerous technical and nontechnical obstacles and impediments inhibit widespread, effective use of geotechnical technologies in transportation works. The results of this project represent the beginning efforts to overcome many of these obstacles and impediments for the betterment of transportation infrastructure in the United States. Achieving our vision will produce a paradigm shift in the accessibility of expedient geotechnical solutions for transportation projects.

In Phase 1, a situation assessment was completed, which assessed the state of the practice of each identified technology for the three project elements. Hence, the focus of Phase 1 was on identifying those geotechnical materials, systems, and technologies that best achieve the SHRP 2 Renewal strategic objectives of rapid renewal, minimal disruption, and long-lived facilities for the three elements. The focus of Phase 2 was on developing mitigation strategies, cataloging the identified technologies, and developing guidance for design, quality control and quality assurance (QC/QA), cost estimation, and specifications. In Phase 2, this was accomplished through six specific tasks:

- Task 8: Test the effectiveness of these mitigation methods approved or amended from Phase 1, and evaluate their effectiveness.
- Task 9: Develop a catalog of materials and systems for rapid renewal projects.
- Task 10: Develop design procedures, QC/QA processes, and guidance for applying these geotechnical materials and systems.
- Task 11: Develop methods for estimating the application costs of these geotechnical materials and systems.
- Task 12: Develop sample guide specifications for these geotechnical materials and systems.
- Task 13: Develop a final report for Phase 2 detailing the work conducted in Tasks 8 through 12.

As the project progressed, the research team developed significant products and tools beyond the scope of these tasks in support of our project vision. These materials include the technology fact sheets, case histories, technology development projects, and, ultimately, the project website.

Completion of these tasks resulted in the establishment of a web-based information and guidance system for geotechnical solutions for transportation infrastructure. This report describes the work products developed during Phase 2 (Chapter 2), provides a detailed description of the R02 website (Chapter 3), describes the mitigation of obstacles (Chapter 4) and the development of background information (Chapter 5), and provides implementation recommendations (Chapter 6).

CHAPTER 2

R02 Project Products

Background

In Phase 2, the focus was on those geotechnical materials, systems, and technologies identified in Phase 1 that possess the most promise for achieving the SHRP 2 R02 objectives of rapid renewal, minimizing disruption, and producing long-lived facilities. The tasks in Phase 2 were designed to catalog the technologies and develop design, construction quality control and quality assurance (QC/QA), guidance procedures, cost estimating tools, and sample guide specifications, all geared toward mitigating the obstacles that prevent widespread and effective use of these technologies. The main end user umbrella product is a web-based information, guidance, and selection system for geotechnical solutions for transportation infrastructure. The website contains the technology catalog and the selection system, as well as sections on geotechnical design philosophy and a geotechnical glossary. Eight end user products are available for each of the geoconstruction technologies in the catalog. In total, there are more than 400 individual project products contained within the website umbrella. These products are tools for assessing and engineering geoconstruction technologies for transportation infrastructure. The background information developed for the website is contained in stand-alone project documentation (i.e., not published) reports.

Currently, transportation engineers, planners, and officials lack a readily available, comprehensive system to access critical information for geoconstruction technologies, and they lack a tool to assist in deciding which technologies are potentially applicable to their projects. The goals of the web-based information and guidance system were established to satisfy the following needs:

- Provide an information system that contains a comprehensive technology catalog and technology selection assistance.
- Provide selection assistance to the user to develop a short list of applicable technologies based on a few key project and site characteristics.
- Provide information and guidance for engineers to select and design a technology for a specific project.
- Provide an interactive, fully functional, and populated program to house the information system and guide the user through the selection assistance.
- Provide a glossary of the abbreviations and terms used throughout the information and guidance system.

The system provides the information necessary for determining the applicability of specific technologies to specific situations and then guides the user to supporting information needed to apply the selected technology to a specific project. The system is based on the three project elements: constructing new embankments and roadways over unstable soils, widening and expanding existing roadways and embankments, and stabilizing the working platform. During Phases 1 and 2, the R02 research team identified a large number of ground improvement and geoconstruction technologies and processes applicable to the three elements. The number of technologies was winnowed to 46 and are considered particularly applicable to the three elements. The identified technologies are listed here and will be referenced throughout this report:

- Aggregate columns
- Beneficial reuse of waste materials
- Biotreatment for subgrade stabilization
- Blasting densification
- Bulk-infill grouting
- Chemical grout injection systems
- Chemical stabilization of subgrades and bases
- Column-supported embankments
- Combined soil stabilization with vertical columns
- Compaction grouting

- Continuous flight auger piles
- Deep dynamic compaction
- Deep mixing methods
- Drill-and-grout and hollow bar soil nailing
- Electroosmosis
- Excavation and replacement
- Fiber reinforcement in pavement systems
- Geocell confinement in pavement systems
- Geosynthetic-reinforced construction platforms
- Geosynthetic-reinforced embankments
- Geosynthetic reinforcement in pavement systems
- Geosynthetic separation in pavement systems
- Geosynthetics in pavement drainage
- Geotextile encased columns
- High-energy impact rollers
- Hydraulic fill with geocomposite drains and vacuum consolidation
- Injected lightweight foam fill
- Intelligent compaction and roller integrated compaction monitoring
- Jet grouting
- Lightweight fill, EPS geofoam, low-density cementitious fill
- Mechanical stabilization of subgrades and bases
- Mechanically stabilized earth wall systems
- Micropiles
- Onsite use of recycled pavement materials
- Partial encapsulation
- Prefabricated vertical drains and fill preloading
- Rapid impact compaction
- Reinforced soil slopes
- Sand compaction piles
- Screw-in soil nailing
- Shoot-in soil nailing
- Shored mechanically stabilized earth wall system
- Traditional compaction
- Vacuum preloading with and without prefabricated vertical drains (PVDs)
- Vibro compaction
- Vibro concrete columns

The information and selection guidance system guides the user to one or more potential technologies that may be suitable for a particular project based on general project information. From these potential technologies, the user can access the additional information necessary for further project-specific screening (i.e., depth limits, soil types, groundwater conditions, project types, project-specific constraints, general advantages/disadvantages). For each technology, the user can access design methodologies, quality control and assurance methods, cost information, and specifications.

Eight products or user tools were developed for each of the 46 technologies. An exception is where insufficient information was available to develop such a tool (e.g., cost estimating tool for an emerging technology). The eight tools are the following:

- Technology fact sheet
- Photographs (of technology)
- Case histories
- Design guidance
- QC/QA procedures
- Specifications
- Cost information and cost estimating tool
- Bibliography

Each tool is described in the following sections explaining its purpose, information contained in the tool, and its format. A section summarizing the review processes employed for the development of these tools follows. Example tools may be viewed on the Geotechnical Solutions for Transportation Infrastructure website.

The web-based system was developed specifically for transportation agency personnel at local, state, and federal levels and for consultants providing engineering services to transportation agencies. The primary audience is geotechnical engineers, but the products are useful to various personnel, including civil/structural design and construction engineers, pavement design and construction engineers, project managers, and district engineers, as well as procurement, research, and maintenance specialists. Nonpublic groups, such as contractors, consultants, architects, engineers, academics, and students, will also find the system useful. In addition, the international community can use the system, and this will spur technology exchange and advancements here in the United States. The website is discussed in more detail in Chapter 3.

The website and downloadable technical products and tools will be used by both technical and nontechnical audiences to learn about the technologies. The website can be used to investigate candidate solutions for general and for project-specific site conditions by technology category classifications, overall technologies catalog, or using the selection system. A user is able to easily locate procedures for design and QC/QA and to develop cost estimates and specifications. The interactive nature of the website allows the user to test various project solutions more efficiently than currently possible. Nontechnical users will find the technology fact sheets, photographs, and case histories valuable for quickly developing a basic understanding of geoconstruction technology. The case histories provide examples where the technology has been used, and they include STA technical contacts, when available.

The primary value of the web-based information and guidance system is that it collects, synthesizes, integrates, and organizes a vast amount of important information about geotechnical solutions in a system that makes the information readily accessible to STA personnel. Furthermore, it is readily updatable. There is nothing else like it currently available. The system saves users time and makes users more efficient in selecting and designing geoconstruction systems for transportation infrastructure. Each of the technology products and tools provides value in concisely summarizing information organized by technology. The website was enthusiastically received when previewed at the 2011 Transportation Research Board Annual Meeting and at workshops with the Louisiana Department of Transportation and Development (DOTD), the Minnesota Department of Transportation (MnDOT), and the Transportation Association of Canada. In summary, this product makes geotechnical solutions more accessible to STAs for rapid renewal and improvement of the transportation infrastructure.

Technology Fact Sheets

Purpose of the Fact Sheets

Each technology fact sheet is a one-sheet (double-sided) summary of key features of a technology. Its purpose is twofold. The fact sheet is a concise introduction to a technology for those unfamiliar with (or with limited knowledge of) that technology. The fact sheet is also a concise summary of applicability and limitations of a technology for use by those already familiar with the technology. Thus, the fact sheet product is a tool for use by the full spectrum of STA personnel, and others.

Information Contained in the Fact Sheet

The format of the fact sheet was developed to organize and present information on different aspects of engineering with a geoconstruction or ground improvement technology. The information is presented in a consistent format, thus aiding the user in comparing different technologies. Information for the fact sheet came from the respective technology comprehensive technical summary (see Phase 2 *Technology Evaluation Methodology Report*).

Each fact sheet contains summary information under each of the following categories:

- Photograph or schematic of technology
- Basic function
- Advantages
- General description
- Geologic applicability (soil types, depth, etc.)
- Construction methods
- Additional information
- SHRP 2 R02 applications (Elements 1, 2, and 3)
- Example successful applications
- Complementary technologies
- Alternate technologies
- Potential disadvantages
- Key references
- Date summary prepared or revised

Each category is subtitled on the fact sheet and contained within a table cell. All information is contained on the front and back sides of a single sheet. The list of technologies is shown in Table 1 on the fact sheet.

Photographs

Purpose of Photographs

The purpose of this product is to introduce a technology. The photographs are a visual introduction to a technology for those unfamiliar with (or with limited knowledge of) that technology.

Information Contained in the Photograph Sheet

Several photographs may be presented, depending on the technology being addressed. Photographs may include a structure under construction, a constructed structure, equipment used with a technology, material installation, QC/QA, or aesthetics of a technology.

Case History Summaries

Background

A component of the R02 catalog of materials and systems for rapid renewal projects is case history summaries for the identified technologies. Case histories are a key instrument to overcoming obstacles and resistance to using a particular technology by a transportation agency. The lack of accessible case histories was identified in Task 2 of the Phase 1 Report as one of the top six obstacles inhibiting widespread use of ground improvement technologies.

Case histories document who, where, why, and how transportation agencies and others have used a particular technology. Many items such as construction methodology, timing, cost, and QC/QA methods employed can be highlighted in such project summaries. Thus, these summaries demonstrate the successful application of a technology to transportation engineers and management.

Case histories are widely used by vendors and contractors to promote the use of various geoconstruction techniques. Likewise, case histories are widely used within other industries and technologies. These case histories highlight the benefits of using a technology and promote use by others. Case histories produced by vendors and contractors are typically commercially slanted to promote their particular product or firm, which limits their relevancy to transportation engineers and management. One to three case histories were developed for each technology and are on the initial (beta test–ready) Geotechnical Solutions for Transportation Infrastructure website.

Purpose of R02 Case History Summaries

The purpose of the R02 case histories is twofold. These case histories promote the use of new technologies by a transportation agency and will help develop technology leaders within individual agencies. Case histories provide a means for engineers using such technologies to be recognized by their peers. Development of technology leaders within an agency and on regional and national bases is critical to overcoming obstacles that limit wider spread use of such technologies. Thus, the desired primary source of case histories is transportation agency personnel, providing unbiased information to share with their colleagues.

Format

A consistent format was developed to produce the case histories products. Each case history is no more than two pages in length. Only brief summaries of the desired information are to be provided. The following items, as available for a particular project, are to be provided (unavailable items should be left blank):

- Technology name
- Project name
- Location (e.g., city, state, route number)
- Owner
- Contractor
- Engineer
- Year constructed
- Project photograph or drawing
- Project summary or scope
- Complementary technologies used
- Alternate technologies
- Additional photo (optional)
- Additional drawing (optional)
- Performance monitoring (if available)
- Cost information (if available)
- Case history author or submitter
- Project technical paper (cite if available)
- Date prepared

This format should also be used to capture additional, future STA case history information to facilitate additions to the web-based system. The format is easy to use and does not require significant time for the submitter to complete, thus helping to encourage submission of additional case histories by agency personnel.

Populating

The initial population of case histories was developed from information captured in the comprehensive technical summary (see *Technology Evaluation Methodology Report*) developed for each technology. An average of two case histories per technology was developed to provide this initial population. Many of the source documents are technical papers and not necessarily authored by agency personnel (as desired).

It is planned that the population of case histories will be significantly expanded, with agency users submitting additional case histories. This should occur during the beta testing program and be a continual process once the website is fully released.

Submission Guidelines

The geotechnical solutions website will be seeking additional geoconstruction case history summaries to populate its database. Case history summaries for technologies addressed within this website are desired. A guideline for who may submit case histories has been established, as follows:

- Case histories authored or submitted by Department of Transportation (DOT) and other transportation agency personnel are desired.
- A DOT (or other transportation agency) contact for each case history is desired. Generally, this should be the author or submitter. A university researcher may also be listed as the contact.
- In addition to submissions from DOT personnel, case histories will be accepted from others if the case history is documented in any of the following:
  - Research report;
  - Published technical paper;
  - Federal Highway Administration (FHWA) or other federal government agency publication; or
  - DOT or other state agency publication.

All case history summaries must be submitted in the R02 format (see Appendix A). All case histories are limited to a maximum of two pages. Each applicable cell of the template should be completed, and it should be noted where information is not available or is not applicable. An electronic copy of the case history template (in Microsoft Word) will be provided and should be used by authors and submitters.

Design Guidance

Purpose of the Design Guidance

A design guidance product is provided for each technology. The purpose of this product is to provide guidance on engineering and designing with a particular technology to STA personnel and others. This product will likely be used during the planning, technology selection, and design phases of a project. The design guidance product is a concise summary of a preferred or of various design procedures, applicable to a respective technology. Thus, the design guidance product is a tool intended for use by STA engineers (typically geotechnical or pavement engineers) and others.

Information Contained in the Design Guidance

The design guidance starts with a clear statement of whether there is a preferred design procedure. A preferred design procedure is typically a procedure well documented in an FHWA reference manual. A complete reference is provided to the FHWA (or other) source of the preferred design procedure, including a link to download or to purchase the reference manual.

If there is no preferred (e.g., FHWA) design procedure, it is clearly stated that no FHWA procedure is available. Then, other design procedure(s) recommended for use are listed. Where applicable, it is noted if a procedure is proprietary. A complete reference is provided to the design procedure(s), including a link(s) to download or to purchase.

A summary of the design procedure(s) (preferred or recommended) is then presented. If more than one recommended procedure is presented, the differences in the procedures are highlighted. Typical inputs and outputs for the design procedure(s) are listed in a table.

Quality Control and Quality Assurance

Purpose of the QC/QA Procedures Guidance

A QC/QA procedures product is provided for each technology. The purpose of this product is to readily provide current QC/QA procedures applicable to particular technology to STA personnel and others. This product may be widely used during the planning, design, specification writing, or construction phase of a project. The QC/QA procedures product is a concise summary of various procedures applicable to a respective technology that may be employed to ensure quality in the constructed works. Thus, the QC/QA procedures product is a tool for use by the full spectrum of transportation agency personnel, and others.

Information Contained in the QC/QA Procedures

The QC/QA guidance starts with a clear statement of whether there is an FHWA document that addresses QC/QA procedures for this technology. If so, a complete reference is provided to that FHWA document, including a link to download or to purchase the document. Any recommended materials to supplement the FHWA document are noted.

The components of a QC/QA program and typical items used to measure and document quality for the particular technology are listed in a table. Differentiation between QC and QA, between existing and emerging procedures, between process control and related material, and between material and system behavior are shown in this table.

Guidelines on individual QC and QA methods are provided. The following information is provided for each method:

- Name of method
- Reference(s) for method
- Summary of method
- Statement on accuracy and precision
- Implementation requirements
- Comments (as applicable)

Cost Information and Estimating Tools

Purpose of Cost Information and Estimating Tools

Selection of a specific geotechnical solution should be based first on sound engineering, while recognizing that conditions may identify two or more technologies as potential solutions; when this occurs, it may be appropriate to consider the initial cost of a solution in the selection of a technology. The cost information and estimating tools are intended to provide guidance to the user for developing a conceptual cost estimate for a specific project.

The cost information products and tools produced as a part of this project are intended to provide the user with a means for understanding what variables may affect the cost of a given geotechnical solution, as well as developing a preliminary cost estimate for a given technology on a project-specific basis. Many factors can affect cost for a specific project (i.e., soil type, labor rates, and utility conflicts); identifying and understanding how these variables affect cost can be beneficial when evaluating the applicability of a geotechnical solution. It is important to note that although initial cost is a consideration when selecting a solution, it should not be the driving force; performance, construction time, life-cycle costs, and safety should be factored into the evaluation of alternative geotechnical solutions.

Information Gathered in the Cost Information and Estimating Tool Process

The comprehensive technology summary (CTS) project documentation reports provided the starting point for collecting cost information on each technology. Sections of the CTS that were used to identify potential cost variables were the following:

- Technology applicability screening parameters
- Case histories
- Summary of design procedures
- Summary of QC/QA procedures
- Cost information
- Available specifications

The CTS documents and cited references were used to identify potential cost variables, to develop guidance on the impact of these variables, and to identify sources for collecting actual project cost data.

Gathering actual project cost data was the next step for developing the cost information summaries and associated conceptual estimating tools. An extensive search of state DOT bid tabulations was made to gather unit cost information for each technology. Bid Express, which is a subscription service provided by Info Tech, Inc., was the primary source for the collection of DOT bid tabulation data. There are 35 state DOTs that use this service for housing bid information. In addition, the Caltrans website was used to collect project cost data for highway projects in California. In general, this data collection consisted of two steps:

1. Conduct a search by state to identify bid items by technology.
2. Once a bid item is identified, search within that state for bid tabulation results.

There is little uniformity between state DOTs for bid item descriptions. In many cases, it was necessary to search the state DOT website for standard specifications and special provisions to verify that a bid item description fit with a specific technology.

Project cost data was sorted by technology and reviewed with the following criteria in mind:

- Whenever possible, bid tabulation data from multiple sources was used to provide some geographical diversity.
- Obvious unbalanced bids were excluded from the calculation of minimum, maximum, and average unit prices.
- Where a large enough sample of bid tabulations was available, the most current unit prices were reported.

Despite the extensive cost research performed, there were a limited number of technologies for which reliable cost data were unavailable. In some cases, this was because the technology had only recently been developed. In other cases, the technologies were not necessarily new, but had been rarely used.

Reports and Products

Two estimating products were produced for the R02 technologies, a cost information summary and a conceptual cost estimating tool. The cost information document is the primary source for an introduction to cost variables, approximate cost ranges, and actual bid tabulation data. The conceptual cost estimating tool is a spreadsheet that allows the user to input project-specific conditions and unit costs to produce a preliminary cost estimate. Inputs that require preliminary design information are identified. Unit cost inputs should be based on the typical cost ranges or the historical cost information contained in the cost information summaries.

Both a cost information document and a conceptual cost estimating tool were developed for the majority of the 46 technologies. However, a conceptual cost estimating tool could not be developed, at this time, for a few technologies because of limited use of the technology in the United States to date and unavailability of reliable cost data. Neither of these tools was developed for the base-level technologies of excavation and replacement and traditional compaction since STAs have well-established local costs.

Format

Each cost information document is divided into the following sections:

- Commentary: provides a brief description and typical units used for measurement and payment.
- Cost information summary: identifies project variables that may affect cost, describes associated technologies that may need to be included with a given technology (i.e., working platform may be required), and includes a table with approximate cost ranges.
- Historical cost information: provides a sample of actual state DOT bid tabulation data for the technology.
- Conceptual cost estimating tool: provides a link to a spreadsheet estimating tool, or provides a simple step-by-step procedure for estimating a cost, or advises the user that a cost estimating tool or procedure is not appropriate for this technology.

The spreadsheets used for conceptual estimating use a step-by-step layout that varies by technology because different inputs are required to estimate costs.

Specifications

Purpose of Specification Products

The purpose of the specification product is to provide users with a tool that aids in preparation of a project or general STA specification. Thus, the specification product provides guidance to users and is not a ready-to-use specification. This product is based on existing specifications.

Information Contained in Specification Guidance

Generally, all technologies have a Review of Existing Specifications section. A brief discussion on each of the specifications collected and evaluated, as part of the specification assessment, is presented. A table listing these specifications and identifying the type of specification is provided. Specification types are noted as method approach, performance approach, or combined performance–method approach. A performance level is noted for those specifications that use a performance approach.

The review section is followed by either a Preferred Specification section or a Summary of Example Specifications section. A preferred specification is typically a specification from an FHWA manual. A complete reference is provided to the FHWA (or other) source of the preferred specification. A brief discussion is presented with a preferred specification, based on the Task 12 assessment, and notes any important items that are missing and additional comments.

The Summary of Example Specifications may include multiple specifications. A brief discussion is presented for each specification, based on the Task 12 assessment, and notes any important items that are missing and additional comments.

Bibliography

Purpose of Bibliography

The bibliography documents the source documents that were used to complete the CTS, design and QC/QA assessment, and specification assessment documents for a given technology. The bibliography product is a tool for engineering with a technology by STA personnel. It is proposed (Phase 3) that links for downloading or ordering of cited references be provided on the Geotechnical Solutions for Transportation Infrastructure website.

Information Contained in Bibliography

The bibliography contains complete reference information for each item cited. Additionally, a matrix table is provided to indicate what type of information is contained in each listed reference. This provides a means for users to efficiently identify the information provided in each reference. The following information topics are listed in the matrix table:

- Technology overview
- Site characteristics
- Analysis techniques
- Design procedure
- Design codes
- Construction methods
- Construction time
- Equipment and contractors
- Construction loads
- Contracting
- Construction specifications
- QC/QA
- Performance criteria
- Monitoring
- Geotechnical limitations
- Nongeotech limitations
- Case history
- Environmental impacts
- Initial cost
- Life-cycle costs
- Durability
- Reliability

Review Processes

Five of the products were developed by the same team of student/researcher and mentor that researched and prepared the source documents for that respective technology. Source documents are the CTS, design and QC/QA assessment, and specification assessment. The products were typically drafted by the students or researchers and then reviewed by the mentors. The photographs, design guidance, QC/QA procedures, specifications, and bibliography products were prepared by this process. The technology fact sheet and case history products were prepared by the two project co-managers. Information from the CTS (post-mentor review) was used to prepare these two products for each respective technology. The cost estimating products were prepared by the cost specialist on the project team. All of the Element 1 and 2 cost estimating products were reviewed by one of the project principal investigators (PIs), and all Element 3 cost estimating products were reviewed by another PI. Review focused on content, consistency between technologies, and unit costs. The next step in the review process was a peer review of all the products and background documents for each respective technology. The peer review team was a group of three students. Each student reviewed every document in sequential order and produced one peer-reviewed document. The process started with review of the technology fact sheet, followed by the remaining products, and finishing with the source documents. This peer review process evaluated each document and product for content, consistency, notation, grammar, and formatting. The peer-reviewed materials then went back to the respective producer to address the peer review comments and finalize the document or product.

The final draft products and source documents then underwent three (or more) additional reviews. The full set of products and documents for a technology was re-reviewed by the PI mentor(s) of that technology. All products and source documents for all 46 technologies were reviewed by both of the project co-managers. These reviews checked each document and product for content, consistency, notation, grammar, and formatting. The print-ready PDF files were specifically checked for formatting in the project manager review.

Future Work

The primary product of Phase 2 of the R02 project is the Geotechnical Solutions for Transportation Infrastructure website. It is an umbrella housing hundreds of products and tools, and it is a primary tool for mitigation of obstacles currently limiting use of these technologies in transportation works. To achieve the R02 project vision, future work of website testing and development must be completed, and then the Geotechnical Solutions for Transportation Infrastructure website can be released and made accessible to those working on transportation infrastructure projects throughout the United States.

The proposed Phase 3 preimplementation works includes the addition of links on the Geotechnical Solutions for Transportation Infrastructure website. It is proposed that links be provided on the bibliography products for downloading or ordering of cited references. Links would include those for downloading electronic copies of noncopyrighted materials (e.g., FHWA manuals), as well as links to purchase copyrighted materials (e.g., professional journal papers).

Product development work will continue in the future with operation and maintenance of the Geotechnical Solutions for Transportation Infrastructure website. Additional sets of products will be added when the website is expanded to include more technologies. Existing products will be updated with maintenance of the website products, as appropriate.

Case history products for the existing technologies will be added with operation of the website. It is anticipated that the number of case histories will grow substantially over time as STA personnel add to the database. Additionally, some of the technologies may be further subdivided (e.g., lightweight fill separated into specific types). Therefore, future work may include a search mechanism for the case history database. Searches by location (e.g., state), date, primary purpose of constructed works, technology subdivision category, and the like may aid users in locating applicable information within a large database.

Additional case histories by agency personnel will be solicited during the next phase of the project work (the website beta testing) and added to the database. In Phase 3, the existing case histories will be forwarded to respective source authors for their review, and to solicit photographs and drawings (where not already provided).

The Geotechnical Solutions for Transportation Infrastructure website is intended to be a living site. As such, technology cost data will need to be reviewed and updated on a regular basis. The schedule and scope of updating need to be defined as implementation of this SHRP 2 work proceeds.

CHAPTER 3

SHRP 2 R02 System

Introduction

The main product of the R02 project is a web-based information and guidance system for geotechnical solutions for transportation infrastructure. The web-based information and guidance system contains important information for the 46 geoconstruction technologies previously identified under Background in Chapter 2. This information allows for technology screening, applying, designing, cost estimating, specifying, and monitoring those technologies. The information and guidance system provides a compilation and toolkit of geotechnical information to address all phases of decision making, from planning to design to contract specifications to construction, which will allow transportation projects to be built faster, to be less expensive, or to last longer. The website allows immediate and well-organized access to the results of the second Strategic Highway Research Program Renewal Project R02 (SHRP 2 R02) research project products. The title for the website, Geotechnical Solutions for Transportation Infrastructure, comes from the objectives associated with the SHRP 2 R02 project. The website is currently housed at http://www.intrans.iastate.edu/geotechsolutions/index.cfm.

The information and guidance system has intentionally avoided endorsing certain geoconstruction technologies over others. To the extent possible, naming specific manufacturers and contractors has also been intentionally minimized. The intent of the system is to offer a means for evaluating a particular geoconstruction technology. A thorough study of the information and guidance system should enable the user to assess where, when, and how a certain geoconstruction technology should be used.

Two systems are referenced in this report. The first system is the web-based information and guidance system, which refers to the entire website and contains a vast amount of technical and nontechnical information and guidance. Within the information and guidance system, a dynamic interactive selection assistance tool has been developed. This is a knowledge-based decision support system that assists in identifying candidate technologies.

The four primary components of the web-based information and guidance system are illustrated in Figure 3.1. The catalog of technologies provides a listing of all the technologies with associated links to the products and tools for the respective technologies. Technology selection contains a listing of technologies by classification and an interactive tool to identify candidate technologies for specific geoconstruction applications using project information and constraints. Final technology selection requires project-specific engineering. Before technology selection, site-specific conditions and constraints must be identified. The geotechnical design process presents an overview of the considerations involved in evaluating site conditions and implementing a geoconstruction technology. This website contains technical terms and industry-specific jargon. Therefore, abbreviations and glossary terms have been compiled to assist in understanding the acronyms and terminology used throughout this website and in its documents.

Framework for the System

The R02 web-based system provides a framework for using the technologies. "Information and guidance" refers to the entire web-based system that provides products and tools for use of the technologies. "Interactive selection assistance" refers to the portion of the website that assists the user in determining a list of candidate technologies for a specific set of project conditions. The objectives of the information and guidance website are to do the following:

- Identify potential technologies for design and construction applicable to
  - Construction over unstable soils,
  - Construction over stable or stabilized soils,
  - Geotechnical pavement components (base, subbase, and subgrade), and
  - Working platforms.

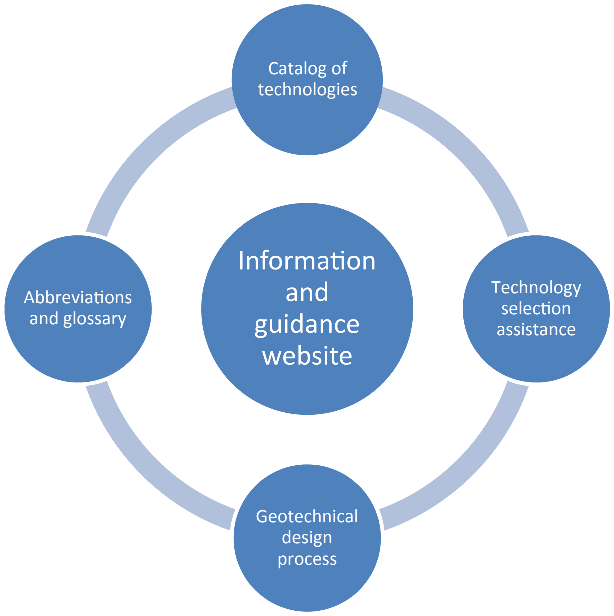


Figure 3.1. Relationship of the four primary components of the information and guidance website.

- Provide assistance to identify a short list of applicable technologies.
- Provide guidance for detailed project-specific screening of technologies.
- Provide an interactive, programmed system.
- Provide up-to-date information in technology products and tools.

The information and guidance website is simple, functional, and completely populated. The selection assistance tool guides a user to a short list of potential (unranked) technologies. The entire system is updatable.

The system was developed along the lines of the three elements listed in Chapter 1; however, the final applications were divided into four areas, as shown in Figure 3.2. The system was developed with input from the research team members, the project advisory board, an expert contact group, FHWA, and SHRP 2. Meetings were conducted throughout the project to bring together STA personnel, practitioners, contractors, and academics who work with the relevant geotechnical materials, systems, and technology areas. These meetings provided valuable brainstorming opportunities to identify technical and nontechnical obstacles limiting widespread effective use of these technologies, best available opportunities for advancing the practice of existing and emerging technologies, and future directions of these technologies in transportation works. Comments from these meetings assisted in developing the objectives, content, and details of the final system.

The information for identifying technologies that may apply to a particular set of geotechnical and loading conditions comes from the R02 team's work efforts, including the development of three source documents for each of the technologies

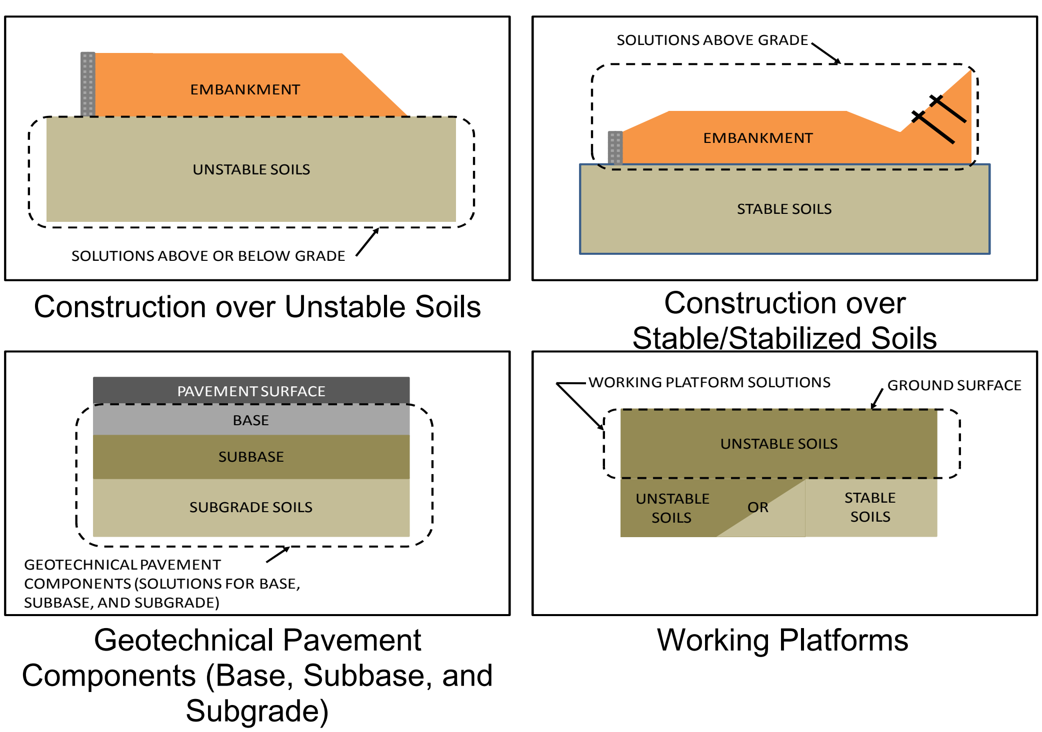


Figure 3.2. Illustration of four application areas for the technologies.

listed under Background in Chapter 2. These source documents are the comprehensive technology summary (CTS), the design quality control assessment (QC), and the design quality assurance (QA) assessment.

The web-based system is programmed utilizing Adobe ColdFusion software in conjunction with a Microsoft Access database. This combination of software allowed the tables developed as part of the selection assistance tool to be ported to a database that can be dynamically queried via the web. The combination of Adobe ColdFusion and Microsoft Access provided these benefits:

- Built-in searching, control, and backtracking mechanisms
- An internal database to hold the knowledge base
- Tools with windows, menus, frames, and drop boxes
- The ability to house the system on a server and allow the program to be run by multiple users via the web

Like most geotechnical analytical solutions, the guidance provided must be measured against the opinion of an experienced geotechnical engineer practicing in the local area of the project. The selection assistance tool was developed with a "keep it simple" philosophy, using two approaches. The first approach is that the tool conservatively removes potentially inapplicable technologies during the process. The second approach, which is a common theme throughout the selection assistance procedure, is that the tool will lead to a short list of candidate technologies. Hence, the final selection of the appropriate technology will be the responsibility of the user. The tool leads the user to multiple technologies for a particular project, and it provides information necessary to understand, design, specify, estimate costs, and verify construction. This tool does not replace the project geotechnical engineer. The geotechnical engineer's judgment is the final step in the selection process, which takes into consideration the following: local geological conditions, local construction practices, construction costs, maintenance costs, design and quality control issues, performance and safety (e.g., pavement smoothness, hazards caused by maintenance operations, and potential failures), inconvenience (an important factor, especially for heavily traveled roadways or long detours), environmental aspects, aesthetic aspects (appearance of completed work with respect to its surroundings), and many other factors.

Web-Based Information System

The homepage for the web-based information system is shown in Figure 3.3. The title of the web page is shown in the upper left corner. Along the left side of the page are several buttons (Home, Project Background, Geotechnical Design Process, Catalog of Technologies, Technology Selection System, Glossary, Abbreviations, Frequently Asked Questions, Submit a Comment, Links, and About this Website) that are always available to the user. The part outlined in the bold box will change as other pages are selected. In subsequent screenshots, only the material within the bold box is shown. As shown within the bold box in Figure 3.3, there are four main parts to the system: Geotechnical Design Process, Catalog of Technologies, Technology Selection, and Glossary.

The Geotechnical Design Process page is included to alert the user to the basic background information needed to conduct geotechnical design, such as project loading conditions and constraints, soil site conditions, and evaluation of alternatives. The page contains links to FHWA documents on review of geotechnical reports, evaluation of soil and rock properties, subsurface investigation, and instrumentation. In addition, links to several geotechnical design manuals by state departments of transportation are provided. During the development of the system, it was realized that numerous technical terms and abbreviations were used and that in some cases different technologies used terms in different ways. Thus, a Glossary is included with the system so that users are able to find definitions of terms used in the various documents.

The technologies can be accessed in several ways. The Catalog of Technologies page provides a listing of the 46 ground improvement and geoconstruction technologies in the system, organized to address the three element areas. An exception is that two traditional technologies—excavation and replacement, and traditional compaction—are included because they are often-used, "base" technologies, to which ground improvement and geoconstruction methods are compared. The list of technologies in the catalog is shown under Background in Chapter 2. The name of each technology is a hot-link button on the website that takes the user to a web page for that technology. The technology-specific web pages will be discussed in more detail subsequently. The Technology Selection page provides two further means of accessing technologies: through a classification system and through an interactive selection system. The classification system groups technologies into the following categories:

- Earthwork construction
- Densification of cohesionless soils
- Embankments over soft soils
- Cutoff walls
- Increased pavement performance
- Sustainability
- Soft-ground drainage and consolidation
- Construction of vertical support elements
- Lateral earth support
- Liquefaction mitigation
- Void filling

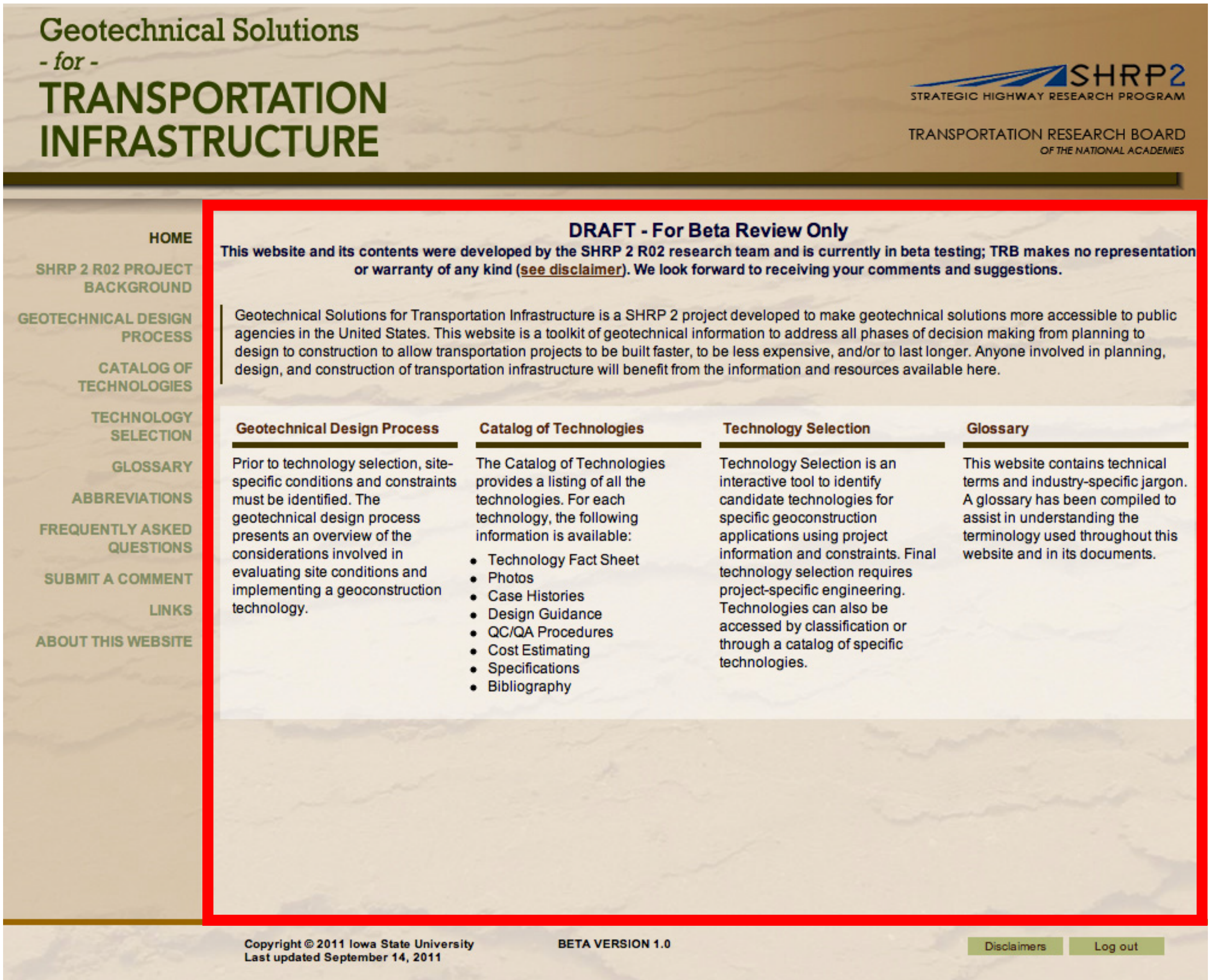


Figure 3.3. Homepage for the SHRP 2 R02 project information and guidance system.

Thus, an experienced engineer can access solutions according to particular categories of problems. The interactive selection system provides the user the opportunity to assess technologies based on several applications. A selection procedure has been developed for each application area shown in Figure 3.2, and as defined in the R02 project work scope. The third element area, stabilization of pavement working platforms, was split into two parts to recognize differences between permanent and temporary applications.

The interactive selection system is entered through the screenshot shown in Figure 3.4, wherein the first decision in the process is to select the potential application. In the selection system, the list of applicable technologies is shown on the right side of the page (see Figure 3.4), all of which are hot-linked to their respective technology pages. At the start of the selection, all technologies are shown on the right side, and as selections are made, nonapplicable technologies are grayed out.

After clicking on one of the four application areas shown in Figure 3.4, the user will encounter a page requesting additional information to narrow the list of candidate technologies for the particular application. The requested input and order of queries to the user were established after considering the effect of the requested information on the determination of the potential technologies list. Potential queries (in no particular order) generated during development of the system include the following:

- What type of project is being constructed?
- What is the size of the project being constructed?
- Are there any project constraints to be considered in selecting a possible technology?

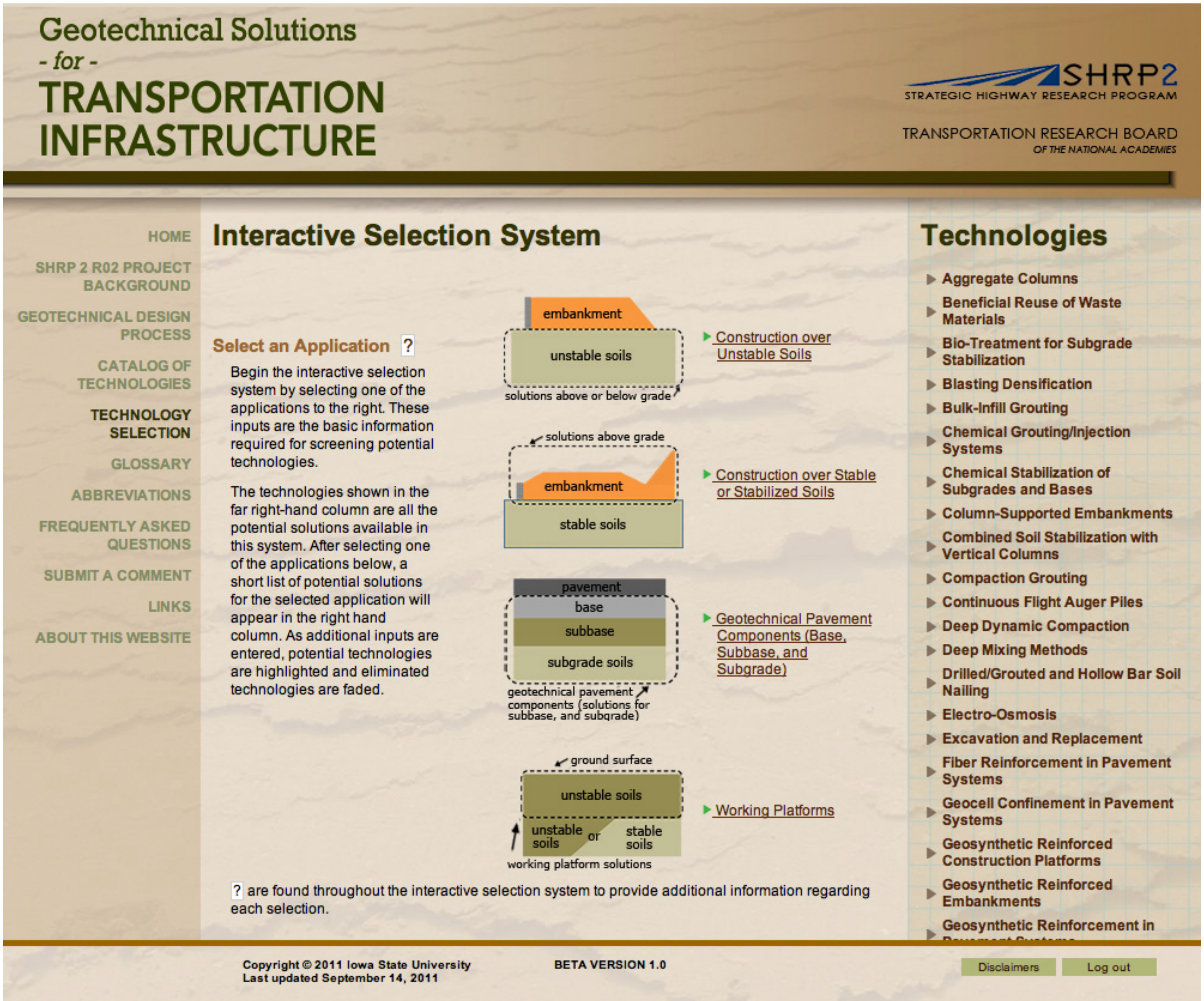


Figure 3.4. Screenshot for the Interactive Selection System page.

- What is the soil type that needs to be improved?
- To what depth do the unstable soils extend?
- At what depth do the unstable soils start?
- Is there a "crust" or "rubble fill" at the ground surface?
- What is the depth to the water table?
- How does the water table fluctuate?
- What constraints (i.e., utilities, material sources, or existing adjacent structures) exist?
- What is the desired outcome (i.e., decrease settlement, decrease construction time, or increase bearing capacity) of the improvement?
- With which technologies does the user already have experience?

The questions used to narrow the technologies are dependent on the application selected. Generally, three or four questions are used to develop a short list, which can then be further refined by answering additional questions. To illustrate use of the system, solutions for Construction over Unstable Soils are presented herein in more detail. The other three applications are discussed in detail in the Web-Based Information and Guidance System Development Report.

Construction over Unstable Soils

Selecting the Construction over Unstable Soils application leads to a decision process for foundation soil improvement or reduced loading. This application is focused on ground improvement to support embankments or transportation structures, such as walls or box culverts over unstable soils. This system is focused on identifying geoconstruction solutions to these problems; however, users should also consider that structural solutions to such problems may be preferred alternatives.

From the list of potential queries, two questions (What is the soil condition that needs to be improved? To what depth do the unstable soils extend?) were selected as the initial questions to reduce the number of potential technologies for this application. These two queries were most beneficial in providing a preliminary short list of applicable technologies. A screenshot of the first page for the Construction over Unstable Soils application is shown in Figure 3.5. The list of technologies shown on the right side of this page has narrowed from the complete list shown on the previous Interactive Selection System page (see Figure 3.4). The unstable soil conditions considered in the system are:

- Unsaturated and saturated, fine-grained soils
- Unsaturated, loose, granular soils
- Saturated, loose, granular soils
- Voids—sinkholes, abandoned mines, etc.
- Problem soils and sites—expansive, collapsing, dispersive, organic, existing fill, and landfills

Figure 3.6 shows a screenshot of what appears after answering the question about soil type. On the right side of the screenshot several technologies are grayed, indicating that they generally are not appropriate for the soil type selected (unsaturated and saturated, fine-grained soil).

The next question to be answered is the depth range for improvement. The depth ranges selected for inclusion in the system follow:

- 0–5 ft (0–1.5 m)
- 5–10 ft (1.5–3 m)
- 10–30 ft (3–9 m)
- 30–50 ft (9–15 m)
- Greater than 50 ft (15 m)

After answering the question on unstable soil depth, additional technologies may be grayed on the right side. At this point, the

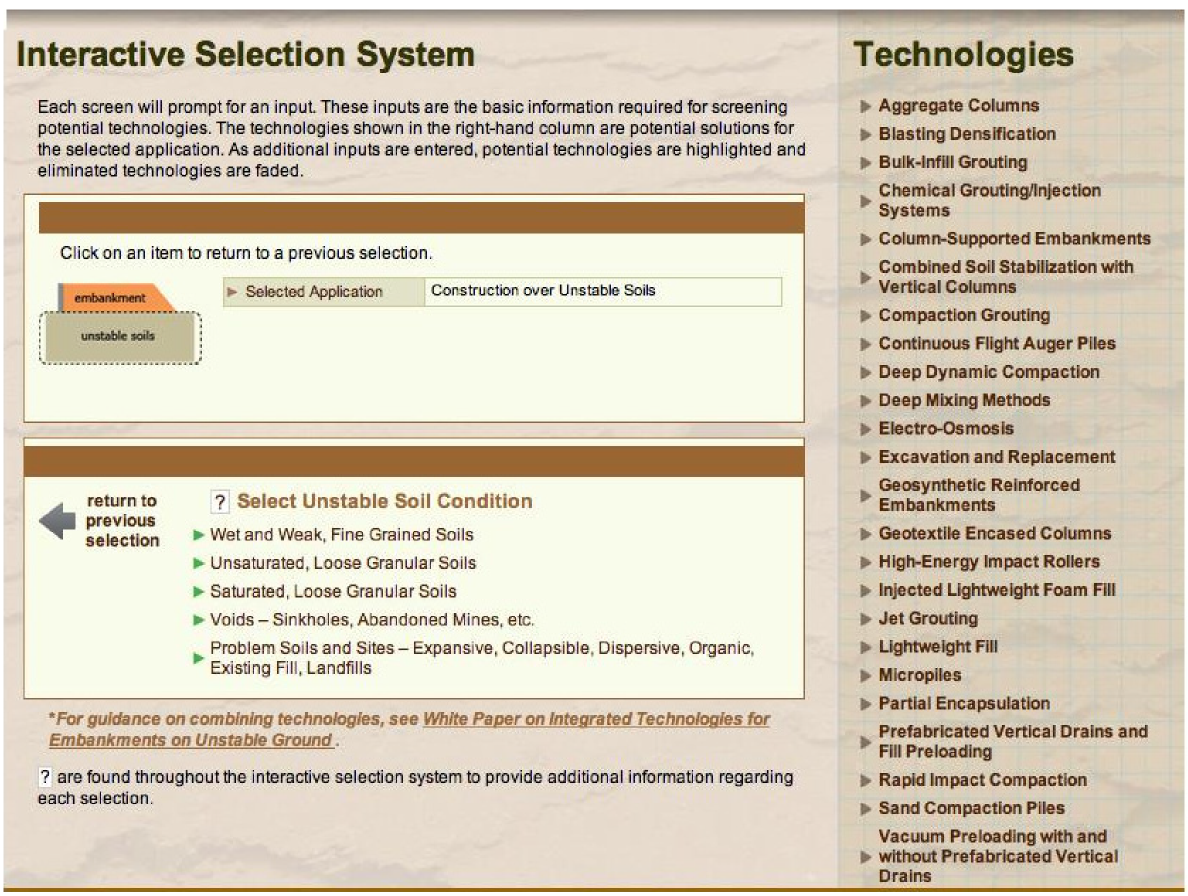


Figure 3.5. Screenshot for the first Construction over Unstable Soils page.

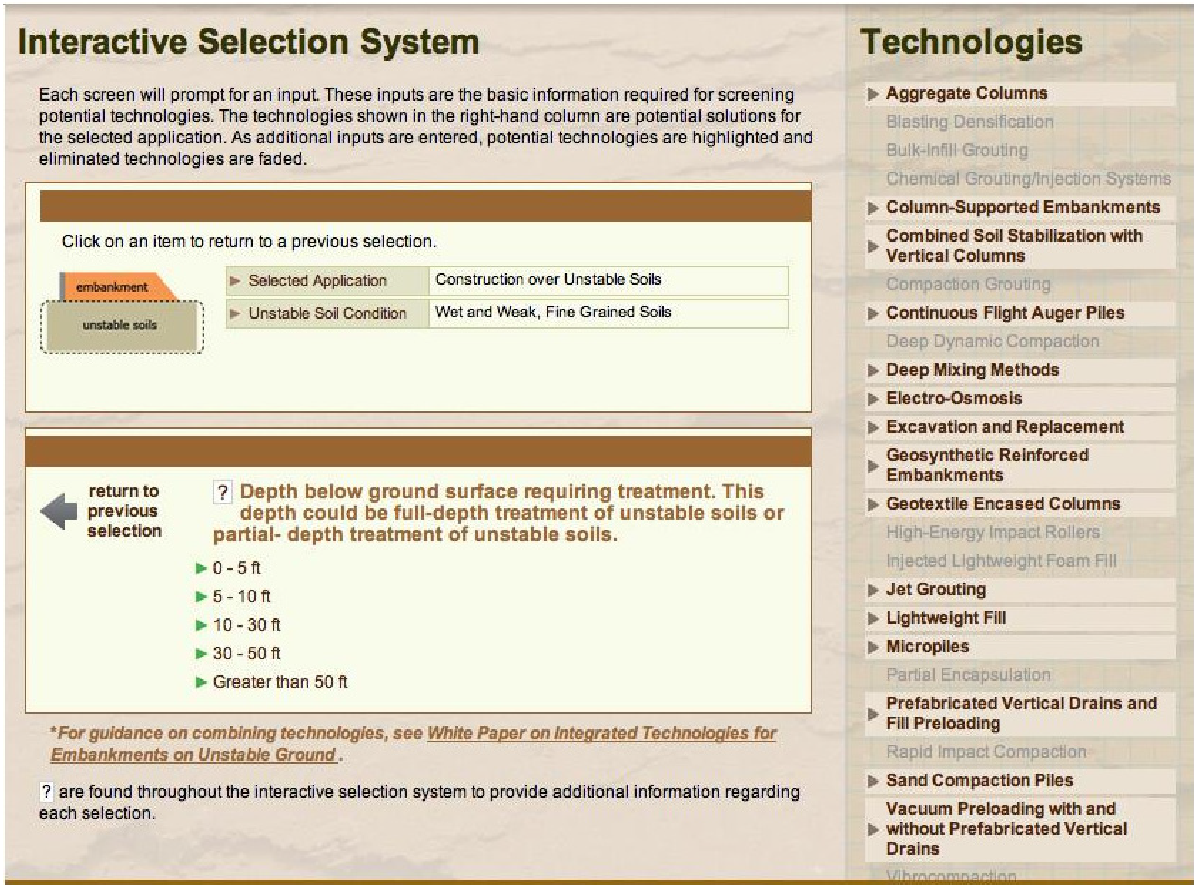


Figure 3.6. Screenshot for the second Construction over Unstable Soils page.

user can stop and assess the candidate list of technology solutions or enter additional project-specific information, as shown in Figure 3.7. Because many of these technologies are used in combination with other ground improvement methods, guidance on combining technologies is contained in the linked white paper titled Integrated Technologies for Embankments on Unstable Ground (see Figures 3.5 and 3.6).

A final technology selection screenshot (Figure 3.8) shows the resulting candidate technologies on the right side of the page when the questions have been answered as indicated. It can be seen that the list of technologies applicable to the selected conditions has been narrowed. At this point, a user can click on any of the highlighted technologies to obtain technology-specific information. For example, clicking on Prefabricated Vertical Drains and Fill Preloading will bring up the screenshot shown in Figure 3.9. The documents listed can be accessed through hot-links on the website. Ratings are provided for each technology on the degree of technology establishment and a technology's potential to achieve SHRP 2 objectives.

As shown in Figure 3.9, several information documents about a given technology are accessible from the system. Table 3.1 provides a list of these products and tools and indicates the document formats. These documents are hot-linked and can be opened from this page, or the box shown can be clicked and the selected documents can be printed or saved to a file for further use.

The information documents are generally provided in Adobe PDF format. Technology fact sheets are two-page summary information sheets that provide basic information on the technology, including basic function, general description, geologic applicability, construction methods, SHRP 2 applications, complementary technologies, alternate technologies, potential disadvantages, example successful applications, and key references. Photos show equipment or methods used in the technology and can be valuable to get a perspective on the technology. Case histories provide a summary of project(s), preferably conducted in the United States by a state department of transportation (DOT), if available, and contain project location, owner, performance, contact information, and a project summary. The design and QC/QA procedures documents provide a summary of recommended procedures for the technology. The recommended design and QC/QA procedures come from an

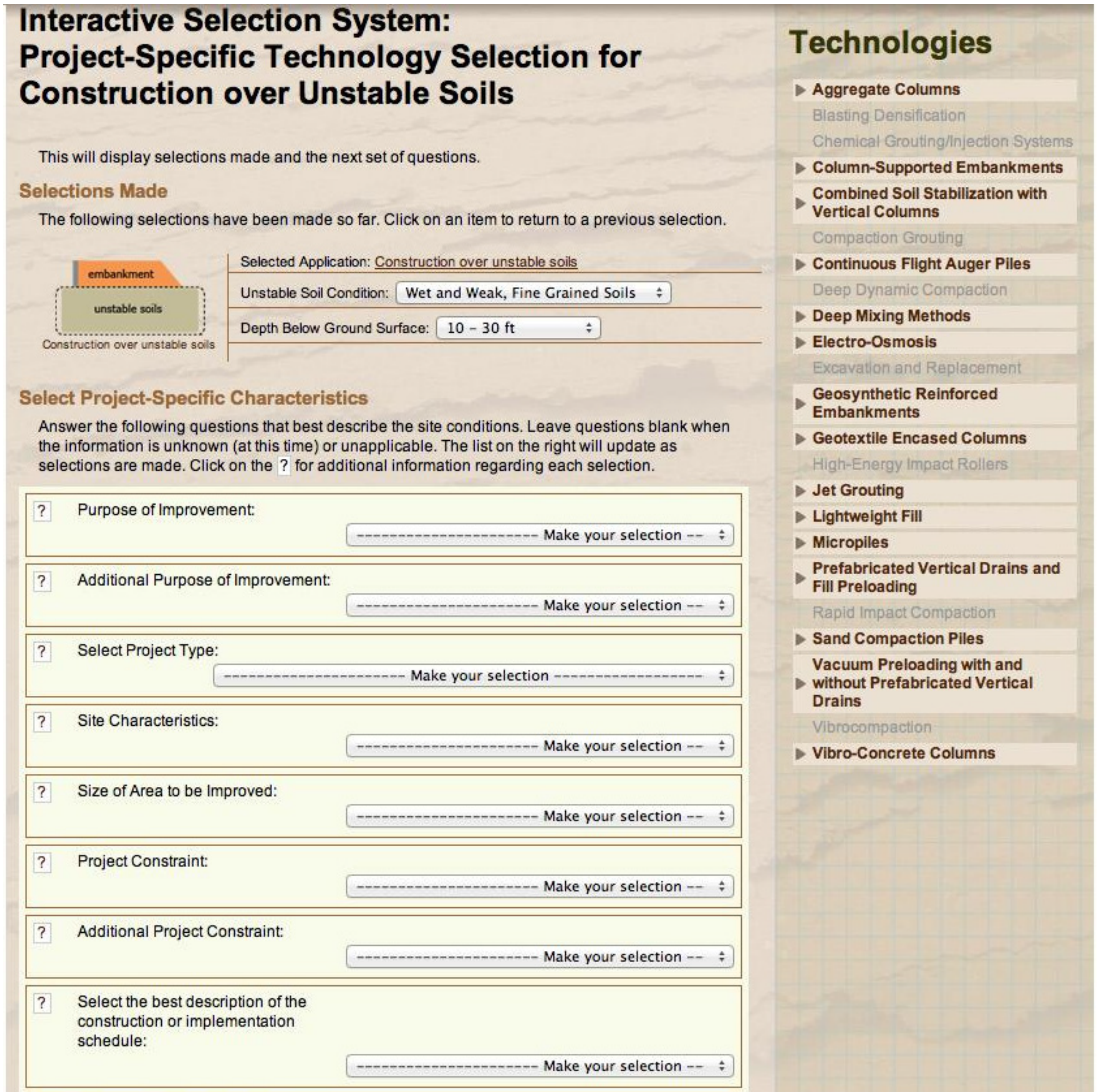


Figure 3.7. First screenshot for Project-Specific Technology Selection for Construction over Unstable Soils.

assessment of the current state of the practice of each technology. In cases where a well-established procedure (e.g., a FHWA manual) exists, that procedure is recommended. In cases of technologies with multiple procedures but with no established procedure, the assessment led to a recommendation of procedure(s) to use. For a few technologies, design or QC/QA procedures were established based on additional research conducted during the project. For most technologies, two cost estimation documents are available. The first provides an explanation of the cost item specific to the technology, generally emanating from the payment methods contained in specifications. Available regional and cost numbers, generally from DOT bid tabs or national databases, are compiled for each technology. The second document for cost estimation consists of an Excel spreadsheet developed to estimate costs for the use of the technology. This document could not be prepared for some technologies due to insufficient information. The spreadsheet can be modified by the user to estimate specific project cost based on either a preliminary or final design. Example specification(s) are provided for each technology in Adobe PDF and Microsoft Word (if available). The final document available for each technology is a bibliography compiled during the research project.

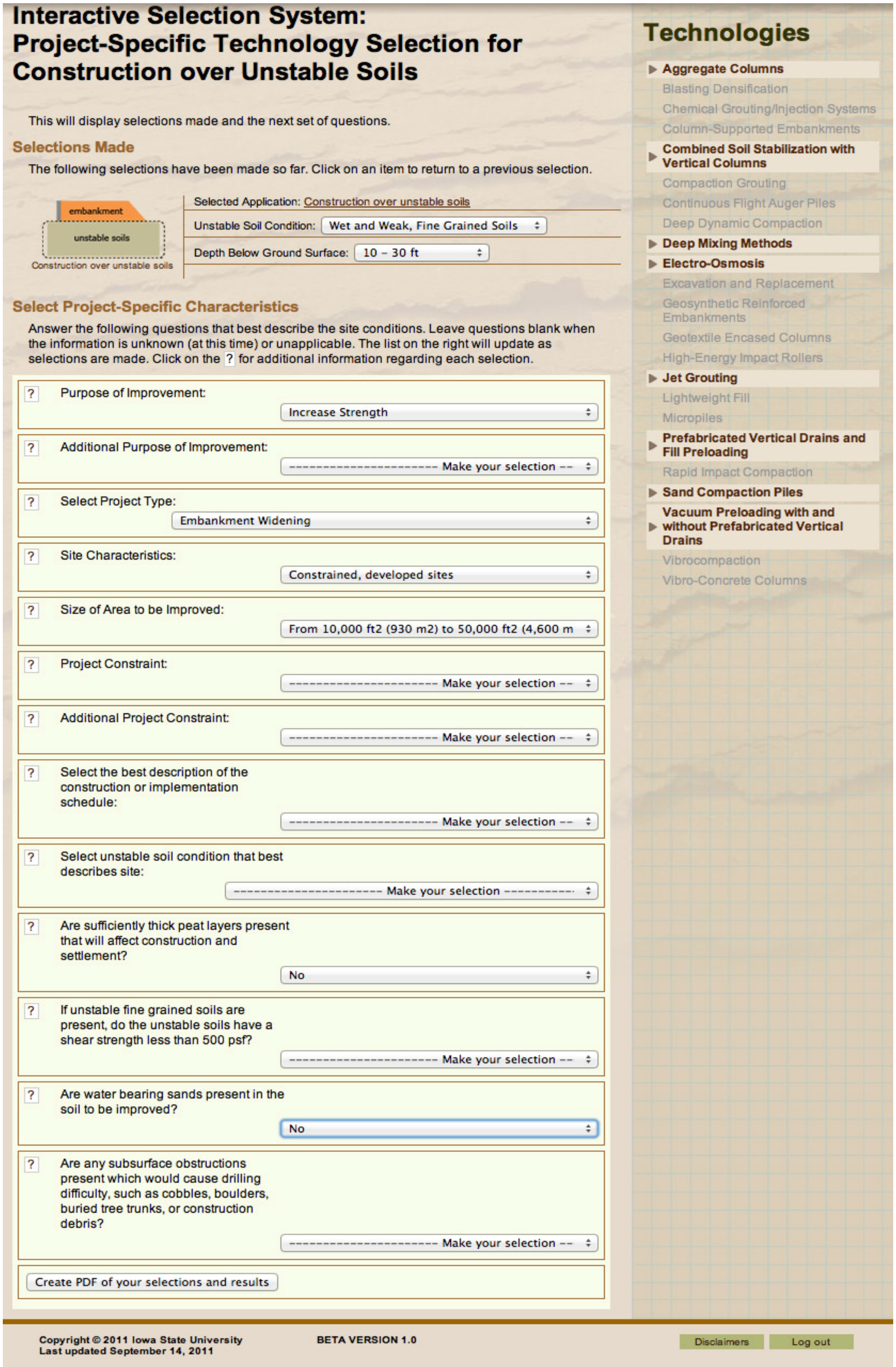


Figure 3.8. Second screenshot for the Project-Specific Technology Selection for Construction over Unstable Soils.

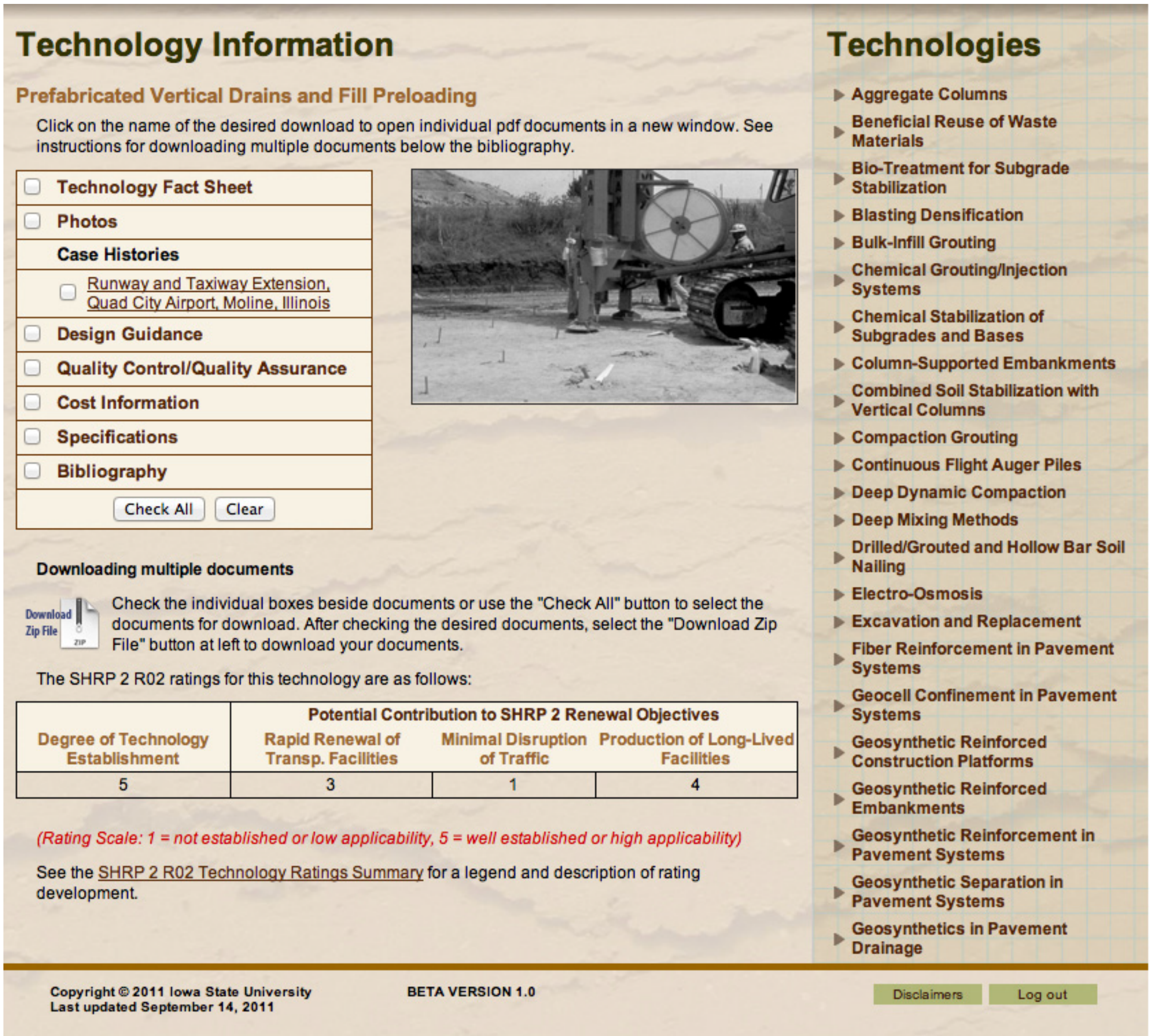


Figure 3.9. Screenshot for the Prefabricated Vertical Drains and Fill Preloading Technology list of available documents.

Table 3.1. Information and Guidance System Products and Tools

Available for Review or Download	Format
Technology fact sheets	Adobe PDF
Photos	Adobe PDF
Case histories	Adobe PDF
Design procedures	Adobe PDF
QC/QA procedures	Adobe PDF
Cost estimation	Adobe PDF and Microsoft Excel
Example or guide specifications	Adobe PDF or Microsoft Word
Bibliography	Adobe PDF

Other Pages

Buttons for frequently used pages are located on the left side of the homepage for the web-based system (see Figure 3.3). The Geotechnical Design Process, Catalog of Technologies, and Technology Selection system pages have been discussed in some detail. Other pages, such as Project Background, Glossary, Abbreviations, About this Website, and Frequently Asked Questions, are self-explanatory. They are reviewed in more detail in the Web-Based Information and Guidance System Development Report. To keep the system a living, updatable system, an extensive comment page has been developed and is shown in Figure 3.10. Comments can be submitted related to a case history for a technology, photographs or videos, specifications, cost information, and references, as well as general comments about the information and guidance system.

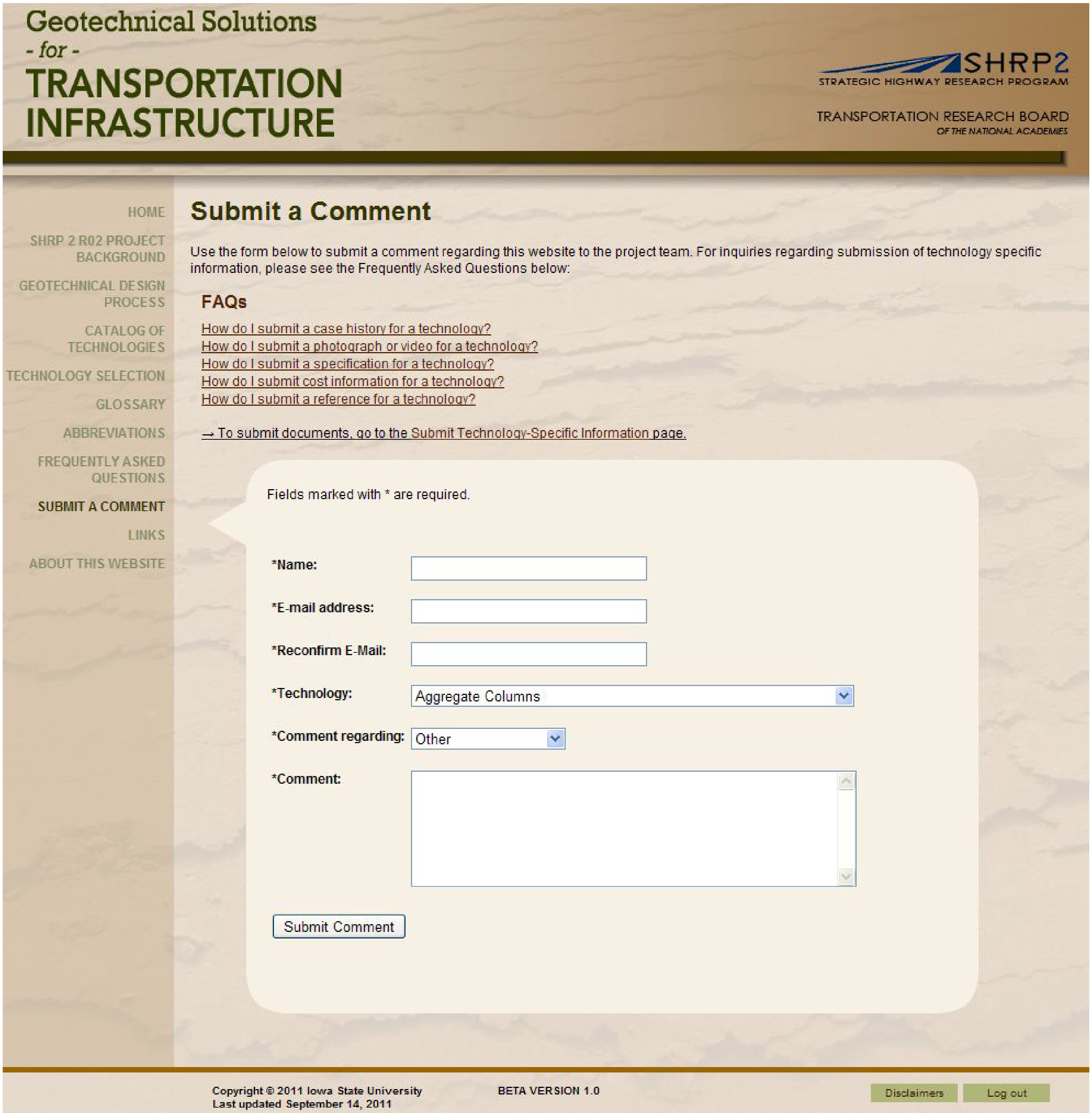


Figure 3.10. Screenshot of Submit a Comment page.

Summary

Programming of the information and guidance system is functionally complete. Internal review of the programming and project documents has been completed. Revisions and additions are actively being incorporated with every review and comment cycle. The next step is a beta testing program, as described in Chapter 6. Prior to full, public release of the Information and Guidance System website, the beta testing should be performed and website and products revised as appropriate.

CHAPTER 4

Mitigation of Obstacles

Introduction

Task 8 of Phase 2 is to test the effectiveness of these mitigation methods approved or amended from Phase 1 and evaluate their effectiveness. The Task 8 work scope was derived from Tasks 4 and 5, reported and discussed in the Phase 1 Report. Task 4 of Phase 1 identified a collection of nongeotechnical constraints that interfere with more widespread use of soil improvement technologies. Task 5 of Phase 1 identified potential mitigation measures for these nongeotechnical constraints.

In Phase 1, the research team and advisory board identified 15 primary obstacles. These are listed in Table 4.1. The research team organized the obstacles into two categories: general and project-specific. General obstacles are not tied to the characteristics of a particular project. For example, lack of knowledge about soil improvement technologies is a general obstacle; whereas, interference of existing utilities on technology implementation is a project-specific obstacle. Overcoming many of the general obstacles can also help overcome project-specific obstacles. For example, improving knowledge about technologies in general can promote selection of particular technologies to overcome project-specific constraints, such as existing utilities.

Quantitative ratings of the average degree to which each obstacle interferes with the broader use of ground improvement technologies are provided in Table 4.1. The more encompassing nature of some of the general obstacles likely resulted in their higher ratings than for some of the project-specific obstacles. Strategies that address nongeotechnical obstacles in both project-specific and general categories were identified. These strategies are as follows:

- Education and training
- Agency, industry, and academic collaborations
- Policy development

Qualitative estimates of the effectiveness of various strategies to help overcome the obstacles are presented in Table 4.1. Several mitigation measures that use these strategies to overcome the Task 4 obstacles were identified, and are listed in Table 4.2. Approaches to evaluate the effectiveness of each mitigation measure are also listed.

Other R02 project tasks also address several obstacles. For example, Tasks 9 through 12 all contribute to the state of knowledge about geoconstruction/soil improvement technologies, so they contribute to overcoming Obstacle 4-1, which is lack of knowledge about technologies. More specifically, the catalog of technologies in Task 9 and the technology guidance in Task 10 are both useful in addressing the project-specific Obstacles 4-8, 4-10, 4-11, 4-12, and 4-13, because they will provide the needed information and methods to select technologies that are compatible with or overcome project-specific constraints.

It will be difficult to precisely measure the effectiveness of many of the measures listed in Table 4.2, and many of the proposed measures were not included in the Phase 2 work scope. Note that the information and guidance system website, which holds all of the primary products of this project, addresses Mitigation Method 8.g (see Table 4.2). A readily available method for evaluating the effectiveness of this mitigation method will be tracking the number of hits on this website and website users' surveys.

Task 8 Work Scope

The following specific subtasks in Task 8 were completed in Phase 2. Each of these subtasks is summarized in the sections that follow. Some of the subtasks have individual reports, documents, and products; these are referenced as follows:

8.a. Conduct focused workshops to bring together key stakeholders for information exchange, including emerging opportunities for contractors.

8.b. Survey and interview DOTs to learn which characteristics of DOTs enable use of new technologies and use the results to develop recommended DOT policies to encourage appropriate use of new technologies.

Table 4.1. Task 4 Obstacles and Effectiveness of Mitigation Strategies to Overcome Obstacles

Obstacle[a]	Type of Obstacle	Average Degree of Interference with Technologies[b]	Effectiveness of Strategy to Overcome Obstacle		
			Education and Training	Agency, Industry, and Academic Collaborations	Policy Development
4-1. Lack of knowledge about technologies	General	1.85	High	Medium	Low
4-2. Lack of organizational structure and policies to encourage use of new technologies	General	1.85	Low	Medium	High
4-3. External pressures on agency inhibiting use of new technologies	General	1.55	Low	Medium	Medium
4-4. Lack of qualified contractors, contractor strategies, personnel, materials, and specialty equipment to implement technologies	General	1.76	Medium	Medium	Low
4-5. Proprietary product/process limit competitive bidding	General	1.59	Medium	Medium	Low
4-6. Liability exposure when applying technologies	General	1.61	Low	Low	Medium
4-7. Absence of champion or technical leadership for new technologies	General	1.79	Medium	Medium	Low
4-8. Project conditions (right-of-way, geometry, scale, utilities, and sequence) interfering with application of technologies	Project-specific	1.54	Medium	Low	Low
4-9. Existing market protection interferes with adoption of new technologies	General	1.4	Medium	Medium	Low
4-10. Traffic management needs resulting from technologies	Project-specific	1.49	Medium	Low	Low
4-11. Environmental impacts on technologies	Project-specific	1.29	Medium	Low	Low
4-12. Weather impacts on technologies	Project-specific	1.08	Medium	Low	Low
4-13. Impact of technologies on the public	Project-specific	1.41	Medium	Low	Low
4-14. Lack of profit or return on investment for technologies	General	1.29	Low	Low	Low
4-15. Requirements for waste disposal from technology implementation	General	0.9	Medium	Low	Low

[a]See the description of Task 4 in the Summary of Phase 1 for discussion of these obstacles.
[b]Values obtained from detailed assessments, which are described in the Summary of Phase 1. The higher the number, the greater the obstacle.

8.c. Develop a promotional or marketing plan for soil improvement technologies within the transportation industry.
8.d. Develop one-page fact sheets on technologies with references to more detailed information.
8.e. Develop a methodology for identifying and evaluating information about new technologies and incorporating new technologies in the system described in Task 9.
8.f. Develop recommendations and a scope of work for a "teach the teachers" course for university professors.
8.g. Prepare recommendations for a soil improvement website, including considerations of financial support, technical quality control, and continual updating of information for new and changing technologies.

Stakeholder Workshops and DOT Interviews

Subtasks 8.a and 8.b consisted of focused workshops with key stakeholders and the collection of information from transportation personnel on policies to encourage appropriate use of new technologies. These two subtasks were accomplished through project team meetings with the advisory board, advisory board review comments, meetings with the FHWA resource center geotechnical engineers, and workshops. These meetings, correspondence, and workshops occurred during the course of Phase 2 work.

A summary listing of activities is presented in Table 4.3. Detailed discussions of each activity are provided in another

Table 4.2. Possible Mitigation Measures for Obstacles and Evaluation of Effectiveness

Mitigation Methods for Nongeotechnical Obstacles from Task 4	Strategy Employed	Obstacles Addressed	Effectiveness of Mitigation Method
8.a. Conduct-focused workshops to bring together key stakeholders for information exchange, including emerging opportunities for contractors	Collaboration	4-1, 4-2, 4-3, 4-4, 4-7, 4-9	Surveys and interviews of participants to determine impact of workshops on practice
8.b. Survey and interview DOTs to learn which characteristics of DOTs enable use of new technologies, and use the results to develop recommended DOT policies to encourage appropriate use of new technologies	Policy development	4-2, 4-3, 4-7	Extent of adoption of the policies; surveys on the impact of the policies on use of soil improvement technologies
8.c. Develop a promotional or marketing plan for soil improvement technologies within the transportation industry	Collaboration	4-1, 4-2, 4-3, 4-4, 4-7, 4-9	Extent of adoption of the plan; compile statistics on technology use by DOTs
8.d. Develop one-page fact sheets on technologies with references to more detailed information	Education and training	4-1, 4-7	Surveys of those who receive the updated materials
8.e. Develop a methodology for identifying and evaluating information about new technologies, and incorporating new technologies in the system described in Task 9	Education and training	4-1, 4-7	Survey recipients of information and document use of new technologies
8.f. Teach the teachers, by providing a short course for university professors	Education and training	4-1, 4-5, 4-7, 4-8, 4-10, 4-11, 4-12, 4-13, 4-15	Surveys of professors and their students
8.g. Create a soil improvement website containing educational materials, videos, graphics, text, and links to additional information	Education and training	4-1, 4-5, 4-7, 4-8, 4-10, 4-11, 4-12, 4-13, 4-15	Number of hits; surveys of target audience.
8.h. Update existing educational materials, including short courses	Education and training	4-1, 4-5, 4-7, 4-8, 4-10, 4-11, 4-12, 4-13, 4-15	Surveys of those who receive and use the updated materials

Phase 2 project report, the Web-Based Information and Guidance System Development Report. Feedback comments from stakeholders are contained in the appendices of that report.

Marketing and Education/ Training Plans

Subtask 8.c is the development of a promotional/marketing plan for soil improvement/geoconstruction technologies within transportation agencies, and includes collaboration strategy Subtask 8.f educational activities, to mitigate obstacles to more widespread use of ground improvement methods by transportation agencies. Another mitigation strategy, education and training, is a key component within the promotional/marketing plan. Subtask 8.f, teach the teachers, and Subtask 8.h, update existing educational materials, are addressed within the proposed promotional/marketing plan.

The proposed marketing plan is for implementation once the R02 project has been completed, and the information and guidance website is fully functional. It is anticipated that this

Table 4.3. Stakeholder Meetings and Workshops

Activity	Location	Date
Project team and advisory board meeting	Kansas City, Mo.	October 2009
Minnesota Department of Transportation briefing and demonstration	Maplewood, Minn.	October 2010
Project team and advisory board meeting	Baltimore, Md.	November 2010
TRB annual meeting workshop	Washington, D.C.	January 2011
Louisiana DOTD workshop	Baton Rouge, La.	April 2011
Soils and Materials Standing Committee, Transportation Association of Canada	Ottawa, Ontario, Canada	April 2011
Renewal TCC presentation	Irvine, Calif.	April 2011
Compaction “roadeo”	Jacksonville, Fla.	May 2011

plan will be reviewed and refined as implementation of the Geotechnical Solutions for Transportation Infrastructure website is defined by SHRP 2, AASHTO, and FHWA.

Marketing the R02 product and tools (i.e., the Geotechnical Solutions for Transportation Infrastructure website) is key to achieving SHRP 2 Renewal objectives of rapid renewal of transportation facilities, minimal disruption of traffic, and production of long-lived facilities for the following elements of construction: new embankment and roadway construction over unstable soils, roadway and embankment widening, and stabilization of pavement working platforms. Marketing of these ground improvement technologies will be directed toward STAs, other transportation agencies, and other entities designing or constructing transportation works. Thus, a multilevel marketing plan has been developed to reach these various stakeholders. Components of the plan can be implemented; it does not need to be implemented in its entirety.

Transportation personnel and related industry personnel to be reached with this marketing plan are: geotechnical engineers, civil/structural design and construction engineers, pavement design and construction engineers, project management, procurement, research, maintenance, district engineers, general contractors, architectural/engineering groups, academics, students, and consultants. Components of the multilevel marketing plan to reach these various stakeholders are categorized as promotional, collaboration, educational and training, demonstration and research and development (R&D) strategy, or outreach strategy, and include the following items:

- Promotional
  - Advocate with trade associations
  - Advocate professional organizations (TRB, ASCE, GI, and International Society for Soil Mechanics and Foundation Engineering)
  - Develop in-house DOT experts
  - DOT internal review team
- Collaboration
  - NHI, NCHRP, AASHTO, FHWA
  - SHRP
  - Highway Innovative Technology Evaluation Center (HITEC)
  - Others: design-build teams, general contractors, academia, industry
- Educational and training
  - FHWA NHI—promote and demonstrate the website
  - Teach the teachers
  - Train all levels of transportation personnel
  - Re-education—especially on new technologies
  - Vendor training
- Demonstration and R&D strategy
  - SHRP preimplementation
  - "Roadeo"—demonstration of emerging compaction technologies
  - Engage academia
  - Scan tour
  - Technology development—enhancement to existing and new technology
- Outreach strategy
  - Internal DOT road map
  - Public outreach
  - Internal review panel (DOT)
  - Universities—engage academia
  - Environmental perception

A final marketing plan will have to detail which of these items to proceed with and provide specific details on implementation for each item. A final marketing plan was not within the scope of the Phase 2 R02 work, because it would have been premature.

Marketing of the R02 products is tied to long-term operation, funding, and maintenance of the Geotechnical Solutions for Transportation Infrastructure website. Where the R02 Geotechnical Solutions for Transportation Infrastructure website will be housed is yet to be determined by SHRP 2, FHWA, and AASHTO. Long-term funding of the website has not yet been identified. These aspects must be defined before finalization and then implementation of a market plan.

Technology Fact Sheets

Subtask 8.d is the development of fact sheets on technologies, with references to more detailed information. The technology fact sheets are one-sheet (double-sided) summaries of key features of a technology. Their purpose is twofold. The fact sheet is a concise introduction to a technology for those unfamiliar with (or with limited knowledge of) that technology. The fact sheet is also a concise summary of applicability and limitations of a technology for use by those already familiar with the technology. Thus, the fact sheet product is a tool for use by the full spectrum of transportation agency personnel.

The format of the fact sheet was developed to organize and present information on different aspects of engineering with a ground improvement technology. The information is presented in a consistent format, thus aiding the user in comparing different technologies. Fact sheets for 46 technologies are available on the Geotechnical Solutions for Transportation Infrastructure website.

Updating

Mitigation work will continue in the future with operation and maintenance of the Geotechnical Solutions for Transportation Infrastructure website. Educational materials will be updated with maintenance of the website products. Additional educational materials will be added for when the website is expanded to include more technologies. Cases history products will be added. These add to the educational database and, more importantly, can lead to development of technology champions within different STAs.

New Technologies

Subtask 8.e is the development of a methodology for identifying and evaluating information about new technologies, and incorporating new technologies in the system. Website users can suggest technologies to be added to the Geotechnical Solutions for Transportation Infrastructure website. How do I suggest adding a technology? is a specific question under the Frequently Asked Questions page of the website, as shown in Figures 4.1 and 4.2. The user is directed to the Submit a Comment form of the website, as shown in Figure 3.10.

Once submitted, a proposed technology will have an initial evaluation of its relevancy to SHRP 2 R02 Element 1, 2, or 3 areas. The next step for adding a technology is the development of the background information on that technology. The key background is the Comprehensive Technical Summary (CTS). The CTS and the other reports that are built on information contained in the CTS are summarized in Chapter 5, Development of Background Information, of this report. The CTS and other report formats are standardized as part of this project and are available for use in assessing new technologies.

Products and tools that will be posted on the website are then developed from the CTS and other background reports. Next, these products, when fully reviewed, are ready for posting on the website. The product templates that have been created as part of this project are available for use in creating products and tools for new technologies.

The next, significant step to adding a technology to the website is integrating it into the selection process. This may require some reprogramming of the existing selection logic.

Completion of the steps just summarized results in the addition of a new technology to the Geotechnical Solutions for Transportation Infrastructure website. Who will perform this work needs to be defined in the implementation phase of this work. It may entail collaboration with others. Likewise, how this work will be funded has to be addressed.

The Geotechnical Solutions for Transportation Infrastructure website can be expanded to include technologies and selection logic for applications other than Elements 1, 2, and 3. For example, the website could be expanded to address deep foundations (piling, shafts, etc.), or earth retention systems, and the like. The development of background information and products and tools would be the same as that used for Elements 1, 2, and 3 technologies. However, a new logic tree would have to be developed and added to the website to address technology selection in a new application area.

Website Recommendations

Subtask 8.g is preparation of recommendations for a soil improvement website, including considerations of financial support, technical quality control, and continual updating of

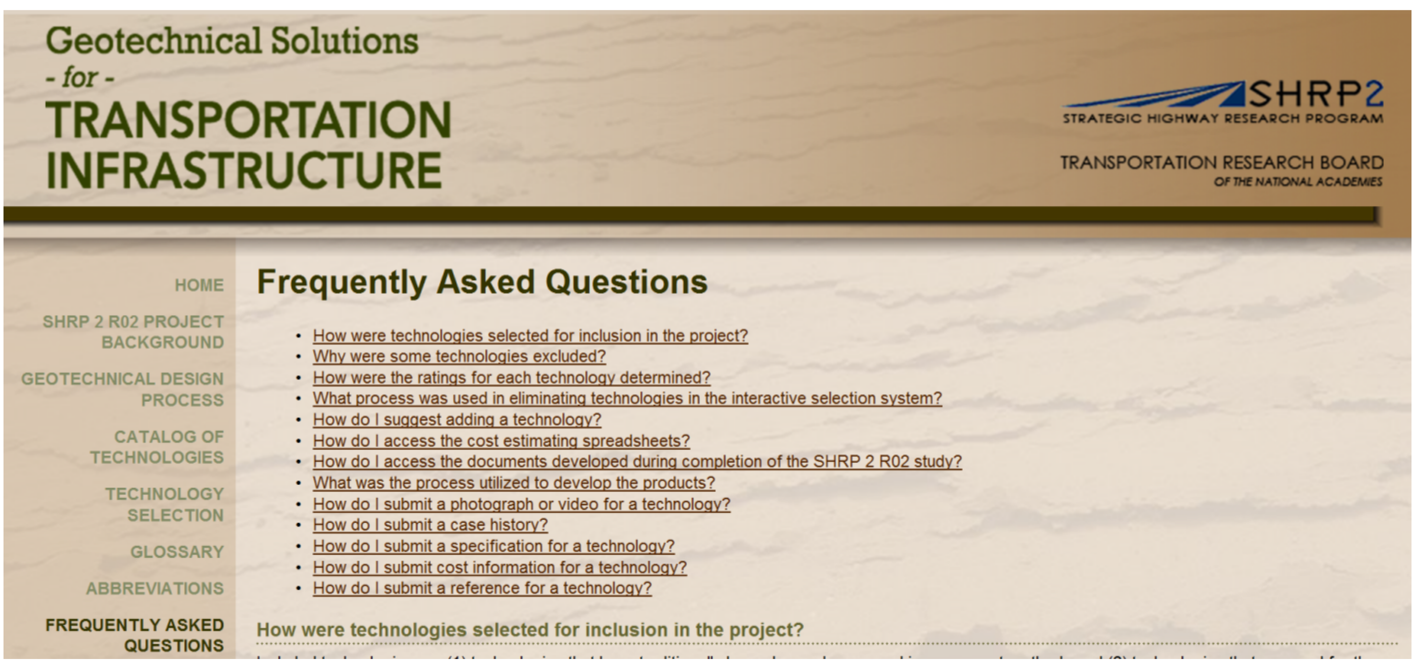


Figure 4.1. Frequently Asked Questions page of the website.

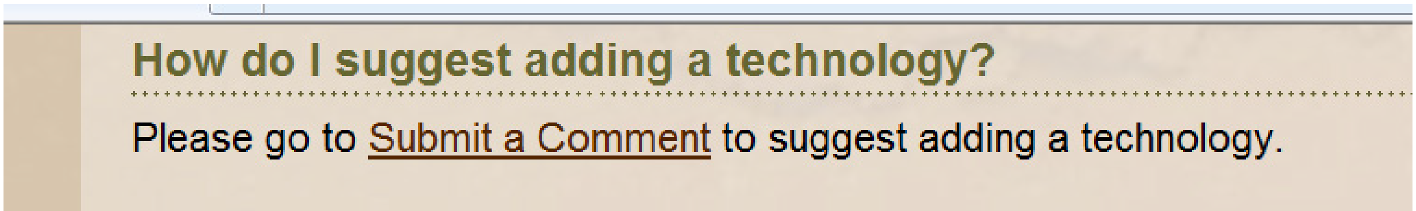


Figure 4.2. Technology addition question and website response.

information for new and changing technologies. This task evolved during the course of the Phase 2 work. The Geotechnical Solutions for Transportation Infrastructure website has been developed and has been refined through an alpha-level testing program. Beta-level testing is recommended as the next phase of work. Recommendations for website technical quality control, updating, and the like are presented within this report in Chapter 6.

CHAPTER 5

Development of Background Information

Introduction

Extensive literature reviews and data mining on each technology were performed to complete project Tasks 9, 10, 11, and 12 (see Chapter 1). A common methodology was developed, refined, and used for all 46 technologies of Elements 1, 2, and 3. This process has resulted in the creation of project technical summaries, task reports, and products and tools. The distinction between items is their intended use. The technical summaries and the task reports are complete with the Phase 2 final submission and will not be updated or revised in the future. The technical summaries and task reports were used to develop the products and tools. The project products and tools are the primary user items on the Geotechnical Solutions for Transportation Infrastructure website. These products and tools are living documents. They will be updated and revised as appropriate during the beta testing phase of the website, and routinely when the website is fully operational. Additional documents will be added to the website (e.g., case histories) as it is used.

The technical summaries and assessment task reports systematically organized and evaluated the background information on each technology, in a consistent format. These comprehensive technical summaries (CTS) and task reports are project working documents, and are not tools to engineer ground improvement works. Additionally, project working document reports on technology evaluation and on product development have been prepared and document the development, formatting, and review process for the technical summaries and assessment tasks, and for the products and tools, respectively. These reports document research and development information, and are not primary user tools. Thus, the project working documents and reports will not be available on the Geotechnical Solutions for Transportation Infrastructure website.

The methodology employed to develop the technical summaries and the task reports is summarized in the following subsections. Additional details are contained the respective project documentation report.

Technical Summaries and Task Reports

Task 9 is the development of a catalog of materials and systems for rapid renewal projects. The materials and systems are the 46 technologies. Each technology was individually researched to gather the information needed to develop a technologies catalog (i.e., the Geotechnical Solutions for Transportation Infrastructure website).

The keystone component in creating the catalog is the CTS developed for each technology. The CTS, a detailed literature review summary for a given technology, is the first document produced for a technology. Its purpose is to serve as the primary document on a given technology for completion of the Phase 2 R02 project tasks. Each respective CTS is a working document that contains source materials for completing Phase 2 Tasks 9, 10, 11, and 12. Subsequent documents, reports, and products for a technology were developed on the basis of information contained within the CTS. The reports and products that flowed from the CTS (for each technology) are illustrated in Figure 5.1.

A design and quality control and quality assurance (QC/QA) assessment and a specification assessment report were prepared for each individual technology. The design and QC/QA assessment reports are detailed assessments of design methods and QC/QA procedures for a given technology. Existing specifications for a given technology are assessed in the specification assessment reports. The CTS, design and QC/QA assessment, and specification assessment reports provided the background information to develop the end user products and tools. Thus, the project working documents/reports are not available on the Geotechnical Solutions for Transportation Infrastructure website.

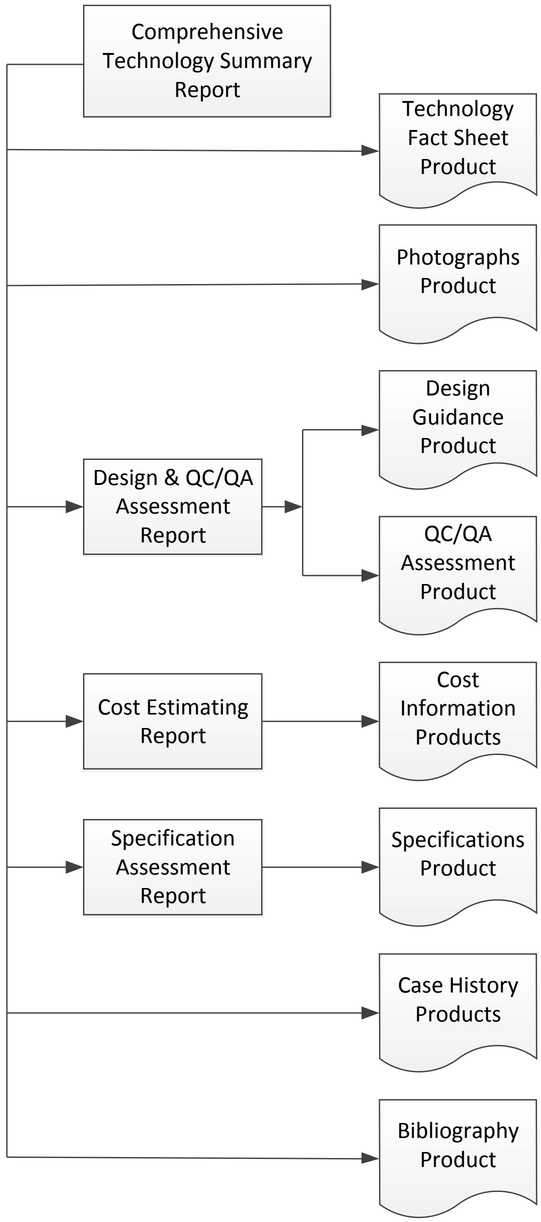


Figure 5.1. Reports and products that flowed from the CTS.

Comprehensive Technology Summary

Purpose of the CTS

The CTS is a detailed literature review summary for a given technology. Its purpose is to serve as the primary, or keystone, document on a given technology for completion of the Phase 2 R02 project tasks. The format of the CTS was developed to organize information into categories applicable to different aspects of engineering with a ground improvement technology. This categorized information was then used to produce project reports and products, as discussed in the following subsections.

Information Gathered in the CTS

Literature for the CTS came from a wide variety of sources. Capturing literature that transportation agency engineers routinely rely on was given high priority. Sources included the following:

- Federal Highway Administration (FHWA) design and guideline manuals
- American Association of State Highway and Transportation Officials (AASHTO) manuals and specifications
- *Transportation Research Record: Journal of the Transportation Research Board*
- National Cooperative Highway Research Program (NCHRP) reports
- *NCHRP Synthesis of Highway Practice*

Literature was also gathered from university research reports and papers, conference technical papers, journal technical papers, and the like. Additionally, example specifications were gathered from individual STAs.

For the identified technologies, a comprehensive set of references was collected and is detailed in the Phase 1 *Literature Review Database* document. This database was placed on a web-based searchable system and was used by the project team in Phase 2 work.

To categorize the literature, a matrix of relevant categories was developed for each technology and then populated by the research team members. Twenty-two categories were included in the matrix for each technology, including technology overview, site characterization, analysis techniques, design procedures, design codes, construction methods, construction time, equipment/contractors, contracting, QC/QA, performance criteria, monitoring, geotechnical limitations, nongeotechnical limitations, case history, environmental impacts, initial cost, life-cycle cost durability, and reliability. The technology matrix is contained in the Bibliography product for each technology—which is contained on the Geotechnical Solutions for Transportation Infrastructure website.

Reports and Products

The CTS is the keystone project working document for a given technology. Additional project working documents and several end user products were developed for each technology based on the CTS. The project products, or user tools, are those items that are posted on the Geotechnical Solutions for Transportation Infrastructure website. These are tools for use by agency personnel on their upcoming projects. It is planned that these products and tools will be refined and updated during the beta testing program of Phase 3 and with continued use of the fully released website. The reports, products, and tools that flowed from the CTS (for each technology) are illustrated in Figure 5.1.

CTS Format

A consistent format was developed to produce a CTS for each technology. The template provides format and instructions for completion of the CTS. There is no page or length limit for a CTS. The following items are to be provided:

- Definition and description of the technology
- Applicability screening parameters for the technology
- Case history summaries
- Summary of design procedures
- Summary of QC/QA procedures
- Cost information
- Summary of available specifications
- Technology matrix
- Bibliography

The technology matrix and bibliography are part of an initial or draft CTS. They are not included in the final project CTS document or report. The technology matrix and bibliography become a website product, which should be updated as necessary.

This template should also be used to develop any and all additional, future technology CTSs. This will provide consistent assessments of technologies and consistency in the development of technology screening tools and end user products and tools.

Assessment of Design Methods and QC/QA Procedures

Purpose of Assessment

Design procedures of one form or another already exist for many of the R02 technologies. Some technologies already have well-established design procedures, some have various published design procedures, some have proprietary design procedures, and others have developing design procedures. Some technologies have worthwhile analysis procedures that are not integrated into comprehensive design procedures. To avoid excluding such material, the design assessment included both design and analysis procedures.

There are also many technologies for which establishing suitable QC/QA procedures is arguably the critical limiting factor preventing more widespread application of the technologies. Providing clear, precise, and effective guidelines for QC/QA procedures will remove an important source of uncertainty that currently makes some designers hesitant to apply these technologies.

The purpose of the assessment of design methods and of QC/QA procedures (design and QC/QA assessment) is to gather design/analysis methods and QC/QA procedures, and then critique and compare these two. The design and QC/QA assessment project working document provides the basis for development of the end user tools and products.

Information Assessed

Design methods and QC/QA procedures for the assessment came from various sources. Capturing literature that transportation agency engineers routinely rely on was a high priority. This included the following:

- FHWA design and guideline manuals
- AASHTO manuals and specifications
- *Transportation Research Record: Journal of the Transportation Research Board*
- NCHRP reports
- *NCHRP Synthesis of Highway Practice*

Literature was also gathered from university research reports and papers, conference technical papers, journal technical papers, and the like.

The design and QC/QA assessment critiques and characterizes the design and analysis methods and QC/QA procedures that were identified in the CTS document. There is no length limit for an assessment. The design and analysis portion of the assessments includes the following:

- Listing of all input and output parameters for each design/analysis method, in matrix form. In the matrix, specific input and output items appropriate for a particular technology are arranged in the following categories: performance criteria and indicators, subsurface conditions, loading conditions, material characteristics, geometry, and construction techniques.
- Comparative assessment of all design/analysis methods, in matrix form. The matrix contains four sections: design/analysis procedures, references, applications, and assessment of design/analysis procedure.
- Comparative characterization of all design/analysis methods, in matrix and comment forms. This includes a descriptive summary of each method, categorized ratings on each method, and comments on the ratings.

The QC/QA portion of the assessment also uses a matrix to systematically organize and evaluate information on existing procedures. The matrix has six sections: QC/QA methods, references, QC/QA objectives, applicability to QC and QA, assessment of QC/QA methods, and usefulness of QC/QA method for application. Generally, all the desired outputs from design procedures (from the first matrix in this document) should be subject to QC/QA activities and should be reflected in the QC/QA matrix.

Report and Products

A design and QC/QA assessment project working report has been prepared for each technology. The assessments and characterizations in the design and QC/QA assessment are used to develop the design guidance and the QC/QA procedures tools and products for the Geotechnical Solutions for Transportation Infrastructure website.

Assessment of Existing Specifications

Purpose of Assessment

Several specifications exist for many of the R02 technologies. Most technologies already have well-established STA specifications or guideline specifications, though some have proprietary specifications, and a few emerging technologies do not have a generic specification.

The purpose of the assessment of existing specifications (specification assessment) is to gather existing specifications; critique, characterize, and compare these; and provide recommendations on specification preparation for a technology.

Information Assessed

Individual specifications for the specification assessment came from diverse sources. This included the following:

- FHWA design and guideline manuals
- AASHTO manuals and specifications
- Standard specifications and special provisions from individual STAs
- NCHRP reports and *NCHRP Synthesis of Highway Practice*

The specification assessment critiques and characterizes the specifications that were identified in the CTS document. There is length limit for an assessment. The specification assessment also uses a matrix to systematically organize and evaluate information. The matrix is used to assess existing specifications for clarity, risk allocation, ability to be fairly bid, constructability, QC/QA verification, and completeness.

Report and Product

A specification assessment project working document has been prepared for each technology. The assessment and characterization in the specification assessment is used to develop the specifications guidance tool or product for the Geotechnical Solutions for Transportation Infrastructure website.

Review Processes

Typically, lead authorship of a CTS, design and QC/QA assessment report, and specification assessment report was given to one or two of the student researchers. One of the principal investigators served as a mentor and as the primary reviewer of each draft CTS. Additional reviewers included other principal investigators, advisory board members, and outside technical experts. The top of each document shows the lead author or authors, the mentor or primary reviewer, and any additional reviewers. Usually, the same authors, mentors, and reviewers were used on all three documents for a given technology.

Two additional reviews were completed in the fall of 2011. A peer review process was completed by student researchers. These student researchers reviewed the documents, reports, and products for all 46 technologies. This peer review focused on consistency between technologies and within products of an individual technology.

This was followed by reviews performed by the technology mentor or primary reviewer and by Vernon Schaefer and Ryan Berg, the R02 project managers. These were reviews of all the final documents, reports, and products for a particular technology. The primary focus of these reviews was consistency within all the technology products, documents, and reports.

Development Projects

Nine development projects were completed during the research to fill knowledge gaps for specific technologies and applications. The decision-making process to select these specific topics for advancement was documented in the Phase 1 report. A brief summary of each project follows. A separate report for each project has been prepared.

The R02 development projects are the following:

- Review and update of settlement methods for stone columns
- Development of a design procedure for vibro concrete columns
- Assessment of design of shoot-in soil nailing
- Guidelines for reinforced soil facing
- Review of existing design methods and development of a recommended design method for column-supported embankments
- Use of multiple technologies for stabilizing soft soils
- Performance verification of stabilized subgrades
- Comparison of surface compaction technologies through a compaction roadeo
- Assessment of geocell-reinforced recycled asphalt pavements

Settlement Analysis of Stone Columns

Stone column technology lacks a standard design procedure for accurately estimating settlements. The R02 project team believes that current methods for estimating settlements of stone columns are conservative. An extensive literature review was conducted to identify case histories where stone columns were used to reduce settlements. Case histories selected for evaluation had sufficient information provided for analysis and had data on settlements measured in the field. Based on analyses using three methods of estimating settlements and the measured settlements in the field, a statistical analysis was completed to evaluate the accuracy of each method. A parametric study of the procedures was conducted to assess the critical design inputs.

The report of this study provides a listing of case histories that document the successful and unsuccessful implementation of this technology, a summary of the settlement analysis procedures considered in this study, and a presentation of the comparisons between calculated and measured settlements. The work completed as part of this project may be used in the future to identify or develop a preferred procedure for estimating settlement of stone column reinforced sites. The preferred procedure could be an existing method or some modification of an existing method.

It is recommended that this report be made available for download (in PDF format) from the Geotechnical Solutions for Transportation Infrastructure website, specifically, from the aggregate columns document page. This will allow the user to learn about the various methods available for estimating settlements for stone column–reinforced ground.

Design Procedure for Vibro Concrete Columns

Vibro concrete columns (VCCs) are a foundation solution that can be used to improve load capacity and reduce settlements. Columns are constructed using a procedure similar to that for dry, bottom-feed dry stone columns but use concrete instead of stone. Advantages over stone columns are that VCCs demonstrate higher load capacity and they can be used in soils not suitable for stone columns (e.g., peat and compressible clay).

VCC technology lacks a standard design methodology, so VCCs are currently designed using modified drilled shaft or driven pile design methods. Drilled shaft design methods tend to over predict capacity, while driven pile methods tend to under predict capacity. To promote VCCs as a rapid and cost-effective technology, it is necessary to provide a standard design methodology that more accurately predicts capacity. The objectives of the VCC development project are to assess current design procedures based on available load test data and, to the extent possible, develop a standard design methodology for VCCs that more accurately predicts capacity.

Efforts have included the review of available literature on VCCs, collection of VCC case histories with load test data, and review of failure criteria for piles. A stand-alone VCC capacity program has been developed for easy calculation and comparison of design capacities. The program allows the user to input soil profile and column information, and it automatically determines capacity based on several drilled shaft and driven pile design methods. Results from the program will be compared with actual VCC load test data to evaluate the individual methods' accuracy and applicability to VCC design. A manual to explain the use of the program and the design method calculations has also been prepared.

It is recommended that this report be made available for download (in PDF format) from the Geotechnical Solutions for Transportation Infrastructure website, specifically, from the VCC document page. This will allow the user to more accurately and efficiently design VCCs.

Assessment of Design of Shoot-In Soil Nailing

Roadway widening and new roadway construction projects in rough terrain often require retaining walls. Drilled and grouted soil nails have been a traditional reinforcement method for these situations. In recent years, shoot-in or launched soil nails have become a viable alternative form of retaining wall and slope reinforcement in both temporary and permanent applications. This technology is directly applicable to Element 2, roadway and embankment widening. Other launched soil nail uses include bluff stabilization, micropiling, and excavation shoring.

Launched soil nailing is a relatively new technology developed in the United Kingdom in the early 1990s. A compressed air cannon, typically mounted on a traditional tracked excavator, uses pressures approaching 2,500 psi to launch the nails into the ground in a single blow at speeds in excess of 200 mph. Groups of these nails can be quickly installed to support retaining walls or unstable slopes. The soil nails used are typically 1½-in. diameter, 20-ft long steel or steel-tipped fiberglass tubes. After installation, an inner reinforcing steel bar is inserted and the annular spacing is filled with grout to transfer longitudinal shear stresses to the reinforcement and to provide corrosion protection for the steel. The tubes can also be perforated to allow for pressure injected grout to permeate into the surrounding soil and further increase the soil bond to the nail. Advantages of launched soil nailing include rapid installation and cost savings. Also, because the soil nail launcher can be mounted various highly mobile equipment, this technology can be applied in hard-to-access areas and in areas with narrow right-of-ways, with minimal disturbance to the surrounding area.

For the shoot-in soil nailing technology, the project goal is to review the different existing design methodologies and generate a technical evaluation report analyzing the design, construction, performance, and quality assurance aspects of the technology. A report detailing the technology background, applications, QC/QA procedures, and materials and equipment has been completed. Three design methodologies were examined: the FHWA method, the French method, and a method developed by Soil Nail Launcher, Inc. These methods were analyzed and compared via an ongoing literature review and sample soil nail wall designs.

It is recommended that this report be made available for download (in PDF format) from the Geotechnical Solutions for Transportation Infrastructure website, specifically, from the shoot-in soil nailing document page. This report will give general technology background for new users and provide guidance on available design methods.

Guidelines for Reinforced Soil Facing

Reinforced soil slope (RSS) technology uses geosynthetic or steel reinforcing elements within a soil slope to create a stable slope at a steeper slope angle than traditional, unreinforced slopes. Steepened slopes are desirable in some transportation applications. Typical RSS facing ranges vegetation and bioengineered faces to flexible armor systems. The purpose of RSS facing is to minimize erosion, protect the reinforcing elements, and contribute to the aesthetic quality of the structure. Without proper design and detailing of the RSS face, soil raveling, soil sloughing, erosion, or surficial slope failures may occur.

Typically, soil reinforcement manufacturers or vendors develop RSS-specific facing details and guidelines as an integral part of an RSS product. A project owner or DOT may choose to incorporate additional criteria or design considerations to the facing selection. Some facing details are well documented and established and others are not. The lack of accessible, documented, and proven facing details and designs continues to significantly limit the use of RSS by state DOTs.

The objective of this project is to develop comprehensive guidelines for reinforced soil slope facing and a catalog of design and construction details. The proposed document will include facing and vegetation selection guidelines, example specifications, design and construction details, and maintenance recommendations. The final report will be available in hard copy and electronic formats with drawings and details available in various program formats.

Various detail drawings and manufacturer literature have been collected from members of the Geosynthetic Materials Association (GMA) and from other industry sources. These resources were used to generate standard facing details for common facing types that could be used by DOTs. The report provides a description of each facing type and project criteria that are considered when selecting a facing. Several detail drawings have been developed.

It is recommended that this report be made available for download (in PDF format) from the Geotechnical Solutions for Transportation Infrastructure website, specifically, from the RSS document page. This will allow the user to learn about facing types and selection alongside the design, QC/QA, and specifications documents.

Development of a Recommended Design Method for Column-Supported Embankments

When an embankment is required over ground that is too soft or compressible to provide adequate support, columns of strong material can be placed in the soft ground to provide the necessary support by transferring the embankment load to a firm stratum. Several types of columns may be used for this technology, such as aggregate columns, deep-mixing-method columns, and traditional piles. A load transfer platform or bridging layer, consisting of compacted select fill with or without geosynthetic reinforcement, may be constructed immediately above the columns to help transfer the load from the embankment to the columns. A literature review revealed 12 design procedures for column-supported embankments (CSEs).

CSEs have the advantages of more rapid single-phase construction, reduced total and differential settlements, and protection of adjacent facilities and embankments. The major obstacle preventing widespread use of CSEs is the lack of standard design procedures. The goal of this research was to validate, improve, or develop one or more successful design procedures for widespread use in transportation projects.

A CSE test facility with a 30-ft by 30-ft test area was designed and constructed for the purpose of evaluating the arching and load transfer to the columns that occurs within the embankment. The test process involves an innovative use of geofoam for temporary support during embankment construction. After completion of CSE construction, the geofoam was dissolved to remove embankment support between precast concrete columns to simulate the settlement of soft soil. Five instrumented CSE tests were conducted from April to October 2010 using a total of approximately 2,100 tons of fill material. The key results of the CSE tests and resulting data analysis are the following:

- The critical height for 6-ft center-to-center spacing of 2-ft-diameter round columns in a square array is approximately 6.5 ft without trafficking loads and 7.5 ft after trafficking with a small skid-steer, rubber-tired loader. The critical height is the embankment height above which differential surface settlements were not observed.
- The Adapted Terzaghi and Hewlett and Randolph Methods for determining the vertical stress on the geosynthetic reinforcement are consistent with the test results.

- The Parabolic Method for determining the tension and strain in the geosynthetic reinforcement is consistent with the test results.
- The load-displacement compatibility approach by Filz and Smith incorporates soft-soil support and is consistent with the test results when the load is shared between the concrete columns and the geofoam before it is dissolved. The method developed by Filz and Smith also uses the Adapted Terzaghi and Parabolic Methods and forms the basis of the recommended design procedure contained in the report.

It is recommended that this report be made available for download (in PDF format) from the Geotechnical Solutions for Transportation Infrastructure website, specifically from the CSE document page. The report includes a literature review of design procedures and a complete description of the CSE facility and tests, as well as a recommended design procedure, specification, and QC/QA procedures.

Integrated Technologies for Embankments on Unstable Ground

The SHRP 2 R02 information and guidance system allows users to input project requirements and constraints, and from that obtain a list of potentially applicable ground improvement technologies. It provides users with a list of technologies, but it does not directly inform users of possible situations where the combination of technologies may be beneficial for their project.

The objective of a separate white paper on integrated technologies for unstable ground is to assist in achieving the goal of the SHRP 2 R02 program more efficiently and effectively by using two or more technologies at a site.

The white paper includes a discussion of benefits that combining multiple technologies may provide over the use of a single technology. In addition, it lists the SHRP 2 Elements 1 and 2 technologies that can be used to improve unstable ground under embankments and potential combinations of these technologies. Finally, case histories of successful combinations are summarized and links to additional references provided. The summaries illustrate where and why specific combinations have been used. A summary list of technology combinations is provided. This white paper has been developed to be used in conjunction with the information and guidance system. The white paper is hyperlinked throughout the Geotechnical Solutions for Transportation Infrastructure website.

Performance Verification of Stabilized Subgrades

Chemical stabilization of subgrades can improve the support conditions under pavements with increased strength/stiffness and resistance to seasonal changes, which should, in turn, contribute to better long-term performance of pavements. The *Mechanistic–Empirical Pavement Design Guide* (MEPDG) provides typical elastic modulus values and empirical equations to estimate elastic modulus values of stabilized soils for use in design. The modulus values provided in the guide are based on laboratory measurements obtained in short-term. The design also recommends typical deteriorated elastic modulus values for stabilized subgrades. Long-term changes in the performance characteristics of the stabilized subgrade layers are not considered in the design because of performance uncertainty and lack of quantitative long-term performance data. To remedy this, performance data on test sections that are at least 10 years old is crucial to gain understanding on the long-term strength, stiffness, and mineralogical and microstructural characteristics of chemical stabilized subgrades.

The main objectives of the project were to (a) document engineering properties (in situ strength and stiffness) and mineralogical and microstructural characteristics of chemically stabilized subgrades that are at least 10 years old, in comparison with natural subgrades at the same sites, and (b) understand factors that contribute to long-term engineering behavior of stabilized subgrade. In situ strength and stiffness characteristics were measured using falling weight deflectometer (FWD), light weight deflectometer (LWD), static plate load test (PLT), and dynamic cone penetrometer (DCP) tests [to determine California bearing ratio (CBR)], and laboratory tests on soil samples obtained from the field. Mineralogical and microstructural analysis was performed using scanning electron microscopy (SEM) and energy-dispersive spectrometry (EDS).

Nine test sections were selected to assess engineering properties of old stabilized subgrades in Texas, Oklahoma, and Kansas. The selection of the test sites was based on the type of subgrade, availability of old construction records, and age. Subgrades at six of these sites were stabilized with lime and the other three with fly ash. Eight test sites were over 10 years old, and one test site was approximately 5 years old. Eight sites consisted of flexible pavement supported on base and stabilized subgrade or just stabilized subgrade; one site consisted of concrete pavement supported on cement-treated base and stabilized subgrade.

In situ and laboratory testing and data analysis for all test sites have been completed and a data report has been generated. Some significant findings from the field and laboratory testing are as follows:

- FWD testing conducted showed nonuniform conditions at each site. Analyses are being performed to determine the influence of various parameters (i.e., pavement thickness, age of stabilized subgrade, thickness of stabilized subgrade, and moisture content) on the relationship between subgrade CBR and FWD surface deflections.

- The in situ elastic modulus of chemical-stabilized subgrades determined from the static PLT varied from 7 MPa to 317 MPa at the nine test sites. The MEPDG recommended typical modulus value for lime-stabilized soils is 310 MPa with a range of 240 MPa to 413 MPa, and a deteriorated modulus value for lime-stabilized soil is 103 MPa. Two of the six lime-stabilized subgrade sites tested showed modulus < 103 MPa (note that MEPDG does not provide typical values for fly ash–stabilized subgrades).
- Field results indicated that the elastic modulus value determined in the field is dependent on the test method used. On average, LWD and the back-calculated FWD modulus were about 0.7 times and 8.3 times the static PLT modulus, respectively. This divergence in calculated modulus values is an important aspect to consider when selecting design values and establishing QC/QA target values.
- The ratio of LWD modulus of stabilized subgrade and natural subgrade varied from about 4 to 11. Similarly, CBR ratios between stabilized and natural subgrade ranged from about 2.2 to 7.4. Results indicated that these ratios are influenced by the thickness of the stabilized layers (the lower the thickness, the lower the ratio).

It is recommended that the detailed report generated from this study be made available for download (in PDF format) from the Geotechnical Solutions for Transportation Infrastructure website, specifically, from the Chemical Stabilization of Subgrade and Base Courses technology page. The report will consist of case study information for each test site along with analysis of the field and laboratory results. This report provides significant new information on the performance of chemical-stabilized layers for use in pavement design.

Comparison of Compaction Technologies Through a Compaction Roadeo

A comprehensive review of literature, a detailed assessment of several technical obstacles that interfere with more widespread use, and evaluation of mitigation strategies and action items in terms of benefit-to-cost (B/C) ratio for each of the Element 3 technologies were completed. Three compaction technologies received high B/C ratios: rapid impact compaction (RIC), intelligent compaction (IC), and high energy impact roller (IR). One major obstacle for widespread implementation of RIC, IC, and IR technologies was identified as lack of well-documented and accessible case histories with benefits related to construction cost, time, efficiency, and effectiveness in consistently obtaining design properties, using these technologies compared to traditional compaction methods. Conducting compaction roadeo field demonstration projects is an effective mitigation strategy to overcome this obstacle. A field demonstration was originally intended to develop detailed case history information for different material and subsurface conditions (e.g., lift thicknesses) comparing the relative compaction efficiency, time, and cost by using the different compaction technologies. However, unavailability of equipment at the time of this project limited use of IC and traditional compaction technologies. The demonstration did include use of geosynthetic and geocells reinforcement technologies.

The main objectives of the project were to (a) evaluate the use of IC technology with on-board computer display system for compacted fill QC/QA testing; (b) evaluate compaction influence depth under the IC roller; (c) evaluate differences in engineering properties between different types of geosynthetic- and geocell-reinforced fill test sections along with unreinforced fill test sections by using different QC/QA testing methods; (d) evaluate differences in the in-ground dynamic stresses under the roller between different test sections; and (e) provide hands-on experience with IC technology and various QC/QA testing technologies, and various geosynthetic and geocell reinforcement products to researchers and practitioners.

The compaction roadeo field demonstration was conducted on the Highway 9B reconstruction project in Jacksonville, Florida, from May 16 to 20, 2011. A Caterpillar CS74 vibratory smooth drum self-propelled IC roller weighing about 34,000 lb was used on the project. Field testing involved construction and testing of five test beds (TBs) on the project site with poorly graded sand embankment fill (A-3) material. TB1 involved constructing six test sections, which included three different geosynthetic reinforcement (biaxial grid, polypropylene combigrid, woven polypropylene fabric) sections, two geocells reinforcement sections (6 in. and 4 in.), and one control section. TB2 involved compacting a thick loose lift (3 ft deep) in two sections—one with BX grid reinforcement and one without reinforcement. TBs 3, 4, and 5 involved mapping production areas using the IC roller and selecting test locations based on the color-coded on-board display unit in the roller for in situ testing. Field testing involved obtaining roller-integrated compaction measurements during compaction/mapping process, and point tests, including dynamic cone penetrometer (DCP) test, static cone penetrometer test (CPT), static plate load test (PLT), falling weight deflectometer (FWD) test, light weight deflectometer (LWD), nuclear gauge (NG), and sand cone density. In addition, all the sections of TB1 were instrumented with piezoelectric earth pressure cells (EPCs) to monitor in-ground total vertical and horizontal stresses before, during, and after compaction.

It is recommended that the detailed field data report generated from this study be made available for download (in PDF format) from the Geotechnical Solutions for Transportation Infrastructure website, specifically, from the Intelligent Compaction, Geosynthetic Reinforcement in Pavement Systems, and Geocell Confinement in Pavement systems pages. The results from this report will allow users to learn about differences in in situ soil characteristics with different geosynthetic and geocell reinforcement methods, compaction influence depth under vibratory compacted roller used on the project, and usefulness of application of IC technology for QC/QA.

Assessment of Geocell-Reinforced Recycled Asphalt Pavements

Geocell confinement technology uses geocell at the bottom portion of bases and subbases or on the top of subgrade in unpaved roads and some paved roads to construct stable pavement systems with less base or subbase thickness than traditional unreinforced pavement systems. The purpose of using geocell in pavement systems is to provide lateral confinement to infill materials, increase the stiffness and shear strength of the reinforced fill, distribute the wheel load to a wider area, and reduce rutting and other pavement distresses. Typically, geocell manufacturers or vendors provide specifications for the use of geocell in pavement applications. The lack of a well-developed design method, defined economical benefits, a well-developed QC/QA methods, documented case histories, and difficulties in compaction limit the use of geocell in pavement systems.

The objective of this project was to explore the possibility of geocell confinement of recycled asphalt pavement (RAP) as a base course material in pavement systems. The development document includes a comprehensive literature review for geocell-confined pavement systems, and experimental study of geocell-reinforced RAP bases for unpaved and paved roads.

Various specifications have been collected from industry sources, and a comprehensive literature review has been conducted. The experimental studies on the creep and cyclic behavior of geocell-reinforced RAP bases over subgrade for unpaved roads have been completed. The development project summary report provides a brief review and description of geocell technology for RAP bases, summarizes the experimental results and findings, and provides recommendations.

It is recommended that this report be made available for download (in PDF format) from the Geotechnical Solutions for Transportation Infrastructure website, specifically, from the Geocell Confinement in Pavement Systems document page. This will allow the user to learn about possible use of geocell with RAP as reinforced bases for unpaved and paved roads.

Future Work

As previously noted, the CTSs, design and QC/QA assessment reports and specification assessment reports are Phase 2 project work documents and reports. These are not primary products and tools and, therefore, will not be available on the Geotechnical Solutions for Transportation Infrastructure website. These documents will not be updated. End user products developed from these documents and posted on the Geotechnical Solutions for Transportation Infrastructure website will be updated as needed.

Future work will include the addition of technologies to the Geotechnical Solutions for Transportation Infrastructure website. The process of adding a technology will start with the development of a CTS, with bibliography and literature matrix included. Then, design and QC/QA assessment and specification assessment reports will be prepared. The detailed templates and instructions for these documents developed in Phase 2 will be used to help ensure consistent information gathering, evaluation, and summarizing processes. The CTS, design and QC/QA assessment report, and specification assessment report will be used to develop the Geotechnical Solutions for Transportation Infrastructure website products and tools for a new technology.

CHAPTER 6

Implementation Recommendations

Introduction

During Phase 2, the R02 project developed and produced a platform for delivering the project products via a website. In implementing the results of this project, the research team recommends an additional development effort to take it to a fully functional website that is open to the general transportation professional. Additional development is recommended for the following three categories:

- Website maintenance and functionality
- Content enhancement
- Training, education, and marketing

Website Maintenance and Functionality

The R02 project developed and produced a platform for delivering the project products via a website. A website was not within the original work scope of the project; the project proposal committed to preparing products in website-ready HTML format. During the course of the project, the research team convinced the SHRP 2 R02 staff that the preferred product delivery platform should be a web-based system. Consequently, the current project products are delivered via a website. However, the current project website requires additional development to make it a fully functional website that is open to the general transportation professional.

As discussed in Chapter 3, during the late stages of Phase 2, the research team conducted an in-house review of the products and the website, often termed an alpha test. The alpha testing uncovered numerous items that were corrected in the web-based information and guidance system. However, the website requires additional development work to make it fully functional for the general transportation professional. Beta testing was not within the scope of this project.

Two levels of beta testing are recommended. Beta 1 testing could be conducted by selected state highway administration (SHA) personnel, technical experts, and geotechnical engineers and by FHWA. Once beta 1 testing is complete, the website system logic and functionality should be updated based on the comments, identified gaps, and suggestions of this review group. After this updating, beta 2 testing could be conducted on two levels, which would run concurrently. One level would be to make the website available and open to the general public, who could provide feedback via the comment buttons on the website. A second level would entail intense testing of the website with small groups of STAs and professional groups. These workshops would be formatted and targeted to specific areas of the system and include a formal evaluation process. Such workshops could be conducted in conjunction with education efforts at state and local geotechnical conferences. The comments and suggestions received during beta 2 testing should be reviewed regularly and the website updated appropriately. Such updating will provide a living system of immense value to the transportation community.

Content Enhancement

The present web-based system contains information and guidance on 46 geoconstruction technologies identified during Phases 1 and 2 of the project. Significant information was collected, synthesized, integrated, and organized for these technologies. However, given the resources available to the research team, not every technology was afforded the same level of scrutiny, nor were all possible geoconstruction technologies included. Thus, the technical content of the website can be improved through enhancement of technologies presently in the system, the addition of other technologies related to the three elements, development of advanced modules that improve the selection methodology within the present framework, and expansion of technologies related to bridge geotechnical components.

The beta testing will provide comments on technologies within the present system. These comments will identify gaps in the present technical content of technologies and the selection system that can be updated, as well as identify additional technologies addressing the three project elements that should be added to the system. An assessment and evaluation of beta comments will identify high-value technical additions for the system. The development of advanced modules can improve the selection system within the present system. Such modules would refine project-specific selection, including SHRP 2 objectives and other project drivers, such as better inclusion of utility, environmental, and other constraints; construction time; constructability; and maintenance in a weighted rating system that would result in a project-specific ranking of technologies.

The present system was developed for the three elements of new embankment and roadway construction over unstable soils, roadway and embankment widening, and stabilization of pavement working platforms. There are numerous technologies related to bridge geotechnical components, such as shallow foundations, deep foundations, and bridge retaining-wall foundation systems, and such special soils as frozen soils, swelling soils, and collapsible soils, which could be added to the system to provide complete one-stop shopping for geotechnical solutions for transportation infrastructure.

Content enhancement related to performance-based specifications can be developed for selected R02 application areas in conjunction with the results of the SHRP 2 R07 Renewal project. Source information exists in the present system that can be used to develop draft performance-based specifications, conduct proof-of-concept use of the specifications with STAs, and update or modify specifications on the basis of demonstration project results.

Training, Education, and Marketing

Although the use of the web-based system is rather intuitive, demonstration of the system through webinars, workshops at state and regional geotechnical conferences, and seminars with SHA personnel would provide training on the use of the system; indeed, such efforts would enhance its use by transportation agency personnel. This hands-on training would also promote the use of the technologies by STAs, help create technology champions within the agency, and provide new case histories and information for enhancing the end products in the information and guidance system. Presentations on the web-based systems at regional, national, and international geotechnical and transportation conferences will provide marketing of the website. Additional detail on training, education, and marketing is described in Chapter 4.

Demonstration projects would provide another means of training and education on the use of the system. Demonstration projects can showcase, for example, newer technologies, test performance specifications, and showcase QC/QA techniques for ground improvement and geoconstruction. Compaction roadeos could be conducted to demonstrate the emerging compaction technologies.

APPENDIX A

End User Product Examples

The website with the end user products for each technology is available through a link on this report's web page (www.trb.org/main/blurbs/168148.aspx). Examples of each of the end user products are provided in this appendix:

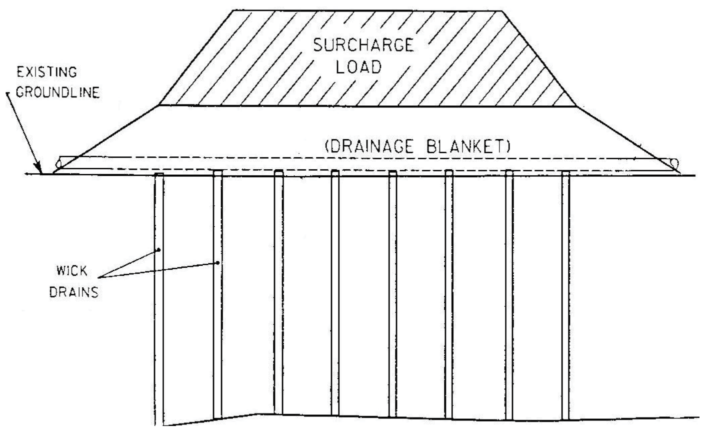
- Technology fact sheet
- Photographs (of technology)
- Case histories
- Design guidance
- QC/QA procedures
- Specifications
- Cost information and cost estimating tool
- Bibliography

Technology Fact Sheet Example

Technology Fact Sheet

PREFABRICATED VERTICAL DRAINS WITH AND WITHOUT FILL PRELOADING

March 2012 http://www.intrans.iastate.edu/geotechsolutions/index.cfm



Schematic of a prefabricated vertical drain installation

Basic Function

Prefabrication Vertical Drains (PVDs) (a.k.a. wick drains) are used to accelerate the settlement and shear strength gain of saturated, soft foundation soils by reducing the drainage path length.

Advantages:

- Decreased construction time
- Low cost
- No spoil
- High production rate
- Durable
- Simple QC/QA procedures

General Description:

PVDs are band shaped (rectangular cross-section) products consisting of a geotextile filter material surrounding a plastic core. Fill preloading consists of placing temporary fill on top of the embankment to speed settlement in the foundation soils.

Geologic Applicability:

- Saturated low strength, inorganic clays and silts.
- PVDs are routinely installed to depths of 100 feet (30.5 meters).
- PVDs have been installed to more than 200 feet (61 meters) on some projects.

Construction Methods:

Installation of PVDs requires site preparation, construction of a drainage blanket and/or a working mat, and installation of the drains. Site preparation includes removal of vegetation and surface debris, and obstacles that would impede installation of the PVDs. It may be necessary to construct a working mat to support construction traffic and installation rig loads, which can later serve as the drainage blanket. There are many different ways of installing PVDs, but most methods employ a steel covering mandrel that protects the PVD material as it is installed. All methods employ some form of anchoring system to hold the drain in place while the mandrel is withdrawn following insertion to the desired depth. The mandrel is penetrated into the compressible soils using either static or vibratory force.

R02 GEOTECHNICAL SOLUTIONS FOR SOIL IMPROVEMENT,
RAPID EMBANKMENT CONSTRUCTION,
AND STABILIZATION OF PAVEMENT WORKING PLATFORM

SHRP2 STRATEGIC HIGHWAY RESEARCH PROGRAM

Technology Fact Sheet Example (continued)

Additional Information:

Design considerations include drain spacing, flow resistance and installation disturbance. Quality control tests usually relate to the material properties of the drain and the measurement of settlement and pore pressures during consolidation. Factors which affect the unit cost of installing PVDs include: the type, strength and depth of the soil, the specifications and requirements, the size of the project, material cost, and labor cost. The installed costs of PVDs are in the range of $2.50 to $3.25 per meter. Mobilization costs will typically range from $8,000 to $10,000 plus the cost of instrumentation and installation of a drainage blanket.

SHRP2 Applications:

- New Embankment and Roadway Construction
- Embankment Widening

Example Successful Applications:

Airport Runway and Taxiway Extension, Moline, IL

Complementary Technologies:

PVDs with a preload are typically not used in conjunction with other technologies.

Alternate Technologies:

Deep foundation elements, sand drains, vacuum preloading, stone columns, deep dynamic compaction, grouting, deep soil mixing, excavation and replacement, and lightweight fill.

Potential Disadvantages:

- Stiff soil layers increase installation difficulty leading to increased cost.
- Limited headroom can be a limitation.
- Settlements observed in field generally do not match oedometer tests.

Key References for this Fact Sheet:

Elias, V., Welsh, J., Warren, J., Lukas, R., Collin, J.G., and Berg, R.B. (2006). "Ground Improvement Methods-Volume I." Federal Highway Administration, Publication No. FHWA NHI-06-019.

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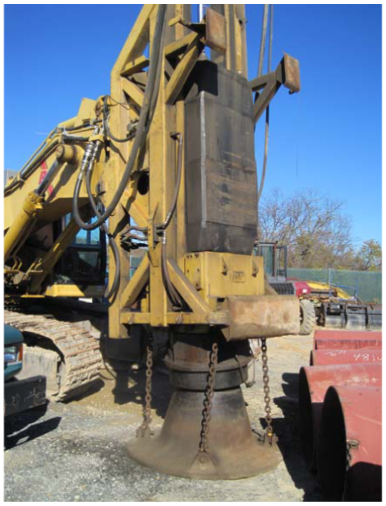
Rixner, J.J., Kraemer, S.R. and Smith, A.D. (1986). "Prefabricated Vertical Drains." *U.S. Federal Highway Administration, Research, Development and Technology, Vol. I: Engineering Guidelines, Report No. FHWA/RD-86/168.*

R02 GEOTECHNICAL SOLUTIONS FOR SOIL IMPROVEMENT,
RAPID EMBANKMENT CONSTRUCTION,
AND STABILIZATION OF PAVEMENT WORKING PLATFORM

SHRP2 STRATEGIC HIGHWAY RESEARCH PROGRAM

Photographs Example

Rapid Impact Compaction



Hammer and anvil portion of rapid impact compactor.
From the files of P. Becker.

Rapid impact compactor following first pass of compaction points.
From the files of P. Becker.

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R02 GEOTECHNICAL SOLUTIONS FOR SOIL IMPROVEMENT,
RAPID EMBANKMENT CONSTRUCTION,
AND STABILIZATION OF PAVEMENT WORKING PLATFORM

SHRP2
STRATEGIC HIGHWAY RESEARCH PROGRAM

PHOTOGRAPHS

Photographs Example (continued)

Rapid Impact Compaction

Rapid impact compactor in the process of compaction.
From the files of P. Becker.

Case History Example

Column Supported Embankment
Minnesota Trunk Highway 241 Widening
– Project Case History –

Location: TH 241 near St. Michael, MN, southwest of I-94/TH 241 interchange

Owner: Minnesota Department of Transportation

Contractor:

Engineers: Mn/DOT and The Collin Group

Year Constructed: 2006

Project Summary/Scope:
A pile supported embankment was constructed on Trunk Highway (TH) 241 near St. Michael, MN, about 2000 feet southwest of I-94/TH 241 interchange. This project involved widening of a highway from 2 to 4 lanes. The new embankment was a widening of an existing embankment. Differential settlement between the new embankment section and the old section was a concern.

Subsurface Conditions: 30 feet of highly organic silt loams and peats underlain by about 20 feet of silty organic soils. Below that were 12 feet of loamy sand underlain by 35 feet of gravelly sand. A well cemented sandstone laid 100 feet below the ground surface. The section of highway was bordered on the northwest by a small pond and on the southeast by marshy terrain

Pile spacing was 7 feet on-center and the diameter of pile caps was 2 feet. The Load Transfer Platform (LTP) embankment was designed using the beam design method. Piles consisted of steel pipes filled with concrete. Four layers of geosynthetic reinforcement were used with granular fill. The total thickness of the LTP was 3 feet (~ 1 meter).
Backfilling of the embankment was completed on October 10, 2006.
Instrumentation data is presented through June 4, 2007.

Complementary Technologies Used:
Geofoam lightweight fill, reinforced soil slope, and geosynthetic construction platform stabilization technologies were also used for this embankment widening.

R02 Geotechnical Solutions for Soil Improvement, Rapid Embankment Construction, and Stabilization of Pavement Working Platform

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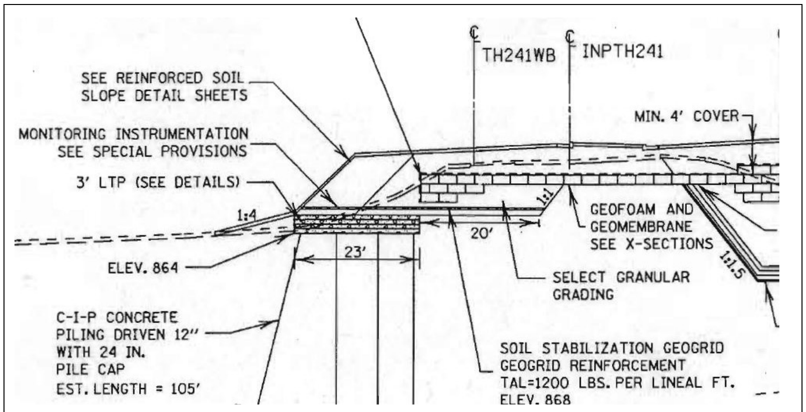
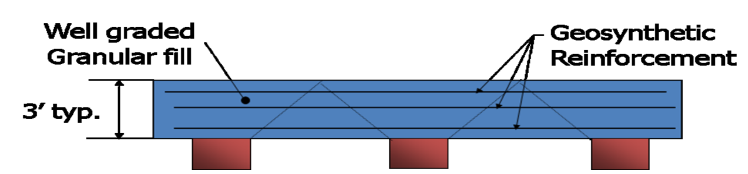
STRATEGIC HIGHWAY RESEARCH PROGRAM

PROJECT CASE HISTORY

Case History Example (continued)





Performance Monitoring:
The embankment was instrumented with 48 sensors including strain gages, earth pressure cells, and settlement systems. Settlements, geosynthetic strains, and pile strains/loads are presented in the technical paper for an approximately 18-month period following construction. A finite element analysis was performed using STRAND7. Instrumentation results are compared with the finite element analysis.

Case History Author/Submitter:
Rich Lamb, P.E.
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Project Technical Paper:
Wachman, G.S., Biolzi, L. and Labuz, J.F. (2010). "Structural behavior of a pile-supported embankment," Journal of Geotechnical and Geoenvironmental Engineering, Vol. 136, No. 1, pp 26-34.

Date Case History Prepared: 21 July 2010

Design Guidance Example

MECHANICALLY STABILIZED EARTH WALLS

DESIGN GUIDANCE

Preferred Design Procedure

The Federal Highway Administration (FHWA) has a set of design documents for this technology. The documents are summarized below.

Publication Title	Publication Year	Publication Number	Available for Download
Mechanically Stabilized Earth Walls and Reinforced Slopes, Design and Construction Guidelines	2009	Vol. I – FHWA-NHI-10-024, and Vol. II – FHWA-NHI-10-025	Yes[1]

[1] *Link:* http://www.fhwa.dot.gov/engineering/geotech/retaining/100317.cfm

Summary of Design/Analysis Procedure: Load Resistance Factor Design (LRFD)

Current FHWA Reference(s): *Berg et. al (2009)*

Supporting Reference(s): *AASHTO (2010)*
Tanyu et. al (2008)

The Load Resistance Factor Design (LRFD) Method utilizes limit equilibrium analysis to determine the geometric and reinforcement requirements to prevent internal and external failure. Material resistance and uncertainty in applied loads are accounted for separately in the LRFD method making the geotechnical analysis more consistent with structural design. The LRFD method has four different limit states. These limit states represent distinct structural performance criteria: (1) strength limit states, (2) serviceability limit states, (3) extreme-event limit states, and (4) fatigue limit states Most geotechnical MSE wall projects will utilize strength of service limit states with a check of serviceability limit states. Walls subjected to earthquakes or large vehicle loads are also designed for extreme-event limit states. The following is a summary for the design of mechanically stabilized earth walls as presented in the FHWA document. Table 1 summarizes the required inputs and outputs used in the LRFD procedure.

STEP 1. Establish the geometric, loading, and performance requirements for design.

A. Geometry
   a. Wall heights
   b. Wall batter
   c. Backslope
   d. Toe slope

Design Guidance Example (continued)

MECHANICALLY STABILIZED EARTH WALLS

DESIGN GUIDANCE

B. Loading Conditions
  a. Soil surcharges
  b. Live (transient) load surcharges
  c. Dead (permanent) load surcharges
  d. Loads from adjacent structures that may influence the internal or external stability of MSE wall system, e.g., spread footings, deep foundations, etc.
  e. Seismic
  f. Traffic barrier impact

C. Performance Criteria
  a. Design code (e.g., AASHTO LRFD 2007)
  b. Maximum tolerable differential settlement
  c. Maximum tolerable horizontal displacement
  d. Design life
  e. Construction constraints

STEP 2. Establish project parameters.

A. The following must be defined by the agency (Owner) and/or the designer:
  a. Existing and proposed topography
    i. Subsurface conditions across the site
      1. Engineering properties of foundation soils (γ_f, c'_f, ϕ'_f, c_u)
    ii. Groundwater conditions
  b. Reinforced backfill – engineering properties of the reinforced soil volume (γ_r, ϕ'_r)
  c. Retained backfill – engineering properties of the retained fill (γ_b, c'_b, ϕ'_b), addressing all possible fills (e.g., in-situ, imported, on-site, etc.). Cohesion in the retained backfill is usually assumed to be equal to zero. See FHWA Earth Retaining Structures reference manual (Tanyu et al. 2008) for guidance on value of cohesion and calculation of the lateral pressure if a cohesion value is used in design

Additional information can be found on FHWA manual page 4-9 to 4-10.

STEP 3. Estimate wall embedment depth and reinforcement length.

A. The process of sizing the structure begins by determining the required embedment and the final exposed wall height, the combination of which is the full design height, H, for each section or station to be investigated. Use of the full height condition is required for design as this condition usually prevails in bottom-up constructed structures, at least to the end of construction.

Additional information can be found on FHWA manual page 4-11.

Design Guidance Example (continued)

MECHANICALLY STABILIZED EARTH WALLS

DESIGN GUIDANCE

STEP 4. Define nominal loads.

A. The primary sources of external loading on an MSE wall are the earth pressure from the retained backfill behind the reinforced zone and any surcharge loadings above the reinforced zone. Thus, the loads for MSE walls may include loads due to horizontal earth pressure (EH), vertical earth pressure (EV), live load surcharge (LS), and earth surcharge (ES). Water (WA) and seismic (EQ) should also be evaluated if applicable. Stability computations for walls with a near vertical face are made by assuming that the MSE wall acts as a rigid body with earth pressures developed on a vertical pressure plane at the back end of the reinforcements.

Additional information can be found on FHWA manual page 4-11 to 4-17.

STEP 5. Summarize load combinations, load factors, and resistance factors.

A. Maximum permanent loads, minimum permanent loads, and total extremes should be checked for a particular load combination for walls with complex geometry and/or loadings to identify the critical loading.
B. Live loads are not used on specific design steps since they contribute to stability. These are identified in subsequent design steps.
C. Resistance factors for external stability and for internal stability are presented in respective design step discussions that follow. Internal stability resistance factors are listed later.

Additional information can be found on FHWA manual page 4-17 to 4-18.

STEP 6. Evaluate external stability.

A. As with classical gravity and semigravity retaining structures, four potential external failure mechanisms are usually considered in sizing MSE walls:
   a. Sliding on the base
   b. Limiting eccentricity (formerly known as overturning)
   c. Bearing resistance
   d. Overall/global stability

Additional information can be found on FHWA manual page 4-18 to 4-31.

STEP 7. Evaluate internal stability.

A. The step by step internal design process is as follows:
   a. Select a reinforcement type (inextensible or extensible).
   b. Select the location of the critical failure surface.

Design Guidance Example (continued)

MECHANICALLY STABILIZED EARTH WALLS

DESIGN GUIDANCE

c. Select a reinforcement spacing compatible with the facing.
d. Calculate the maximum tensile force at each reinforcement level, static and dynamic.
e. Calculate the maximum tensile force at the connection to the facing.
f. Calculate the pullout capacity at each reinforcement level.

Additional information can be found on FHWA manual page 4-31 to 4-59.

STEP 8. Design of facing element.

A. Facing elements are designed to resist the horizontal forces developed. Reinforcement is provided to resist the maximum loading conditions at each depth in accordance with structural design requirements in Section 5, 6, and 8 of AASHTO (2007) for concrete, steel, and timber facings, respectively. The embedment of the soil reinforcement to panel connector must be developed by test to ensure it can resist the T_{MAX} loads.

Additional information can be found on FHWA manual page 4-58 to 4-59.

STEP 9. Assess overall/global stability.

A. This design step is performed to check the overall, or global, stability of the wall. Overall stability is determined using rotational or wedge analyses, as appropriate, to examine potential failure planes passing behind and under the reinforced zone. Analyses can be performed using a classical slope stability analysis method with standard slope stability computer programs. In this step, the reinforced soil wall is considered analogous to a rigid body and only failure surfaces completely outside a reinforced zone (e.g., global failure planes) are considered. Computer programs that directly incorporate reinforcement elements (e.g., ReSSA) can be used for analyses that investigate both global and compound failure planes.

Additional information can be found on FHWA manual page 4-59 to 4-61.

STEP 10. Assess compound stability.

A. Additional slope stability analyses should be performed for MSE walls to investigate potential compound failure surfaces, i.e., failure planes that pass behind or under or through a portion of reinforced soil zone. For simpler structures with rectangular geometry, relatively uniform reinforcement spacing, and a near vertical face, compound failures passing through both the unreinforced and reinforced zones will not generally be critical.
B. However, if complex conditions exist such as changes in reinforced soil types or reinforcement lengths, high surcharge loads, seismic loading, sloping faced structures,

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STRATEGIC HIGHWAY RESEARCH PROGRAM

Design Guidance Example (continued)

MECHANICALLY STABILIZED EARTH WALLS

DESIGN GUIDANCE

significant slopes at the toe or above the wall, or stacked (tiered) structures, compound failures must be considered.

Additional information can be found on FHWA manual page 4-61 to 4-64.

STEP 11. Wall drainage system.

A. Drainage is a very important aspect in the design and specification of MSE walls. The Agency should detail and specify drainage requirements for vendordesigned walls. Furthermore, the Agency should coordinate the drainage design and detailing (e.g., outlets) within its own designers and with the vendor.
   a. Subsurface drainage must be addressed in design. The primary component of an MSE wall is soil. Water has a profound effect on soil, as it can both decrease the soil shear strength (i.e., resistance) and increase destabilizing forces (i.e., load). Thus, FHWA recommends drainage features be required in all walls unless the engineer determines such feature is, or features are, not required for a specific project or structure.
   b. Surface drainage is an important aspect of ensuring wall performance and must be addressed during design and during construction. Appropriate drainage measures to prevent surface water from infiltrating into the wall fill should be included in the design of a MSE wall structure.
   c. Potential scour in walls greatly affects wall performance and should be addressed with additional detailing considerations if there is an issue. The wall embedment depth must be below the Agency-predicted scour depth. Wall initiation and termination detailing should be considered and be designed to prevent scour. Riprap may be used to protect the base and ends of a wall. The reinforced wall fill at the bottom of the structure may be wrapped with a geotextile filter to minimize loss of fill should scour exceed design predictions.

Design Guidance Example (continued)

MECHANICALLY STABILIZED EARTH WALLS

DESIGN GUIDANCE

Table 1. Typical inputs and outputs for design and analysis procedures.

Performance Criteria/Indicators	Design code (e.g., AASHTO LRFD 2007)
	Maximum tolerable differential settlement
	Maximum tolerable horizontal displacement
	Design life
	Construction constraints
Subsurface Conditions	Engineering properties of foundation soils (γ_f, c'_f,ϕ'_f, c_u)
	Groundwater conditions
Loading Conditions	Soil surcharges
	Live (transient) load surcharges
	Dead (permanent) load surcharges
	Loads from adjacent structures that may influence the internal external stability of MSE wall system
	Seismic
	Traffic barrier impact
Material Characteristics	MSE Wall materials – classification properties
	MSE Wall materials – shear strength properties
	MSE Wall materials – chemical and biological factors that may be detrimental to reinforcement
	Geosynthetic – tensile strength
	Geosynthetic – load versus strain properties
	Geosynthetic – reinforcement modulus
	Geosynthetic – soil-geosynthetic interface friction angle
Construction Techniques	Subgrade preparation
	Geosynthetic placement procedures
	Fill placement, spreading, and compaction procedures
	Low ground pressure equipment
	Staged construction
	Construction monitoring
Geometry	Wall/Slope height
	Wall/Slope length
	Spacing between reinforcement layers (s)
	Length of reinforcement (L)
	Wall/Slope face angle

Design Guidance Example (continued)

MECHANICALLY STABILIZED EARTH WALLS

DESIGN GUIDANCE

References

Berg, R.R., Christopher, B.R. and Samtani, N. (2009). "Mechanically Stabilized Earth Walls and Reinforced Slopes, Design and Construction Guidelines, Vol. I - FHWA-NHI-10-024, Vol. II – FHWA-NHI-10-025, Federal Highway Administration, Washington, D.C.

AASHTO (2007). *LRFD Bridge Design Specifications*. 4th Edition, with 2008 and 2009 Interims, American Association of State Highway and Transportation Officials, Washington, D.C.

Tanyu, B.F., Sabatini, P.J. and Berg, R.R. (2008). *Earth Retaining Structures*, U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., FHWA-NHI-07-071, 2008.

QC/QA Procedures Example

GEOSYNTHETIC SEPARATION IN PAVEMENT SYSTEMS

QC/QA PROCEDURES

Preferred QC/QA Procedures

The Federal Highway Administration (FHWA) provides QC/QA guidance to assure the strength and serviceability requirements of geosynthetics in pavement separation. It also gives guidance for the proper construction of the pavement system. The documents are summarized below.

Publication Title	Publication Year	Publication Number	Available for Download
Geotechnical Aspects of Pavements	2006	FHWA NHI-05-037	Yes[1]
Geosynthetic Design and Construction Guidelines	2008	FHWA NHI-07-092	No

[1] http://www.fhwa.dot.gov/engineering/geotech/pubs/05037/05037.pdf

There are many QC/QA procedures necessary to ensure a proper performance of the geosynthetics in separation applications. Verification of material properties and exhumation for property evaluation are used for both quality control and quality assurance while dust collection and rut measurement are used for quality assurance. GPR and FWD testing can evaluate pavement layer thickness, moisture distribution, and/or resilient modulus quickly and inexpensively; therefore, they can be used to confirm the benefit of geosynthetic separation and estimate the remaining service life of pavements. In Addition, they provide guidance to select appropriate maintenance and rehabilitation activities.

QC/QA Procedures Example (continued)

GEOSYNTHETIC SEPARATION IN PAVEMENT SYSTEMS

QC/QA PROCEDURES

QC/QA Guidelines

The geotextiles and the threads used in joining geotextiles by sewing shall meet the chemical composition requirements. Fibers used in the geotextile and the threads shall consist of long chain synthetic polymers with at least 95% polyolefins or polyesters by weight. The strength and serviceability requirements of the geotextile for separation in pavement systems can be verified per ASSHTO M288 (1997), Holtz et al. (2008), and state guidance based on the subgrade soil properties. Geotextile labeling, shipment, and storage shall follow ASTM D4873. The QC/QA guidance in ASSHTO M288 (1997) and Holtz et al. (2008) ensures proper geotextile placement, overlapping, aggregate placement, and compaction.

For performance evaluation, the rut measurement is taken directly on the field and an average rut depth is calculated. A linear or nonlinear correlation curve is used to describe the relationship between the development of rutting and cumulative ESALS to predict the service life of the pavement. Although not standard practice, GPR and FWD testing can be used for both quality control and quality assurance. GPR and FWD testing can evaluate pavement layer thickness, moisture distribution, and/or resilient modulus quickly and inexpensively, therefore, they can be used to confirm the benefit of geosynthetic separation, to estimate the remaining service life of pavements, and provide guidance to select appropriate maintenance and rehabilitation activities.

Exploratory excavations (test pits) can be used to observe the conditions of the pavement layers, ground water, and geosynthetics. Several in-situ tests (pocket penetrometer, Torvane, and nuclear densiometer tests) can be performed to determine the subgrade soil conditions. The samples of base and subgrade soils and geosynthetics are also collected for laboratory tests. The laboratory tests, such as moisture content and particle size distribution on the soil samples, and permittivity and wide-width tensile strength test on the exhumed geotextile, can be performed.

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R02 GEOTECHNICAL SOLUTIONS FOR SOIL IMPROVEMENT,
RAPID EMBANKMENT CONSTRUCTION,
AND STABILIZATION OF PAVEMENT WORKING PLATFORM

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QC/QA Procedures Example (continued)

GEOSYNTHETIC SEPARATION IN PAVEMENT SYSTEMS

QC/QA PROCEDURES

QC/QA Methods

Table 1 below presents the objectives of the QC/QA monitoring. Individual QC/QA methods are discussed in more detail on the following pages.

Table 1. Objectives of QC/QA monitoring.

Topics			Results
Existing QC/QA procedures & measurement values	QC	Material Related	Base coarse and subgrade soil properties: CBR, permeability, moisture content, and grain size distribution. Geosynthetic properties: chemical composition of geosynthetic fiber, grab strength, sewn seam strength, tear strength, puncture strength, permittivity, apparent opening size, and UV stability (retained strength).
		Process Control	Labeling, shipment, and storage, placement of a geosynthetic, placement and compaction of a base coarse, width of geosynthetic overlap or seam, and minimum aggregate thickness above geosynthetics.
	QA	Material Related	Moisture content, grain size distribution, pocket penetrometer, torvane, and nuclear densimeter tests.
		Process Control	Field observation (e.g., rutting),
Performance Criteria	Material Parameters		Resilient modulus.
	System Behavior		Rut measurement, surface curvature index (SCI), and base damage index (BDI).
Emerging QC/QA procedures & measurement values	QC	Material Related	
		Process Control	Intelligent compaction control, FWD and GPR testing.
	QA	Material Related	Instrumented (Intelligent) geosynthetics.
		Process Control	Intelligent compaction control, FWD and GPR testing.

QC/QA Procedures Example (continued)

GEOSYNTHETIC SEPARATION IN PAVEMENT SYSTEMS

QC/QA PROCEDURES

QC/QA Method:	**Verification of Material and Its Properties**
Reference(s):	*AASHTO M288 (2006)* *Holtz et al. (2008)*

Method Summary

To maintain the quality in the separation construction, base course and subgrade soil properties shall be verified. Geotextile and its properties shall be confirmed before laying on the prepared subgrade or subbase layer. The Contractor shall provide to the Engineer a record stating the name of the manufacturer, product name, style number, and chemical composition of the fibers. The geotextile labeling, shipment, and storage shall follow ASTM D4873. Engineer may be able to specify class of geotextile based on survivability criteria, aggregate thickness, aggregate size, and construction equipment contact pressure. Geotextile shall be verified using the laboratory tests with the strength requirements such as grab strength, sewn seam strength, puncture strength, apparent opening size etc according to ASSHTO M288 (2006). Permeability and permittivity of geotextile should be greater than those of soil.

Accuracy and Precision

Laboratory tests on geosynthetics, subgrade soil, and base coarse material are highly accurate, precise, and are standardized by ASTM and ASSHTO. The geosynthetic properties like most manufactured materials will take fewer tests to maintain accuracy and precision, while tests on subgrade and base course will take more tests to maintain accuracy and precision.

Adequacy of Coverage

Since most manufactured geosynthetic materials have small variability in properties, a limited amount of tests are enough to cover the properties of the geosynthetic used. However, for subgrade and base course, their properties are more variable and depend on the frequency of the tests.

Implementation Requirements

Implementation of standard ASTM tests is straightforward and easy to incorporate into a QC/QA procedure.

QC/QA Procedures Example (continued)

GEOSYNTHETIC SEPARATION IN PAVEMENT SYSTEMS

QC/QA PROCEDURES

General Comments

Laboratory tests are the common and accurate way to maintain quality control and quality assurance of the pavement materials. Verification of material properties is well adapted for the quality control and assurance on geosynthetics used for separation in pavement systems.

QC/QA Procedures Example (continued)

GEOSYNTHETIC SEPARATION IN PAVEMENT SYSTEMS

QC/QA PROCEDURES

QC/QA Method:	**Rut Measurement**
Reference(s):	*Al-Qadi and Appea (2003)* *Guram et al. (1994)* *Loulizi et al. (1999)*

Method Summary

Rutting indicates the deformation and wear of the materials in the pavement. The deformation in the pavement may be due to the reduction of the resilient modulus of the base layer. The reduction of the resilient modulus can be occurred due to the migration of the fines from the subgrade into the base material. Hence, rut measurements can be considered as a QC/QA method for the geotextile separation. The measurement can be taken on the pavement sections using a straight edge. The average rut depth for the measurement locations is calculated. A terminal rut depth is specified and the service life of the pavement sections is computed by developing a linear or nonlinear curve to describe the relationship between the development of rutting and cumulative ESALs over time for the sections.

Accuracy and Precision

The rut measurement is taken directly on the field and an average rut depth is calculated. A linear or nonlinear correlation curve is used to describe the relationship between the development of rutting and cumulative ESALS to predict the service life. This method indirectly evaluates the benefit of a geosynthetic separator, especially when a control section is available.

Adequacy of Coverage

Rut development on the surface of the pavement can be estimated. Adequacy of coverage depends on the frequency of tests and the consistency of field conditions.

Implementation Requirements

Measurement of the rut is a straightforward method and can be implemented easily.

QC/QA Procedures Example (continued)

GEOSYNTHETIC SEPARATION IN PAVEMENT SYSTEMS

QC/QA PROCEDURES

General Comments

Rut measurement is an important tool to indirectly check the performance of geosynthetics as a separator in a pavement system. The serviceability ratings are useful to determine the effectiveness, or accuracy of a design.

QC/QA Procedures Example (continued)

GEOSYNTHETIC SEPARATION IN PAVEMENT SYSTEMS

QC/QA PROCEDURES

QC/QA Method:	**GPR System**
Reference(s):	*Al-Qadi and Appea (2003)* *Loulizi et al. (1999)*

Method Summary

Ground-Penetrating Radar (GPR) surveys are performed on the test sections to monitor any changes in the pavement systems. An electromagnetic wave is transmitted through the pavement layers using the GPR. The depth of the hidden interface can be calculated by measuring the time of reflection of the wave and known dielectric constant of the medium above the interface. The changes in the amplitude of the reflected signal at the base/subgrade interface can be monitored to determine whether there is contamination or not due to the migration of the fines from the subgrade into the base layer. When the contamination is present, the amplitude of the reflected wave will be low because of the weak contrast between dielectric constant of the base and subgrade material. This indicates the migration of the fines from subgrade soil to base course material.

GPR passes are periodically taken for the required sections of the pavement. The depth of the hidden interface in the pavement can be obtained measuring the time of reflection of the signal. The changes in amplitude are compared with the initial observed amplitude to determine contamination of the base layer with time.

Accuracy and Precision

Pavement thickness data by GPR are accurate as compared with those obtained through conventional core samples within 3-15% error.

Adequacy of Coverage

The GPR method can evaluate a wide area of a pavement section.

Implementation Requirements

The method is quick and cost effective.

QC/QA Procedures Example (continued)

GEOSYNTHETIC SEPARATION IN PAVEMENT SYSTEMS

QC/QA PROCEDURES

General Comments

The GPR test is easy to implement, accurate, quick, and cost effective. It is typically used for quality assurance and evaluating completed pavement sections.

QC/QA Procedures Example (continued)

GEOSYNTHETIC SEPARATION IN PAVEMENT SYSTEMS

QC/QA PROCEDURES

QC/QA Method:	**FWD System**
Reference(s):	*Al-Qadi and Appea (2003)* *Black and Holtz (1999)* *Hayden et al. (1998)* *Loulizi et al. (1999)*

Method Summary

A nondestructive FWD test is conducted on the pavement to estimate its structural capacity and thus its service life. The FWD equipment can apply an impulse load of 40 kN for 40 ms to simulate the traffic load on the pavement. The deflection data obtained is used to calculate the resilient moduli of the pavement layers using the back-analysis. MODULUS Version 5.0 and ELMOD programs are used for the FWD data analysis. In MODULUS, the resilient moduli of the HMA and aggregate base layers obtained in the laboratory simulating the field conditions at the time of FWD testing are fixed and the subgrade modulus is obtained by iterative back-calculations. In ELMOD, the moduli of the HMA and subgrade layers are fixed and the resilient modulus of the base layer is back-calculated. The temperature correction model developed from statistical analysis of the measured deflections and HMA mid-depth temperatures was applied to the study. The thickness of HMA used for the temperature correction model is obtained by direct measurement of the thickness of the HMA through field cores. The results of Surface Curvature Index (SCI) and Base Damage Index (BDI) for all nine sections are collected during an eight-year period and then are analyzed and corrected to a standard temperature of 25°C. The resilient moduli of the pavement layers obtained using the FWD testing are utilized to calculate the vertical compressive stress using the mechanistic approach. The stress developed under the HMA pavement surface is correlated with the rate of rutting.

Accuracy and Precision

The resilient moduli of the pavement layers were obtained using back-analysis. Resilient modulus is used as a design input for both the empirical and mechanistic-empirical design methods. The back-calculated modulus can be accurate if the moduli of other layers are known, but the analysis procedure does not often give the unique solution if the moduli of other layers are unknown.

Adequacy of Coverage

QC/QA Procedures Example (continued)

GEOSYNTHETIC SEPARATION IN PAVEMENT SYSTEMS

QC/QA PROCEDURES

FWD data can be used to determine the resilient moduli of the pavement layers and rutting rate to estimate the structural capacity and the service life of the pavement. The pavement condition can be evaluated using a reasonable number of FWD tests. Adequacy of coverage depends on the frequency of tests.

Implementation Requirements

This method requires a correction for temperature and assumes the moduli of any two layers simulating the same conditions at the time of FWD testing. Therefore, the implementation requirements are somewhat greater than desired.

General Comments

The FWD test is a common, easy to implement method of testing. It is typically used for quality assurance and evaluating completed pavement sections. This test is used to verify assumed stiffness, monitor performance over time, and to compare the sections with geosynthetics to control pavement systems.

QC/QA Procedures Example (continued)

GEOSYNTHETIC SEPARATION IN PAVEMENT SYSTEMS

QC/QA PROCEDURES

QC/QA Method:	**Exhumation for property evaluation**
Reference(s):	*Black and Holtz (1999)* *Guram et al. (1994)* *Loulizi et al. (1999)*

Method Summary

Exploratory excavations (test pits) are made at each test section to observe the conditions of the pavement layers, ground water, and geosynthetics. Care is needed to remove the base coarse within 25 to 50 mm of the anticipated geosynthetic location to prevent the damage on the geosynthetics and intermixing of the base coarse with the subgrade layer. The samples of the base course are collected for the laboratory analysis. The geosynthetic samples were carefully removed and visual observations are recorded. Exhumed geosynthetic samples are collected for laboratory tests. Several in-situ tests (pocket penetrometer, Torvane, and nuclear densiometer tests) are performed and the samples of subgrade soils are collected for laboratory tests. Permittivity tests are performed on the exhumed geotextiles using a permeameter that was designed and constructed to evaluate the degrees of blinding and clogging of the geotextiles. Wide-width tensile strength tests are conducted on the specimens from each excavated and virgin geotextile to obtain retained strength after years of performance.

Accuracy and Precision

Properties of pavement materials and geosynthetics can be assessed accurately and precisely to evaluate the benefit of geosynthetic separation through a reasonable number of tests.

Adequacy of Coverage

Properties of pavement materials and geosynthetics can be easily accessed through a reasonable number of tests. However, the exhumation process is time-consuming and suitable for limited areas and sections.

Implementation Requirements

Costs are reasonable. For the exhumation, the backhoe is used to remove the pavement and some aggregate base. The remaining aggregates are removed with pick and shovel to within 25

QC/QA Procedures Example (continued)

GEOSYNTHETIC SEPARATION IN PAVEMENT SYSTEMS

QC/QA PROCEDURES

to 50 mm of the geotextile. The final layer is removed by hand. This makes the exhumation time-consuming.

General Comments

This QC/QA procedure is useful to control the performance of the pavement systems. It includes the measurements of the properties of geosynthetics after the construction of the pavements. In this procedure, the subgrade soil and base coarse conditions can be evaluated with the help of the field tests like pocket penetrometer, Torvane, and nuclear densiometer tests.

This procedure is very effective as soil and geotextile properties can be determined accurately and precisely. However, it is time consuming for exhumation and material property determination.

QC/QA Procedures Example (continued)

GEOSYNTHETIC SEPARATION IN PAVEMENT SYSTEMS

QC/QA PROCEDURES

Reference (s)

AASHTO. (2006). *Standard Specifications for Geotextiles - M 288.* Standard Specifications for Transportation Materials and Methods of Sampling and Testing, 26th Edition, American Association of State Transportation and Highway Officials, Washington, D.C.

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Specifications Example

GEOSYNTHETIC REINFORCED EMBANKMENTS

SPECIFICATIONS

Review of Existing Specifications

In total, three specifications have been collected and evaluated for geosynthetic reinforced embankments. One specification was from the Washington Department of Transportation and the other two guide specifications were from geosynthetic suppliers. All of the specifications are method specifications and are summarized in Table 1 on the following page. Because the reinforcement requirements for soft-ground embankment construction will be project-specific, the required geosynthetic properties must be updated for each project. The bidding, construction, and monitoring phases are fairly standard for this technology.

The preferred specification was developed by the Washington Department of Transportation and can be found in the *Geosynthetic Design & Construction Guidelines – Reference Manual* (FHWA NHI-07-092), as referenced below. The specification is included with this document. This specification is also presented in Technical Summary #11 from the FHWA *Ground Improvement Methods Reference Manual* – Volume 2 (FHWA NHI-06-020), which presents an excerpt from *Geosynthetic Design & Construction Guidelines*. The specification found in the FHWA manual from the Washington Department of Transportation was the only specification indentified developed by a state department of transportation.

Publication Title	Publication Year	Publication Number	Available for Download
Geosynthetic Design & Construction Guidelines – Reference Manual	2008	FHWA NHI-07-092	No[1]

[1] Materials can be obtained through www.nhi.fhwa.dot.gov

Specifications Example (continued)

GEOSYNTHETIC REINFORCED EMBANKMENTS

SPECIFICATIONS

Table 1. Specification identification table.

		Specification Name/Number				
		High Strength Geotextile for Embankment Reinforcement	Guideline Specification for Embankment on Soft Soils	Geosynthetic Reinforcement for Embankment over Soft Soils		
Specification type	Method approach	✓	✓	✓		
	Performance approach					
	Combined performance/ method approach					
	└Performance level					
References	Holtz et al. (2008)	✓				
	Polyfelt Americas (1994)		✓			
	Propex Geosynthetics (2006)			✓		

Performance level:
1 - Actual performance measured after construction (e.g., settlement at a specific time) and warranty provisions might be included
2 - Performance-related properties measured at end of construction (e.g., CPT, vane shear, etc.)
3 - Design properties measured during construction (e.g., modulus measured for each lift)
4 - Design-related properties measured during construction (e.g., density and water content measured for each lift)

Specifications Example (continued)

GEOSYNTHETIC REINFORCED EMBANKMENTS

SPECIFICATIONS

Summary of Example Specifications

Specification Name/Number:	**High Strength Geotextile For Embankment Reinforcement** (from Washington Department of Transportation, October 27, 1997)
Reference(s):	Holtz et al. (2006)

The specification found in the FHWA manual from the Washington Department of Transportation was the only specification indentified developed by a state department of transportation. The bidding, construction, and monitoring phases are fairly standard for this technology. Reinforcement requirements for soft-ground embankment construction will be project specific and the required geosynthetic properties must be updated for each project. The specification would need to be modified to allow the use of geogrid reinforcement, particularly seaming and placement procedures. One possible area requiring additional consideration would be if staged construction was to be utilized in conjunction with this technology. The preferred specification could also be extended to include performance measures to control and possibly accelerate construction rates, as recommended by Holtz et al. (2008), creating a combined method/performance specification.

Specification Name/Number:	**Guideline Specification for Embankment on Soft Soils**
Reference(s):	Polyfelt Americas (1994)

The specification presented in the Polyfelt manual is a generic guideline specification. The geotextile properties section refers to Polyfelt products, but the remainder of the specification is applicable to all geosynthetic reinforced embankment construction.

Specifications Example (continued)

GEOSYNTHETIC REINFORCED EMBANKMENTS

SPECIFICATIONS

Specification Name/Number:	**Geosynthetic Reinforcement for Embankment over Soft Soils, Section 31 34 19.18 [02377]**
Reference(s):	Propex Geosynthetics (2006)

The specification prepared by Propex Inc. is a generic guide specification. The accepted manufacturer section only lists Propex Inc. as acceptable, but a substitution section is also provided. The specification is applicable to all geosynthetic reinforced embankment construction.

References

Holtz, R.D., Christopher, B.R. and Berg, R.R. (2008). *Geosynthetic Design and Construction Guidelines*, U.S. Department of Transportation, Federal Highway Administration, National Highway Institute, Washington, D.C., FHWA-NHI-07-092.

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Propex Geosynthetics (2006). "Guide Specification - Geosynthetic reinforcement for embankment over soft soils." Propex Inc., Chattanooga, Tennessee, 37422, USA, Phone (800) 621-1273, obtained from Propex website, fixsoil.com, downloaded December 23, 2010.

Specifications Example (continued)

GEOSYNTHETIC REINFORCED EMBANKMENTS

SPECIFICATIONS

EXAMPLE SPECIFICATION

From Holtz et al. (2006)

High Strength Geotextile For Embankment Reinforcement

Description

This work shall consist of furnishing and placing construction geotextile in accordance with the details shown in the plans, these specifications, or as directed by the Engineer.

Materials

Geotextile and Thread for Sewing

The material shall be a woven geotextile consisting only of long chain polymeric filaments or yarns formed into a stable network such that the filaments or yarns retain their position relative to each other during handling, placement, and design service life. At least 95 percent by mass of the material shall be polyolefins or polyesters. The material shall be free from defects or tears. The geotextile shall be free of any treatment or coating which might adversely alter its hydraulic or physical properties after installation. The geotextile shall conform to the properties as indicated in Table 1.

Thread used shall be high strength polypropylene, polyester, or Kevlar thread. Nylon threads will not be allowed.

Geotextile Approval

Source Approval

The Contractor shall submit to the Engineer the following information regarding each geotextile proposed for use:

Manufacturer's name and current address,
Full Product name,
Geotextile structure, including fiber/yarn type, and
Geotextile polymer type(s).

If the geotextile source has not been previously evaluated, a sample of each proposed geotextile shall be submitted to the Olympia Service Center Materials Laboratory in Tumwater for evaluation. After the sample and required information for each geotextile type have arrived at the Olympia Service Center Materials Laboratory in Tumwater, a maximum of 14 calendar days will be required for this testing. Source approval will be based on conformance to the applicable values from Table 1. Source approval shall not be the basis of acceptance of specific lots of material unless the lot sampled can be clearly identified, and the number of samples tested and approved meet the requirements of WSDOT Test Method 914.

Specifications Example (continued)

GEOSYNTHETIC REINFORCED EMBANKMENTS

SPECIFICATIONS

Geotextile Properties

Table 1. Properties for high strength geotextile for embankment reinforcement.

Property	Test Method[1]	Geotextile Property Requirements[2]
AOS	ASTM D4751	0.84 mm max. (#20 sieve)
Water Permittivity	ASTM D4491	0.02/sec. min.
Tensile Strength, min. in machine direction	ASTM D4595	(to be based on project specific design)
Tensile Strength, min. in x-machine direction	ASTM D4595	(to be based on project specific design)
Secant Modulus at 5% strain	ASTM D4595	(to be based on project specific design)
Seam Breaking Strength	ASTM D4884	(to be based on project specific design)
Puncture Resistance	ASTM D4833	330 N min.
Tear Strength, min. in machine and x-machine direction	ASTM D4533	330 N min.
Ultraviolet (UV) Radiation Stability	ASTM D4355	50% Strength Retained min., after 500 Hrs in weatherometer

[1] The test procedures are essentially in conformance with the most recently approved ASTM geotextile test procedures, except geotextile sampling and specimen conditioning, which are in accordance with WSDOT Test Methods 914 an 915, respectively. Copies of these test methods are available at the Olympia Service Center Materials Laboratory in Tumwater, Washington.

[2] All geotextile properties listed above are minimum average roll values (i.e., the test result for any sampled roll in a lot shall meet or exceed the values listed).

Geotextile Samples for Source Approval

Each sample shall have minimum dimensions of 1.5 meters by the full roll width of the geotextile. A minimum of 6 square meters of geotextile shall be submitted to the Engineer for testing. The geotextile machine direction shall be marked clearly on each sample submitted for testing. The machine direction is defined as the direction perpendicular to the axis of the geotextile roll.

The geotextile samples shall be cut from the geotextile roll with scissors, sharp knife, or other suitable method which produces a smooth geotextile edge and does not cause geotextile ripping or tearing. The samples shall not be taken from the outer wrap of the geotextile nor the inner wrap of the core.

Specifications Example (continued)

GEOSYNTHETIC REINFORCED EMBANKMENTS

SPECIFICATIONS

Acceptance Samples
Samples will be randomly taken by the Engineer at the job site to confirm that the geotextile meets the property values specified.

Approval will be based on testing of samples from each lot. A "lot" shall be defined for the purposes of this specification as all geotextile rolls within the consignment (i.e., all rolls sent to the project site) which were produced by the same manufacturer during a continuous period of production at the same manufacturing plant and have the same product name. After the samples and manufacturer's certificate of compliance have arrived at the Olympia Service Center Materials Laboratory in Tumwater, a maximum of 14 calendar days will be required for this testing. If the results of the testing show that a geotextile lot, as defined, does not meet the properties required in Table 1, the roll or rolls which were sampled will be rejected. Two additional rolls for each roll tested which failed from the lot previously tested will then be selected at random by the Engineer for sampling and retesting. If the retesting shows that any of the additional rolls tested do not meet the required properties, the entire lot will be rejected. If the test results from all the rolls retested meet the required properties, the entire lot minus the roll(s) which failed will be accepted. All geotextile which has defects, deterioration, or damage, as determined by the Engineer, will also be rejected. All rejected geotextile shall be replaced at no expense to the Contracting Agency.

Certificate of Compliance
The Contractor shall provide a manufacturer's certificate of compliance to the Engineer which includes the following information about each geotextile roll to be used:

Manufacturer's name and current address,
Full product name,
Geotextile structure, including fiber/yarn type,
Geotextile polymer type(s),
Geotextile roll number, and
Certified test results.

Approval Of Seams
If the geotextile seams are to be sewn in the field, the Contractor shall provide a section of sewn seam which can be sampled by the Engineer before the geotextile is installed.

The seam sewn for sampling shall be sewn using the same equipment and procedures as will be used to sew the production seams. The seam sewn for sampling must be at least 2 meters in length. If the seams are sewn in the factory, the Engineer will obtain samples of the factory seam at random from any of the rolls to be used. The seam assembly description shall be submitted by the Contractor to the Engineer and will be included with the sample obtained for testing. This description shall include the seam type, stitch type, sewing thread type(s), and stitch density.

Specifications Example (continued)

GEOSYNTHETIC REINFORCED EMBANKMENTS

SPECIFICATIONS

Construction Requirements

Geotextile Roll Identification, Storage, and Handling

Geotextile roll identification, storage, and handling shall be in conformance to ASTM D 4873. During periods of shipment and storage, the geotextile shall be stored off the ground. The geotextile shall be covered at all times during shipment and storage such that it is fully protected from ultraviolet radiation including sunlight, site construction damage, precipitation, chemicals that are strong and acids or strong bases, flames including welding sparks, temperatures in excess of 70^{o} C, and any other environmental condition that may damage the physical property values of the geotextile.

Preparation and Placement of the Geotextile Reinforcement

The area to be covered by the geotextile shall be graded to a smooth, uniform condition free from ruts, potholes, and protruding objects such as rocks or sticks. The Contractor may construct a working platform, up to 0.6 meters in thickness, in lieu of grading the existing ground surface. A working platform is required where stumps or other protruding objects which cannot be removed without excessively disturbing the subgrade are present. All stumps shall be cut flush with the ground surface and covered with at least 150 mm of fill before placement of the first geotextile layer. The geotextile shall be spread immediately ahead of the covering operation. The geotextile shall be laid with the machine direction perpendicular or parallel to centerline as shown in Plans. Perpendicular and parallel directions shall alternate. All seams shall be sewn. Seams to connect the geotextile strips end to end will not be allowed, as shown in the Plans. The geotextile shall not be left exposed to sunlight during installation for a total of more than 14 calendar days. The geotextile shall be laid smooth without excessive wrinkles. Under no circumstances shall the geotextile be dragged through mud or over sharp objects which could damage the geotextile. The cover material shall be placed on the geotextile in such a manner that a minimum of 200 mm of material will be between the equipment tires or tracks and the geotextile at all times. Construction vehicles shall be limited in size and weight such that rutting in the initial lift above the geotextile is not greater than 75 mm deep, to prevent overstressing the geotextile. Turning of vehicles on the first lift above the geotextile will not be permitted. Compaction of the first lift above the geotextile shall be limited to routing of placement and spreading equipment only. No vibratory compaction will be allowed on the first lift.

Small soil piles or the manufacturer's recommended method shall be used as needed to hold the geotextile in place until the specified cover material is placed.

Should the geotextile be torn or punctured or the sewn joints disturbed, as evidenced by visible geotextile damage, subgrade pumping, intrusion, or roadbed distortion, the backfill around the damaged or displaced area shall be removed and the damaged area repaired or replaced by the Contractor at no expense to the Contracting Agency. The repair shall consist of a patch of the same type of geotextile placed over the damaged area. The patch shall be sewn at all edges.

If geotextile seams are to be sewn in the field or at the factory, the seams shall consist of two parallel rows of stitching, or shall consist of a J-seam, Type Ssn-1, using a single row of

Specifications Example (continued)

GEOSYNTHETIC REINFORCED EMBANKMENTS

SPECIFICATIONS

stitching. The two rows of stitching shall be 25 mm apart with a tolerance of plus or minus 13 mm and shall not cross, except for restitching. The stitching shall be a lock-type stitch. The minimum seam allowance, i.e., the minimum distance from the geotextile edge to the stitch line nearest to that edge, shall be 40 mm if a flat or prayer seam, Type SSa-2, is used. The minimum seam allowance for all other seam types shall be 25 mm. The seam, stitch type, and the equipment used to perform the stitching shall be as recommended by the manufacturer of the geotextile and as approved by the Engineer.

The seams shall be sewn in such a manner that the seam can be inspected readily by the Engineer or his representative. The seam strength will be tested and shall meet the requirements stated in this Specification.

Embankment construction shall be kept symmetrical at all times to prevent localized bearing capacity failures beneath the embankment or lateral tipping or sliding of the embankment. Any fill placed directly on the geotextile shall be spread immediately. Stockpiling of fill on the geotextile will not be allowed.

The embankment shall be compacted using Method B of Section 2-03.3(14)C. Vibratory or sheepsfoot rollers shall not be used to compact the fill until at least 0.5 meters of fill is covering the bottom geotextile layer and until at least 0.3 meters of fill is covering each subsequent geotextile layer above the bottom layer.

The geotextile shall be pretensioned during installation using either Method 1 or Method 2 as described herein. The method selected will depend on whether or not a mudwave forms during placement of the first one or two lifts. If a mudwave forms as fill is pushed onto the first layer of geotextile, Method 1 shall be used. Method 1 shall continue to be used until the mudwave ceases to form as fill is placed and spread. Once mudwave formation ceases, Method 2 shall be used until the uppermost geotextile layer is covered with a minimum of 0.3 meters of fill. These special construction methods are not needed for fill construction above this level. If a mudwave does not form as fill is pushed onto the first layer of geotextile, then Method 2 shall be used initially and until the uppermost geotextile layer is covered with at least 0.3 meters of fill.

Method 1

After the working platform, if needed, has been constructed, the first layer of geotextile shall be laid in continuous transverse strips and the joints sewn together. The geotextile shall be stretched manually to ensure that no wrinkles are present in the geotextile. The fill shall be end-dumped and spread from the edge of the geotextile. The fill shall first be placed along the outside edges of the geotextile to form access roads. These access roads will serve three purposes: to lock the edges of the geotextile in place, to contain the mudwave, and to provide access as needed to place fill in the center of the embankment. These access roads shall be approximately 5 meters wide. The access roads at the edges of the geotextile shall have a minimum height of 0.6 meters when completed. Once the access roads are approximately 15 meters in length, fill shall be kept ahead of the filling operation, and the access roads shall be kept approximately 15 meters ahead of this filling

Specifications Example (continued)

GEOSYNTHETIC REINFORCED EMBANKMENTS

SPECIFICATIONS

operation as shown in the Plans. Keeping the mudwave ahead of this filling operation and keeping the edges of the geotextile from moving by use of the access roads will effectively pre-tension the geotextile. The geotextile shall be laid out no more than 6 meters ahead of the end of the access roads at any time to prevent overstressing of the geotextile seams.

Method 2
After the working platform, if needed, has been constructed, the first layer of geotextile shall be laid and sewn as in Method 1. The first lift of material shall be spread from the edge of the geotextile, keeping the center of the advancing fill lift ahead of the outside edges of the lift as shown in the Plans. The geotextile shall be manually pulled taut prior to fill placement. Embankment construction shall continue in this manner for subsequent lifts until the uppermost geotextile layer is completely covered with 0.3 meters of compacted fill.

Measurement
High strength geotextile for embankment reinforcement will be measured by the square meter for the ground surface area actually covered.

Payment
The unit contract price per square meter for "High Strength Geotextile For Embankment Reinforcement", shall be full pay to complete the work as specified.

Cost Information Example

COLUMN SUPPORTED EMBANKMENTS (Load Transfer Platform (LTP))

COST INFORMATION

Commentary

Because the scope of this technology is limited to the load transfer platform, cost information on column supported embankments is identical to geosynthetic reinforced embankments. Information regarding columns that may be used in conjunction with a column supported embankment is provided separately under the following technologies:

- Continuous flight auger piles
- Deep mixing methods
- Geosynthetic encased columns
- Micropiles
- Aggregate columns
- Vibro-concrete columns

Cost Information Summary

Production rates for the installation of geosynthetic reinforced load transfer platforms are highly sensitive to the delivery rate of granular material. Equipment and labor resources are easily adjusted to match the delivery rate of granular material. Information is provided on two categories of geosynthetics: first, those that are used for the load transfer platform, and second, geosynthetics that are used solely to provide a working platform for a subsequent ground improvement technology. The following table lists construction cost items associated with geosynthetic reinforced load transfer platforms used in column supported embankments, along with approximate cost ranges. Cost ranges are based on data from 2005 through 2010. Readers should carefully examine the project characteristics and constraints and determine to what degree if any these factors may influence the actual cost associated with constructing geosynthetic reinforced embankments.

Cost Information Example (continued)

COLUMN SUPPORTED EMBANKMENTS (Load Transfer Platform (LTP))

COST INFORMATION

Pay Item Description	Quantity Range	Unit	Low Unit Price	High Unit Price	Factors Which May Potentially Impact Costs
Geosynthetics Used for Load Transfer Platform	Greater Than 5,000	SY	$2.50	$12.00	Geogrids are more expensive than fabrics Woven fabrics are more expensive than nonwoven fabrics Heavier fabrics cost more Smaller dimension grids and heavier grids cost more Specified lap widths impact the total quantity of material required Production rates are generally limited by the delivery rate of granular material
Geosynthetics Used for Working Platforms	Greater Than 5,000	SY	$1.00	$3.50	Same as above
Granular Fill Material	Greater Than 2,500	TON	$7.00	$20.00	Material specifications and haul distance will impact unit costs Haul route conditions will impact unit costs

Historical Cost Information

A sample of actual project costs for geosynthetics used as reinforcement is shown in the table below.

Pay Item Description	Quantity	Unit	Low Unit Price	High Unit Price	Average Unit Price	No. of Bids	Bid Date	Source/Agency
Geosynthetic Reinf. Found. Over Soft Soils	4,835	SY	$3.13	n/a	n/a	1	3/4/2009	Florida DOT
Miscellaneous Geogrid Reinforcement, Type I	8,375	SY	$2.70	$5.60	$4.19	7	4/23/2009	Oregon DOT

Cost Information Example (continued)

COLUMN SUPPORTED EMBANKMENTS (Load Transfer Platform (LTP))

COST INFORMATION

A sample of actual project costs for geosynthetics used in working platforms is shown in the table below.

Pay Item Description	Quantity	Unit	Low Unit Price	High Unit Price	Average Unit Price	No. of Bids	Bid Date	Source/ Agency
Reinforcement Grid (Biaxial, Type 2)	90,023	SY	$2.53	n/a	n/a	1	7/29/2009	Florida DOT
Geogrid Base Reinforcement	72,000	SY	$1.00	$2.40	$1.79	10	6/5/2009	Arizona DOT
	28,100	SY	$1.75	$3.25	$2.21	9	6/12/2009	
	5,735	SY	$1.60	$3.50	$2.22	6	9/25/2009	
Stabilization Geotextile, Special	12,320	SY	$146	$4.80	$2.55	12	3/5/2010	Michigan DOT
	3,210	SY	$2.45	$3.25	$2.65	4	10/1/2010	
Geotextile Stabilization	32,367	SY	$0.84	$1.46	$1.15	6	3/25/2010	New York DOT
	5,200	SY	$1.09	$2.51	$1.58	8	5/20/2010	
	13,459	SY	$1.05	$2.51	$1.46	7	6/10/2010	
Special – Geogrid, Type P2 (WT:06)	6,300	SY	$3.36	$3.52	$3.44	2	7/15/2010	Ohio DOT

Conceptual Cost Estimating Tool

Click here to open a cost estimating spreadsheet for producing a preliminary project scoping estimate.

Cost Information Example (continued)

Conceptual Estimating Tool - Column Supported Embankment

Notes to User:

A. This estimating tool is provided as a means to perform an initial project scoping estimate. Use for any other purpose is strongly discouraged. The accuracy and reliability of the estimated costs are highly dependent upon the user inputs, care should be taken to adjust inputs for specific project characteristics. The user assumes all risks associated with the cost estimates produced by this estimating tool.

B. Guidance on unit cost ranges and potential impacts on cost is provided in the cost information summary for each technology. Users are responsible for determining appropriate unit costs.

C. Cells highlighted in "burnt orange" require user input.

D. Cells with "maroon" colored text are automatically calculated, but may be manually overridden by the user.

1. Calculate the Surface Area Where Columns are to be Installed

Length (ft):	1,000
Width (ft):	90
Area (ft^2):	90,000

2. Estimate the Total Quantity of Columns to be Installed

Design output information required - Preliminary grid spacing and average depth of installation are necessary for this step

Estimated Longitudinal Grid Spacing (ft):	8.00
Estimated Transverse Grid Spacing (ft):	8.00
Number of Columns to be Installed:	1,544
Average Depth of Column Installation (ft):	50
Total Quantity of Columns (lf):	77,175

3. If Needed, Estimate the Materials Required for an Initial Working Platform

Length (ft):	1,000
Width (ft):	90
Quantity of Geosynthetic for a Working Platform (yd^2):	10,000
Optional, Thickness of Granular Layer for Working Platform (in):	12
Optional, Estimated Density of Granular Material for Working Platform (lb/ft^3):	120
Total Quantity of Granular Material for Working Platform (ton):	5,400

4. Calculate the Surface Area of Geosynthetic Reinforced Load Transfer Platform

Length (ft):	1,000
Width (ft):	90
Number of Layers of Geosynthetic Reinforcement:	3
Quantity of Geosynthetic Reinforcement (yd^2):	30,000

5. Estimate the Quantity of Granular Material for the Load Transfer Platform

Thickness of Granular Layer (in):	36
Estimated Density of Granular Material (lb/ft^3):	120
Total Quantity of Granular Material (ton):	16,200

6. Estimated Cost of Column Supported Embankment - Refer to Cost Information Summary for Typical Unit Cost Ranges and Impacts on Unit Prices

	Unit Cost	Quantity	Cost
Optional, Geosynthetic for Working Platform (yd^2):	$ 2.75	10,000	$ 27,500
Optional, Granular Material for Working Platform (ton):	$ 7.50	5,400	$ 40,500
Input Column Type and (unit of measure):	$ 30.00	77,175	$ 2,315,250
Mobilization (lump sum):	$ 20,000.00	1	$ 20,000
Geosynthetic Reinforcement (yd^2):	$ 2.75	30,000	$ 82,500
Granular Material (ton):	$ 10.00	16,200	$ 162,000
Credit Embankment for Volume of the Load Transfer Platform ($/$yd^3$):	$ 4.00	(10,000)	$ (40,000)
Estimated Total Cost of Column Supported Embankment:			**$ 2,607,750**
Estimated Unit Cost of Column Supported Embankment for Area Treated ($/$ft^2$):			**$ 28.98**

R02 GEOTECHNICAL SOLUTIONS FOR SOIL IMPROVEMENT, RAPID EMBANKMENT CONSTRUCTION, AND STABILIZATION OF PAVEMENT WORKING PLATFORM

Page 1 of 1

Bibliography Example

HIGH ENERGY IMPACT ROLLERS

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Bibliography Example (continued)

HIGH ENERGY IMPACT ROLLERS

REFERENCE MATRIX

KEY:
✓ = item addressed in reference

	TECHNOLOGY OVERVIEW	SITE CHARACTERIZATION	ANALYSIS TECHNIQUES	DESIGN PROCEDURE	DESIGN CODES	CONSTRUCTION METHODS	CONSTRUCTION TIME	EQUIPMENT/CONTRACTORS	CONSTRUCTION LOADS	CONTRACTING	CONSTRUCTION SPECS	QA/QC	PERFORMANCE CRITERIA	MONITORING	GEOTECHNICAL LIMITATIONS	NON-GEOTECH LIMITATIONS	CASE HISTORY	ENVIRONMENTAL IMPACTS	INITIAL COST	LIFE CYCLE COSTS	DURABILITY	RELIABILITY	MATERIAL PROPERTIES
Auzins and Southcott (1999)	✓										✓	✓		✓	✓								
Avalle (2004a)	✓	✓						✓				✓		✓			✓	✓					
Avalle (2004b)	✓	✓						✓				✓		✓			✓						✓
Avalle (2004c)								✓				✓				✓							✓
Avalle (2004d)								✓			✓	✓	✓	✓									
Avalle (2006)	✓	✓						✓															
Avalle (2007a)	✓	✓						✓			✓	✓		✓			✓						✓
Avalle (2007b)	✓	✓										✓			✓								
Avalle and Carter (2005)		✓				✓		✓			✓	✓		✓			✓						
Avalle and Grounds (2004)	✓	✓						✓				✓		✓			✓	✓					
Avalle and McKenzie (2005)	✓	✓						✓				✓		✓			✓						
Avalle and Young (2004)		✓						✓				✓		✓			✓						
Avsar et al. (2006)																							
Bouazza and Avalle (2006a,b)	✓	✓						✓				✓		✓			✓						
Broons (2009)	✓							✓															

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R02 GEOTECHNICAL SOLUTIONS FOR SOIL IMPROVEMENT,
RAPID EMBANKMENT CONSTRUCTION,
AND STABILIZATION OF PAVEMENT WORKING PLATFORM

SHRP2
STRATEGIC HIGHWAY RESEARCH PROGRAM

Bibliography Example (continued)

HIGH ENERGY IMPACT ROLLERS

REFERENCE MATRIX (CONTINUED)

KEY:
✓ = item addressed in reference

	TECHNOLOGY OVERVIEW	SITE CHARACTERIZATION	ANALYSIS TECHNIQUES	DESIGN PROCEDURE	DESIGN CODES	CONSTRUCTION METHODS	CONSTRUCTION TIME	EQUIPMENT/CONTRACTORS	CONSTRUCTION LOADS	CONTRACTING	CONSTRUCTION SPECS	QA/QC	PERFORMANCE CRITERIA	MONITORING	GEOTECHNICAL LIMITATIONS	NON-GEOTECH LIMITATIONS	CASE HISTORY	ENVIRONMENTAL IMPACTS	INITIAL COST	LIFE CYCLE COSTS	DURABILITY	RELIABILITY	MATERIAL PROPERTIES
Burgess and Joubert (1995)	✓					✓						✓	✓										✓
Clegg and Berrangé (1971)	✓	✓				✓	✓					✓		✓	✓		✓						
Clifford (1976)																							
CSIRO (2000)	✓													✓									
Davies et al. (2004)		✓				✓						✓		✓			✓						
Hillman et al. (2007)		✓										✓		✓			✓						
Jumo and Geldenhuys (2004)	✓	✓	✓			✓		✓				✓		✓			✓						
Kelly (2000)	✓	✓		✓								✓		✓			✓						
Landpac (2008a)	✓							✓				✓		✓									
Landpac (2008b)								✓			✓												
Landpac (2008c)								✓															
Pinrad (1999, 2001)	✓			✓		✓		✓			✓	✓											
Scott and Suto (2007)		✓										✓	✓				✓						
Utah DOT (2010)						✓					✓	✓											

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R02 GEOTECHNICAL SOLUTIONS FOR SOIL IMPROVEMENT,
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AND STABILIZATION OF PAVEMENT WORKING PLATFORM

SHRP2
STRATEGIC HIGHWAY RESEARCH PROGRAM

Related SHRP 2 Research

- Innovative Bridge Designs for Rapid Renewal (R04)
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