Development of the Geoconstruction Information and Technology Selection Guidance System

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The Second
STRATEGIC HIGHWAY RESEARCH PROGRAM

SHRP 2 REPORT S2-R02-RW-2

Development of the Geoconstruction Information and Technology Selection Guidance System

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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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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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FOREWORD

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

This report describes the development details of the web-based information and guidance system produced as part of SHRP 2 Project R02, Geotechnical Solutions for Soil Improvement, Rapid Embankment Construction, and Stabilization of the Pavement Working Platform. Project background, literature review, development, programming, and testing of the system are detailed in this report. Recommendations for future enhancements of this website are also presented.

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. This project encompasses a broad spectrum of materials, processes, and technologies that are applicable to new embankment and roadway construction over unstable ground, roadway and embankment widening, and stabilization of pavement working platforms.

CONTENTS

CHAPTER 1

Introduction

This report describes the web-based information and guidance system developed as part 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. Project background, literature review, development, programming, and testing of the web-based information and guidance system are detailed in this report. Recommendations for future enhancements of this website are also presented.

The web-based information and guidance system presented herein is intended to overcome many of the technical and nontechnical obstacles encountered by engineers and other transportation personnel that prevent broader and effective use of geotechnical solutions on transportation infrastructure projects. Geotechnical solutions are geoconstruction technologies or ground improvement systems that alter poor soil/ground conditions to meet project requirements. Project R02 includes both embankments and pavement foundations. The term *geoconstruction technologies* describes all the technologies included in the R02 project. Even though many technologies included in the project are traditionally considered to be ground improvement technologies, some of these technologies are not typically grouped with ground improvement.

SHRP 2 R02 Project Background

Although in existence for several decades, many geoconstruction technologies face both technical and nontechnical obstacles preventing broader use in transportation infrastructure projects. The research team for SHRP 2 R02, Geotechnical Solutions for Soil Improvement, Rapid Embankment Construction, and Stabilization of the Pavement Working Platform, has investigated the state of practices of transportation project engineering, geotechnical engineering, and earthwork construction to identify and assess methods to advance the use of geoconstruction technologies. Such technologies are often underused in current practice, and they offer significant potential to achieve one or more of the SHRP 2 Renewal objectives of rapid renewal of transportation facilities, minimal disruption of traffic, and production of long-lived facilities. The R02 project encompasses a broad spectrum of materials, processes, and technologies within geotechnical engineering and geoconstruction that are applicable to one or more of the following three "elements" of construction (as defined in the R02 project scope): new embankment and roadway construction over unstable soils, roadway and embankment widening, and stabilization of pavement working platforms.

The overall vision established for the project is "to make geotechnical solutions more accessible to public agencies in the United States for rapid renewal and improvement of the transportation infrastructure." Phase 1 of the R02 project (completed in August 2008) consisted of six tasks focused on identifying those geotechnical materials, systems, and technologies that best achieve the SHRP 2 Renewal strategic objectives for the three elements. Explicit in the tasks was the identification and evaluation of technical issues; project development/delivery methods; performance criteria and quality control/quality assurance (QC/QA) procedures; and nontechnical issues that significantly constrain use of geotechnical materials, systems, and technologies. Through identification of obstacles, both technical and nontechnical, that constrain usage of geoconstruction methods, and mitigation strategies to overcome the obstacles, the research team developed an approach to identify existing and innovative technologies to enhance geotechnical solutions for transportation infrastructure.

Phase 2 focused on 46 geotechnical materials, systems, and technologies (hereafter referred to as geoconstruction technologies) that best achieve the SHRP 2 Renewal strategic objectives. These identified technologies are listed below:

- 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 selection of technologies to develop this list is primarily an outcome of the Phase 1 work of SHRP 2 R02. However, the list of technologies included in Phase 2 was slightly modified as the result of extensive discussions between the research team and the advisory board and initial Phase 2 work.

Forty technologies identified in the Phase 1 work were carried into the initial Phase 2 work. Two technologies, stone columns and rammed aggregate piers, were combined under the technology named aggregate columns. Biotreatment of subgrade stabilization was re-added (after Phase 1 deletion) to the list of technologies in Phase 2. Traditional compaction, a baseline technology that other technologies are compared to, was added in Phase 2. The geosynthetics in pavements technology from Phase 1 was subdivided into six separate technologies in the Phase 2 work. Shoot-in and screw-in soil nails were subdivided into two technologies in Phase 2. Fiber reinforcement of slopes was dropped in the Phase 2 work. Thus, a total of 46 technologies have been addressed in the Phase 2 work.

Phase 2 included the development of a catalog of materials, processes, and systems for rapid renewal geoconstruction projects; evaluation and listing of design guidance, QC/QA procedures, methods for estimating costs, and sample specifications; and development of an information and guidance system. A catalog was created to detail the requirements for guidance on design, QC/QA, costs, and specifications into an integrated catalog and an interactive selection assistance system. The catalog also contains information necessary for initial project applicability screening of each technology (i.e., depth limits, applicability to different soil types, acceptable groundwater conditions, applicability to different project types, ability to deal with project-specific constraints, and general advantages and disadvantages). The information and guidance system, the web-based system described in this report, provides immediate access to the information contained in the catalog. This web-based system is the umbrella project product; it contains all the primary products and tools developed by the R02 project team.

Project Statement

Transportation engineers, geologists, planners, and officials lack a readily available means to access critical information for geoconstruction technologies and lack a tool to assist in deciding which technologies are potentially applicable to their project. The R02 products and tools are organized and presented on a website in lieu of printed reports because of the advantages a web-based system provides to users. These advantages will significantly improve achievement of SHRP 2 Renewal objectives throughout the United States. Primary advantages of the web-based system are the following:

- It is a living system—that is, updatable and expandable.
- It is readily available.
- It provides a forum for technology usage exchange between state transportation authorities.

The goals of the web-based information and guidance system are:

- Provide an information system that contains the technology catalog, selection system, and a glossary.
- Provide a selection system as part of the information system to develop a short list of applicable technologies based on a few project and site characteristics.
- Provide an interactive, fully functional, and populated program to house the information system and guide the user through the selection system.
- Provide a glossary of the abbreviations and terms used throughout the information and selection system.

Report Organization

Many details included in this report are specific to the development and testing of the web-based information system. Such details are typically omitted from software development reports. The intent of this report is to tell the story of the development of the web-based information and guidance system. A key attribute of a good process is one that can be "read, understood, questioned, communicated, modified, and most important, improved" (Rakitin, 1997). This report provides the information that will support future revisions of the web-based system (i.e., maintain it as a living system).

In documenting the details of this development effort, overlap between several sections of certain chapters and other sections in other chapters could not be avoided. Cross-referencing is provided, as appropriate.

Anticipated Outcomes of Project

The primary value of the web-based information and guidance system is that it collects, synthesizes, integrates, and organizes a vast amount of critically important information about geotechnical solutions in a system that makes the information readily accessible to state transportation agency (STA) personnel who need it most. The web-based information and guidance system will be a valuable tool for engineers, planners, and transportation officials when evaluating potential geoconstruction technologies. No system like this exists, either in hard form or through a programmed system.

Providing critical path guidance for emerging technologies will decrease the time required for promising solutions to be used for infrastructure projects. Experienced engineers will benefit from the design, construction, and cost information provided in the catalog. Less-experienced engineers, planners, and others will benefit from the technology selection assistance portion of the system to assess the feasibility of technologies to address project requirements and constraints. STA managers and other personnel unfamiliar with geoconstruction technologies can be directed to this site for introductory summary fact sheets and illustrative photographs.

A significant benefit of the rule-based approach to the information and guidance system is the sharing of knowledge, especially when the knowledge is not the type of knowledge typically published in scholarly publications (Spring et al., 1991). The knowledge in the system addresses the practical aspects of planning, design, construction, and cost, which benefits engineers and officials at all levels of experience. This knowledge is systematically and consistently addressed for each of the 46 technologies.

Study Limitations

Understanding the limitations of the information and guidance system are critical to proper implementation and use in practice. System limitations are detailed in detail in Chapter 6. Some of the limitations of the information and guidance system include the number of technologies considered in the system, the difficulty in measuring the results of the selection system against the opinion of an experienced geotechnical engineer, and the difficulty of anticipating possible project-specific scenarios.

Although a large number of technologies are included, they were limited to fit the SHRP 2–defined scope of the R02 project. This information and guidance system provides tools for engineering of geotechnical solutions. It does not "engineer" solutions, because that must be performed on a project-specific basis.

CHAPTER 2

Background

A literature review was completed to identify similar reports and systems previously developed for geoconstruction technologies. Two broad concepts are discussed herein. First, literature that focuses on previously programmed systems for geoconstruction technologies is presented. Second, literature describing the geotechnical design process and the implementation of a geoconstruction technology is reviewed.

The literature search revealed the commitment of the national research sponsor, the Transportation Research Board (TRB), to compiling and disseminating information regarding problem foundations for highway embankments. In 1966, *Highway Research Record 133* contained five reports on the use of sites with soft foundations. From this record, Moore (1966) summarized the New York State Department of Public Works procedures for dealing with foundation problems. In 1975, *National Cooperative Highway Research Program (NCHRP) Synthesis of Highway Practice 29: Treatment of Soft Foundations for Highway Embankments* provided the first comprehensive review of the design process philosophy, treatment methods, special considerations, subsurface investigation and testing, and foundation treatment design (Johnson, 1975). In 1989, *NCHRP Synthesis of Highway Practice 147: Treatment of Problem Foundations for Highway Embankments* expanded the 1975 *Synthesis* to include more treatment methods and also included a section on construction and performance monitoring (Holtz, 1989).

Previously Programmed Systems

Automated systems for various aspects of geotechnical engineering were found during the study. Toll (1996b) reviewed systems that have been developed for geotechnical applications. By 1996, more than 103 knowledge-based applications had been developed in the field of geotechnical engineering (Toll, 1996a). Previous systems included expert systems, decision support systems, knowledge-based systems, and neural network approaches. Toll (1996b) summarizes the Geotechnical areas where knowledge-based systems have been developed as follows:

- Site characterization
  - Site investigation planning,
  - Interpreting ground conditions,
  - Soil classification and parameter assessment, and
  - Rock classification and parameter assessment.
- Foundations
  - Conceptual design of foundations,
  - Detailed design,
  - Pile driving,
  - Foundation construction, and
  - Foundation problems.
- Slopes
  - Soil slopes and
  - Rock slopes.
- Earth retaining structures.
- Tunnels and underground openings.
- Mining.
- Liquefaction.
- Ground improvement.
- Geotextiles.
- Groundwater and dams.
- Roads and earthworks.

Rule-based systems dominated the earlier systems, with more complex systems being developed more recently. The previously programmed systems described in this section are presented chronologically.

Improve

Chameau and Santamarina (1989) presented the knowledge-based system, Improve, for the selection of soil improvement methods. This system approaches the process of selection as being similar to a classification problem (e.g., analogous to soil classification and mineral identification). The system uses a knowledge representation structure based on "windows" together with a best-first search algorithm. A window refers to a possibility number that characterizes an object with respect to the variable of interest and is a fuzzy set. The search algorithm includes a preprocessor, classification system, case-based system, and postprocessor. The preprocessor collects the required input to form a stack of windows and then compares the input stack to the windows stack with each technology. An acceptability value is determined from this comparison to identify the most suitable technologies. More than 40 technologies, listed below, were considered in the system (Chameau and Santamarina, 1989):

- Densification blasting
- Blasting and vibratory rollers
- Vibratory probe
- Vibratory probe and vibratory rollers
- Vibro compaction
- Vibro compaction and vibratory rollers
- Compaction piles
- Heavy tamping
- Heavy tamping and vibratory rollers
- Vibratory rollers
- Preloading
- Preloading and drains
- Surcharge fills
- Surcharge fills and drains
- Dynamic consolidation
- Electroosmosis
- Drains
- Particulate grouting
- Chemical grouting
- Pressure injected lime
- Displacement grout
- Electrokinetic injection
- Jet grouting
- Remove and replace
- Admixture stabilization
- Displacement blasting
- Prewetting loess
- Prewetting swelling clay
- Structural fill
- Lightweight fill
- Mix-in-place piles
- Mix-in-place walls
- Heating
- Freezing
- Stone columns
- Root piles
- Soil nailing
- Strip reinforcement
- Moisture barriers
- Geotextiles
- Berms

The project-specific information used to sort the geoconstruction technologies is as follows:

- Type of project
- Environmental freedom
- Time available
- Importance of increasing strength
- Importance of reducing deformation
- Importance of modifying permeability
- Position (depth) of layer
- Distance to the neighbor/layer depth
- Structure width/layer depth
- Special soil type
- Particle size
- Relative density
- Saturation conditions
- Stratum (covered or uncovered)
- Stage (built or not built)
- Is surface above water?
- Is surface treatment possible?
- Is layered construction possible?
- Duration of improvement (permanent or temporary)
- Equipment particular to each alternative
- Materials required by each method

The knowledge in the system was acquired from Robert Holtz. Holtz also provided performance feedback that resulted in a systematic consideration of technical limitations of the possible methods. Additionally, common practice does pose some constraints on the applicability of a method (Chameau and Santamarina, 1989).

Chameau and Santamarina (1989) also noted that a geotechnical expert's comprehension of a problem is affected by a large number of factors, including factors that are case-specific, context-dependent, and subjective. Geotechnical experts make decisions based on the recollection of previous cases, which is relevant in geotechnical engineering where an emphasis is placed on experience. Systems such as Improve can help bring the state of the art to practice and train professionals, recognize gaps in knowledge, and transfer the knowledge and accumulated experience of a few to a large number of practitioners. Soil improvement can be readily distilled into a decision support system because it is a well-defined domain, the selection of methods is well documented by the job characteristics and the required soil improvement, documented cases exist, and qualitative variables enter the decision process (Chameau and Santamarina, 1989).

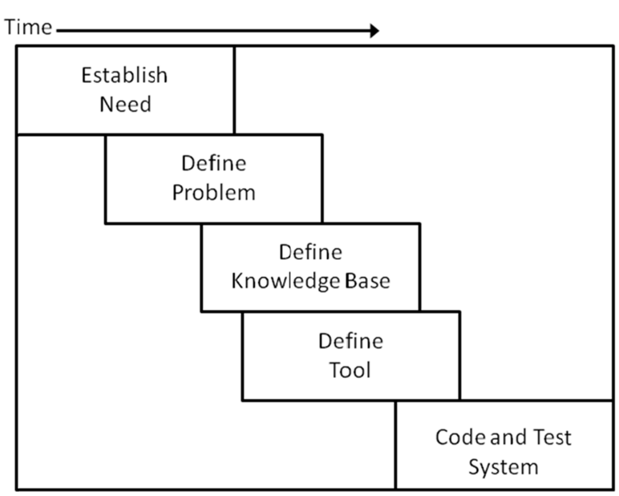
Expert System for Preliminary Ground Improvement Selection

Motamed et al. (1991) developed an expert system for preliminary ground improvement selection (ESPGIS), which is based on a knowledge-based expert system (KBES). The system is menu-driven and can advise the user in selecting a ground improvement method or evaluate the user's preselected method. Motamed et al. (1991) indicate that KBES applications have been implemented in all areas of civil engineering, with 76 operational prototype expert systems reported by 1987. Ground improvement in the United States has not been fully accepted as common practice because of the nature of the construction industry, resulting in a slow transfer of technology from the specialty contractor to the designer. A time lag in the range of 5 to 10 years exists between the introduction of a method and the subsequent widespread acceptance.

The development of the system is presented in five stages, as illustrated in Figure 2.1. First, the problem is defined conceptually, the user group is defined, and the need for an expert opinion is documented. Second, the problem is accurately defined. Third, the knowledge base is acquired from experts and other knowledgeable sources. Fourth, a tool is selected based on the requirements of the problem domain. Fifth, coding and testing of the system is completed.

The preliminary selection of ground improvement methods is not performed until the need for such modification is realized. The preliminary selection is based on the nature of the improvement and on physical subsurface, surface, and surrounding characteristics of the site. In developing the knowledge base for ESPGIS, published information and contractor's literature was used extensively. Motamed et al. (1991) included the following methods in ESPGIS:

- Dynamic compaction
- Vibro compaction
- Vibro replacement
- Compaction grouting
- Preloading
- Wick drains
- Ground anchors
- Minipiles
- Slurry walls
- Diaphragm walls
- Chemical grouting
- Slurry grouting
- Freezing
- Jet grouting
- Lime injection



Source: After Motamed et al., 1991.

Figure 2.1. Stages in building a KBES.

Geotechnical experts were not actively engaged in the development process. The selection of an expert system shell (ESS) was an important in the success potential of a KBES system. The system was coded using VP-Expert in an MS-DOS based system (Motamed et al., 1991).

International Knowledge Data Base for Ground Improvement Geosystems

Yoon et al. (1994) developed an International Knowledge Data Base for Ground Improvement Geosystems (IKD-GIGS), which was to aid rational selections, design, and construction of ground improvement technologies. DiMillio (1999), in *A Quarter Century of Geotechnical Research,* states that the Federal Highway Administration (FHWA) joined forces with the International Center for Ground Improvement Technology in Brooklyn, New York, to develop this system. This system was intended to provide a comprehensive, user-friendly database where a user could retrieve information on possible technologies by viewing similar case histories, problems encountered, possible remedial action schemes, comparative cost data, specifications and codes, and quality control and quality assurance (QC/QA). Yoon et al. (1994) included the following ground improvement technologies in IKD-GIGS:

- Ground improvement technologies
  - Dynamic consolidation
  - Vibro compaction
  - Vacuum consolidation
  - Drainage
  - Preloading
  - Blasting
  - Heating
  - Freezing
  - Stone and lime columns
  - Electrochemical treatment
- Ground reinforcement technologies
  - Reinforced soils
  - Geosynthetics

  - Fiber reinforcement
  - Texsol
  - Mechanically stabilized embankments
  - Anchorages
  - Nails
  - Pinpiles
  - Diaphragm walls
- Ground treatment technologies
  - Compaction grouting
  - Jet grouting
  - Permeation grouting
  - Hydrofracture grouting
  - Compensation grouting
  - Fissure grouting
  - Bulk grouting
  - Slabjacking
  - Deep soil mixing
  - Shallow soil mixing

The system was programmed using a DOS-based system to facilitate the program operating on a personal computer. A relational database system was selected to implement IKD-GIGS because the software was economical, popular, powerful, and easy to use. The database included a compendium of national and international codes of practice, a collection of monitored case histories, and information on instrumented structures. As of 1999, the system contained more than 200 documented records of ground improvement case histories from 15 countries. Yoon et al. (1994) described the initial phase of work and indicated that IKD-GIGS was to be developed through multiple phases. During the development of this SHRP 2 R02 Phase 2 project, the IKD-GIGS system could not be located.

Soil and Site Improvement Guide

Sadek and Khoury (2000) developed a selection system as part of a specialized geotechnical engineering soil improvement course at the American University of Beirut. The main objective of the system was to enhance the quality of the teaching and learning process as it relates to soil improvement. The end product provided a system for learning about different techniques, their advantages and limitations, their applicability under certain conditions, and the associated costs. Seventeen ground modification methods were included in the program and broken into four categories:

- Densification
  - Dynamic deep compaction
  - Surcharging
  - Vibro compaction
  - Vibro replacement
  - Compaction grouting
  - Accelerated consolidation/wick drains
- Adhesion
  - Cement grouting
  - Chemical grouting
  - Slurry grouting
  - Freezing
- Reinforcement
  - Minipiles
  - Soil nailing
  - Soil and rock anchors
- Physicochemical
  - Electroosmosis
  - Lime treatment
  - Soil mixing
  - Vitrification

The Soil and Site Improvement Guide software was developed by using Microsoft Visual Basic and queried a database developed with Microsoft Access (Sadek and Khoury, 2000).

Geotechnical Design Process Review

The SHRP 2 R02 project is applicable to a wide range of projects, from embankments to retaining walls to pavement foundations. Each project will have a unique design process. The literature identified in this section provides some background to the geotechnical design process.

Treatment of Problem Foundations for Highway Embankments

Holtz (1989) addresses the treatment of problem foundations for highway embankments. A list of questions, which begins the process of evaluating project conditions and geoconstruction technologies, is presented in Table 2.1. Table 2.2 describes some of the factors involved in constructing embankments on problem soils. Figure 2.2 illustrates the process of incorporating geotechnical information into project planning.

Preliminary Ground Improvement Selection

Beyond the intricacies of the expert system, the overall ground improvement process is discussed and divided into four parts, as shown in Figure 2.3 (Motamed et al., 1991). The four parts are geotechnical study and evaluation, design and performance prediction, performance of ground improvement, and project evaluation. The geotechnical study and evaluation is typically conducted by the geotechnical engineer and the specialty contractor. Design and performance predictions are prepared if ground improvement is required. At this stage, the specialty contractor prepares detailed designs, work plans, schedules, and estimates. Once construction begins, the process is measured by previously set or established quality control criteria. Project evaluation is the degree to which the ground's performance

Table 2.1. Questions Involved in Constructing Highways on Problem Foundations

Question	Remarks
Elevated structure or embankment?	Will the embankment be stable? What is the probability and cost of failure? Can an embankment provide a satisfactory riding surface? Can added cost of elevated structure be justified? How much time is available for construction? What are relative maintenance costs? What is the economic/design life of the structure?
Can, or should, postconstruction embankment settlements be accepted?	Will settlements be uniform or irregular? Should design remove all primary settlements and reduce secondary compression settlements?

Source: Holtz, 1989.

conforms to the required performance and often includes testing of the ground (Motamed et al., 1991).

Guidelines on Ground Improvement for Structures and Facilities

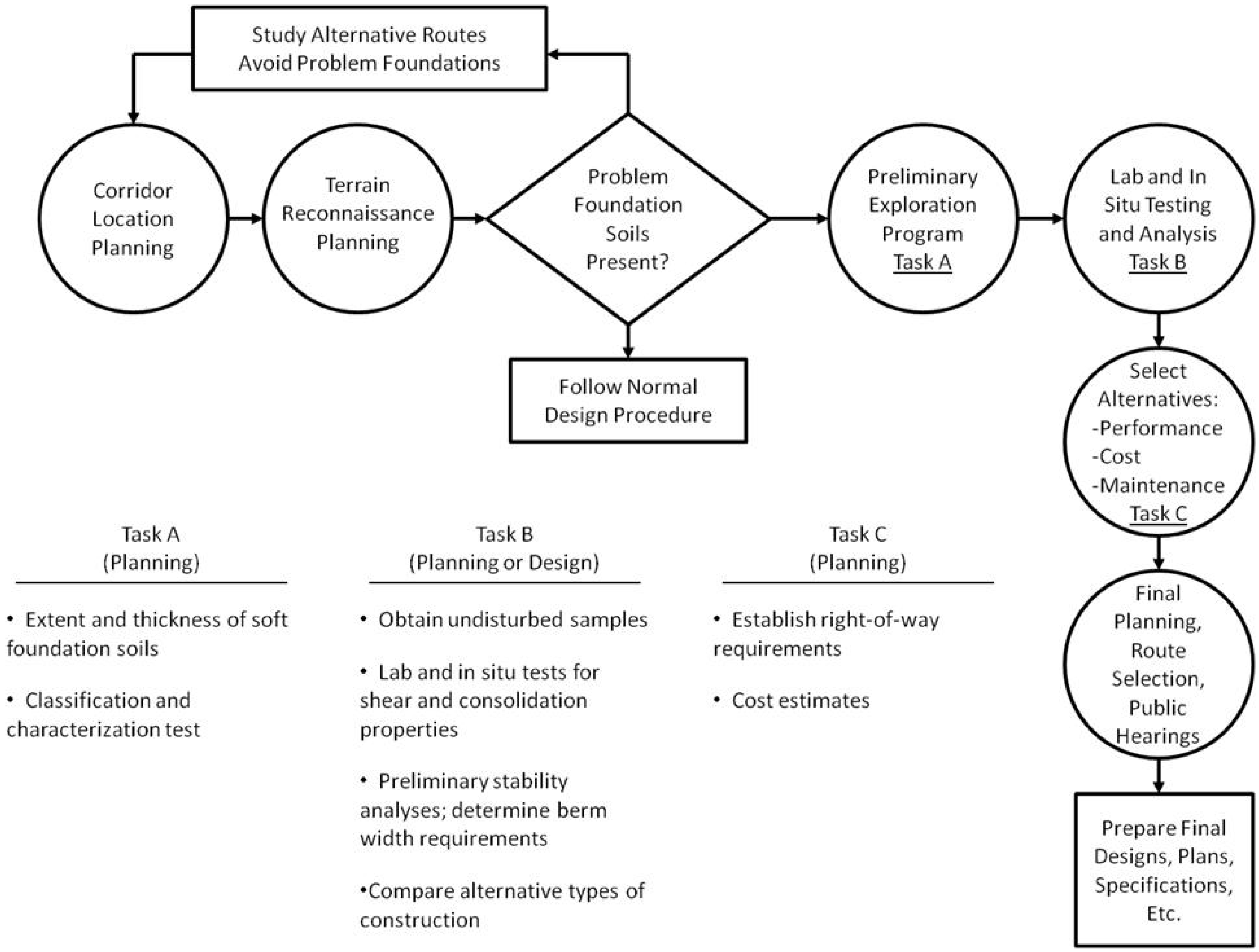
The U.S. Army Corps of Engineers described factors to consider in assessing, designing, and selecting which technique(s) to use for a particular project (U.S. Army Corps of Engineers, 1999). The first area discussed is described as “design considerations and parameters” and considers site constraints, subsurface conditions, scheduling, budget, and availability of contractor. The second area is described as “design procedures” and includes the following steps:

1. Select potential improvement methods.
2. Develop and evaluate remedial design concepts.
3. Choose methods for further evaluation.
4. Perform final design for one or more of the preliminary methods.
5. Compare final designs and select the best one.
6. Field test for verification of effectiveness and development of construction procedures.
7. Develop specifications and QC/QA programs.

Table 2.2. Factors Involved in Constructing Embankments on Problem Foundations

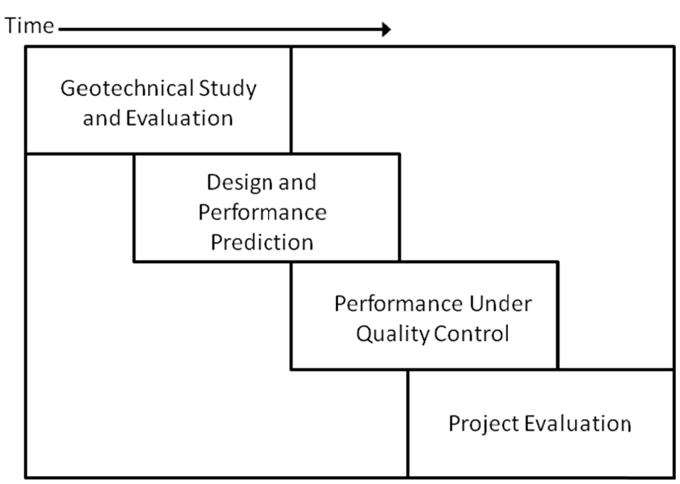
Item	Remarks
Additional construction costs	Substantial; may be as much as several million dollars per mile.
Safety and public relations	Excessive postconstruction differential settlements may require taking part of roadway out of service for maintenance. • Serious safety hazard for heavily traveled roads. • Major inconvenience—public relations problems.
Maintenance cost	May be large • More expensive construction may minimize post-construction maintenance. • Maintenance costs are sometimes regarded as deferred construction costs.
Environmental considerations	May determine type of highway construction and possible alternatives for foundation treatment.
Foundation stability during construction	Detailed subsurface investigations, laboratory and in situ tests, and design studies required.
Tolerable postconstruction total and differential settlements	Appropriate criteria not well formulated; subjective; depends on engineering and public attitudes.
Structure versus embankment	An important decision affecting both construction and maintenance costs.
Construction time available	Some alternatives may be eliminated by need for early completion date.

Source: Holtz, 1989.



Source: Holtz, 1989.

Figure 2.2. Requirements for input of geotechnical information into the corridor planning phase when problem soils are present.



Source: After Motamed et al., 1991.

Figure 2.3. Stages of a ground improvement project.

Soil Improvement

Holtz et al. (2001) discussed the following nine factors to consider in assessing which technique(s) may be the most appropriate:

- Operational criteria for the facility
- Area, depth, and total volume of soil to be treated
- Soil type and its initial properties, depth to water table
- Availability of materials
- Availability of equipment and required skills
- Construction and environmental factors, such as site accessibility and constraints
- Local experience and preference, politics and tradition
- Time available
- Cost

Key Elements in Deep Vibratory Ground Improvement

Bell (2004) discusses the importance of the construction technique in regard to deep vibratory ground improvement. Bell states, "Deep vibratory ground improvement is best understood as a process rather than a product. It can be applied most effectively if all the elements of the process are understood in relation to each other, and if each is given proper attention at all stages." The sequence set forth is apparently chronological, but this may not always be the case. The following key elements are identified in the selection and implementation process:

1. Site evaluation
2. Ground investigation
3. Development of concept
4. Design
5. Construction technique
6. Process evaluation
7. Commissioning and maintenance

Ground Improvement Methods

Elias et al. (2006a) describe the following sequential process for the selection of candidate ground improvement methods for any specific project. The steps in the process include evaluations that proceed from simple to more detailed, allowing for the best method to emerge. The process is described as follows:

1. Identify potential poor ground conditions, their extent, and type of negative impact. Poor ground conditions are typically characterized by soft or loose foundation soils, which, under load, would cause long-term settlement or construction or postconstruction instability.
2. Identify or establish performance requirements. Performance requirements generally consist of deformation limits (horizontal and vertical), as well as some minimum factors of safety for stability. The available time for construction is also a performance requirement.
3. Identify and assess any space or environmental constraints. Space constraints typically refer to accessibility for construction equipment to operate safely and environmental constraints may include the disposal of spoil (hazardous or not hazardous) and the effect of construction vibrations or noise.
4. Assessment of subsurface conditions. The type, depth, and extent of the poor soils must be considered, as well as the location of the groundwater table. It is further valuable to have at least a preliminary assessment of the shear strength and compressibility of the identified poor soils.
5. Preliminary selection. Preliminary selection of potentially applicable method(s) is generally made on a qualitative basis, taking into consideration the performance criteria, limitations imposed by subsurface conditions, schedule and environmental constraints, and the level of improvement that is required. Table 7-23 in Elias et al. (2006a), which groups the available methods in six broad categories, can be used as a guide in this process to identify possible methods and eliminate those that by themselves, or in conjunction with other methods, cannot produce the desired performance.
6. Preliminary design. A preliminary design is developed for each method identified under preliminary selection and a cost estimate prepared based on the data in Table 7-24 in Elias et al. (2006a). The guidance in developing preliminary designs is contained within each technical summary.
7. Comparison and selection. The selected methods are then compared, and a selection is made by considering performance, constructability, cost, and other relevant project factors.

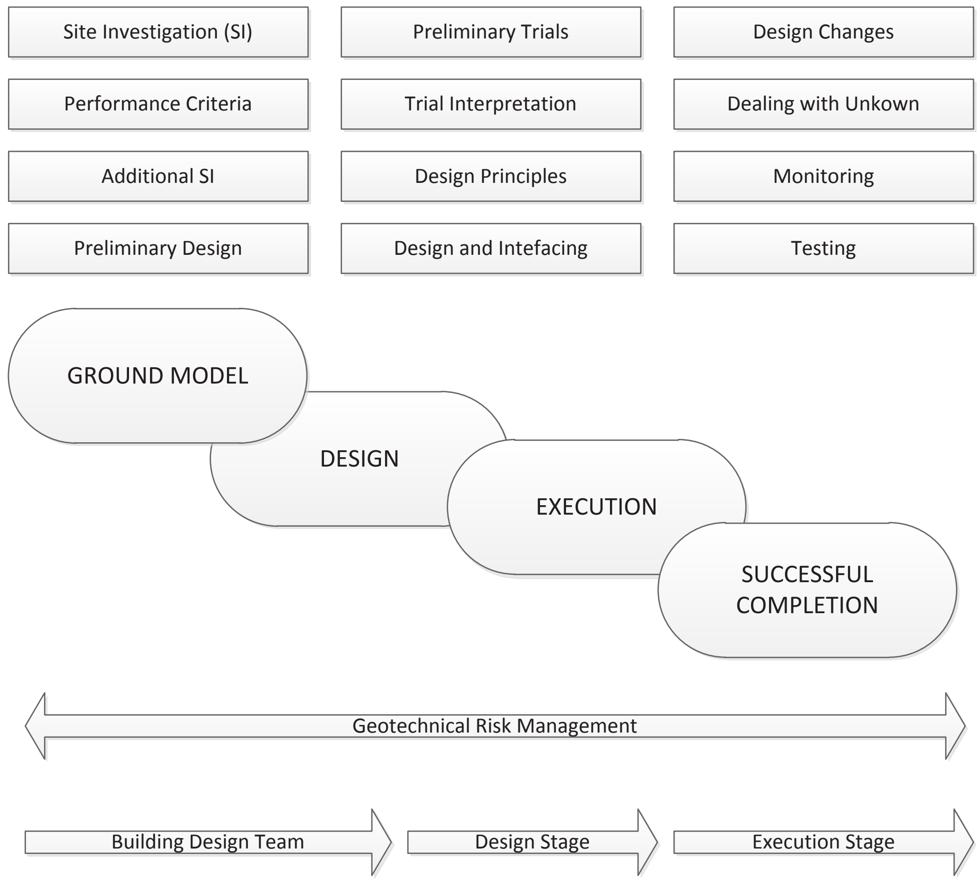
Some Ground Improvement Techniques in the Urban Environment

Serridge (2006) developed Figure 2.4 to describe the key aspects for achieving a successful ground improvement project and provides a detailed discussion on the process with case histories.

Geosynthetic Design and Construction Guidelines

Holtz et al. (2008) presents the following steps for designing a reinforced soil slope.

1. Establish the geometric, loading, and performance requirements for design.
2. Determine the subsurface stratigraphy and the engineering properties of the in situ soils.
3. Determine the engineering properties of the available fill soils.
4. Evaluate design parameters for the reinforcement (design reinforcement strength, durability criteria, and soil-reinforcement interaction).
5. Determine the factor of safety of the unreinforced slope.
6. Design reinforcement to provide stable slope.
    - Method A: Direct reinforcement design.
    - Method B: Trial reinforcement layout analysis.
7. Select slope face treatment.
8. Check external stability.
9. Check seismic stability.
10. Evaluate requirements for subsurface and surface water control.
11. Develop specifications and contract documents.



Source: After Serridge, 2006.

Figure 2.4. Steps for achieving successful ground improvement implementation.

Geotechnical Aspects of Pavements

Christopher et al. (2010) outlines two procedures for using geosynthetic reinforcement for base reinforcement and stabilization. The following design approach is for base reinforcement using geosynthetics, which is summarized from AASHTO 4E and defined by a traffic benefit ratio (TBR) or base-course reduction ratio (BCR).

1. Initial assessment of applicability of the technology
2. Design of the unreinforced pavement
3. Definition of the qualitative benefits of reinforcement for the project
4. Definition of the quantitative benefits of reinforcement (TBR or BCR)
5. Design of the reinforced pavement using the benefits defined in Step 4
6. Analysis of life-cycle costs
7. Development of a project specification
8. Development of construction drawings and bid documents
9. Construction of the roadway

Christopher et al. (2010) also outline the design of the geosynthetic for stabilization using the design-by-function approach in conjunction with AASHTO M288, in the steps from FHWA HI-95-038 (Holtz et al., 1998). A key feature of this method is the assumption that the structural pavement design is not modified at all in the procedure. A limited summary of the procedure outlined in Christopher et al. (2010) is as follows:

1. Identify properties of the subgrade, including CBR, location of groundwater table, AASHTO or Unified Soil Classification System (USCS) classification, and sensitivity.
2. Compare these properties to those appropriate for stabilized subgrade conditions (Christopher et al., 2010; Holtz et al., 2008), or with local policies. Determine if a geosynthetic will be required.
3. Design the pavement without consideration of a geosynthetic, using normal pavement structural design procedures.
4. Determine the need for additional imported aggregate to ameliorate mixing at the base/subgrade interface. If such

aggregate is required, determine its thickness, t_1, and reduce the thickness by 50%, considering the use of a geosynthetic.

5. Determine additional aggregate thickness t_2 needed for establishment of a construction platform. The FHWA procedure requires the use of curves for aggregate thickness versus the expected single tire pressure and the subgrade bearing capacity.
6. Select the greater of t_2 or 50% of t_1.
7. Check filtration criteria for the geotextile to be used. For geogrids, check the aggregate for filtration compatibility with the subgrade, or use a geotextile in combination with the grid meeting the project requirements.
8. Determine geotextile or geogrid survival criteria. The design is based on the assumption that the geosynthetic cannot function unless it survives the construction process.

Principles and Application of Ground Improvement in Asia

Raju (2010) provides a few factors to consider in the important decision of choosing which method to use:

- Suitability of the method
- Technical compliance
- Availability of QC/QA methods
- Availability of material
- Time
- Cost
- Convenience
- Protection of the environment

For additional discussion on each of these factors, please refer to the source.

CHAPTER 3

System Development

The vision for the final system was initially outlined in a preliminary report for this project, the SHRP 2 R02 Phase 1 report, which presented a proposed work plan. The work plan was implemented as part of Phase 2 of the R02 project. A readily accessible and readily usable tool for users will overcome many implementation obstacles and promote more widespread use of soil improvement technologies to achieve the SHRP 2 Renewal objectives. The details from the Phase 2 work plan are included in the following paragraphs.

The HTML system will provide "one-stop shopping" for DOT engineers and others to use in selecting, designing, and specifying soil improvement technologies. To operate the overall system, a designer will begin using the technology guidance system by inputting descriptive information about a particular project under consideration, including the nature of the proposed construction, project size, subsurface conditions, performance expectations, and the like. The guidance system will suggest one or more soil improvement technologies that are applicable to the particular circumstances of the project, and eliminate other technologies that are not applicable. Next, the designer will be able to click on links to learn more about the recommended technologies. This will include descriptive material, summaries of case histories, Phase 1 detailed technology assessments, categorized reference lists, abstracts of references, and direct access to public domain references embedded within the system. Next, the designer will be able to link directly to design procedures, which will also reside within the overall system. Information and guidance about relevant quality control and quality assurance (QC/QA) procedures for construction will be provided. The designer will also be able to access the cost estimating system for developing preliminary cost estimates and comparisons. Finally, guide specifications will be provided in a two-column format, with guide specifications in one column and commentary in the other.

By bringing together in one convenient and comprehensive system all the information needed to select, design, specify, and monitor soil improvement technologies, this system will provide department of transportations (DOTs) and their consultants with the information and tools needed to apply these technologies to achieve SHRP 2 Renewal objectives.

The development of the system has been a continuous cycle of developing, reviewing, revising, and evaluating the revisions. During the first review of the system by the research team and advisory board, mandates for the information and guidance system were established, stating that the system should be the following:

- Simple
- Functional
- Completely populated
- Easy to guide the user to a short list of potential, unranked technologies (selection system)
- Easy to update technology-specific information
- Updatable to add additional technologies

Developing the framework for the information and guidance system required planning and defining the system scope, overall system characteristics, the user, the operating system, and the approach to the selection system.

The system developed was termed an information and guidance system. Other system names, such as a decision support system, were considered, but the term *information and guidance system* was selected as the best descriptor. The system is meant to guide the user in selecting an appropriate geoconstruction technology for the project at hand and then provide all the technology-specific information such that a project-specific determination can be completed. This system provides tools for project-specific engineering.

The system was developed with the intent that both nontechnical and technical personnel would use it, albeit at different levels. In particular, the system was developed with the goal of being beneficial to state transportation agency (STA) personnel, including senior officials, planners, all branches of civil engineers, and geologists. In the technology fact sheets and in the first few steps of the selection assistance procedure, technical terms were intentionally avoided to allow nontechnical users to investigate potential geoconstruction technologies for different types of transportation applications. As the system progresses, an increasing amount of subsurface and technical knowledge is required to refine the list of potential technologies. All users should acknowledge that an expert system deals with subject matter of realistic complexity that normally requires a considerable amount of human experience (Jackson, 1999).

Summary of System Development

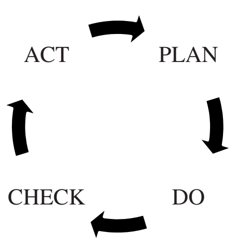
The information and guidance system was in development for approximately 2 years. Another 1 to 2 years of additional refinement are anticipated in the beta testing portion of the project, which is referred to as the preimplementation phase. A constant cycle of review, commenting, and revision was interwoven with every task to develop a usable, quality product. The Shewhart cycle (Naik and Tripathy, 2008), illustrated in Figure 3.1, indicates the continuous cycle of development for the information and guidance system: Plan includes establishment of system objectives and outlining the process to deliver results; Do is the implementation of the plan; Check assesses system results and obtains decision-maker input; and Act involves identification of changes and revisions required to improve the system.

The information and guidance system began with a simple outline and each review cycle yielded revisions, deletions, and additions to the system. A chronological summary of the development of the information and guidance system follows.

Timeline of System Development

October 2009: Project Team and Advisory Board Meeting

The top two goals are (1) for the system to be functional by the end of the project and (2) for all the branches of the system to be populated with information. The development of a system that works and is well populated for the included technologies is more important than developing a complex and sophisticated system. The selection system should be transparent in the sense that it should show which technologies are removed from the recommended list as soon as each piece of project data is entered.



Source: Naik and Tripathy, 2008.

Figure 3.1. Shewhart cycle.

Spring 2010: System Revision

The literature review confirmed the need for an automated system for geoconstruction technologies as envisioned. The initial version of the selection system was drafted in hard copy form using flowcharts and accompanying tables.

April 2010: Project Team Meeting

The next iteration for the vision of the information and guidance system was presented to the project team. The overall system characteristics, the user, the knowledge, the operating system, and the approach to the system were finalized.

Summer 2010: System Revision

The selection system continued refinement in hard copy form using flowcharts and accompanying tables. The need for a glossary became evident as many team members had different opinions on some of the terminology used throughout the system. The options for developing the automated system were explored.

August–September 2010: Reviews

Reviews included the geotechnical group with the FHWA and project team for review of the selection system. The main outcomes of these reviews are:

- Clarification of queries in the selection system
- Refinement of applicable technologies throughout the selection system
- Revision of terminology used throughout the information and guidance system
- Confirmation that the selection system was a viable product

Fall 2010: System Revision

The system structure and programming for the automated information and guidance system were initiated in September 2010. The page layout, functionality, and interrelation of the website pages were determined. The structure of the database was established. Revision of the selection system flowcharts and tables was completed. The products to be available through the system were developed from the project documents. The cost information for each technology will be available through a downloadable product in the system. Example products were prepared for three technologies.

October 2010: Minnesota DOT Workshop

A half-day workshop was held on October 4, 2010, in Maplewood, Minnesota. The workshop was attended by 12 geotechnical and pavement engineers of the Minnesota Department of Transportation (MnDOT) and included one advisory board member. Mr. Ryan Berg conducted the workshop. The motivation for this workshop was to obtain early user input during the initial stages of the information and guidance system development. MnDOT is considered to be progressive and well experienced in the use of ground improvement technologies.

The first portion of the workshop was a walk-through of the guidance system selection logic and products/tools that will be available on the website. Handouts were used to introduce the system. The last portion of the workshop was an open discussion on features and benefits of the website products and tools, features and benefits of the guidance logic, and any additional items raised by attendees. The main outcomes of this workshop are as follows:

- A comprehensive website of tools for engineering with ground improvement methods was enthusiastically received.
- The selection logic for engineering with ground improvement methods was well received. Some concerns raised were:
  - Will the selection process try to go too far? It cannot take out the local, project-specific engineering that is required with such projects.
  - Can the system be misused? Specifically, can district engineers (nongeotechnical) use the system to arrive at a ground improvement method on a project, and bypass consultation or coordination with central office geotechnical group? If so, this could be technically problematic and lead to performance problems or even failures.
  - The selection portion should clearly warn nongeotechnical or nonpavement users from going too far (i.e., project-specific selection should not be completed without geotechnical engineering input).
- The case history summaries were enthusiastically received. MnDOT has recently initiated a similar project summary concept. The R02 format and content were compared to the MnDOT format and content, and found to be practically identical.
- MnDOT recommended that their agency logo be added to any case histories from MnDOT work, and they welcome recognition of their work.

November 2010: Project Team and Advisory Board Meeting

The research project team and advisory board were provided the selection system in flowchart and table format before the meeting and asked to bring comments to the meeting. The web-based system was presented on November 8, 2010. This represented the initial unveiling of the web-based system. After an introduction to the website, the example products for the three technologies were discussed. An emphasis was placed on the products being the ultimate deliverable, and not the working documents developed during the detailed technology review. A considerable amount of time was devoted to review of the selection system and applicable technologies. The flowcharts and tables reviewed at this meeting are not included to avoid any confusion with the final flowcharts and tables discussed in Chapter 5, which details the interactive selection system. The main outcomes of these reviews are summarized as follows:

- Refinement of the selection system.
- The need for a project-specific selection system for construction over unstable soils to further refine applicable technologies. A series of dropdown menus were envisioned to facilitate the detailed selection process.
- Cost spreadsheets should be provided for each technology, and not just a cost summary document.
- The system must be fully populated prior to public release.
- The system must be tested before release.
- A mechanism to capture comments from users must be included.

Winter 2010: System Revision

The development of the automated information and guidance system continued based upon the input from the project team and advisory board November meeting. Revision of the selection system flowcharts and tables was completed. A project-specific selection system was scoped to add to the selection system. The products to be available through the system were developed for additional technologies. Cost-estimating spreadsheets were linked through the cost information products.

January 2011: TRB Workshop

A workshop was held on January 23, 2011, in Washington, D.C. This workshop provided the first public viewing of the system. Attendees were from industry, academia, state health agencies (SHAs), and federal agencies. The workshop included a preview of the information and guidance system, as well as three example projects of how the system could be used.

Five members of the project team led the various parts of the workshop. The main outcomes of this workshop are outlined as follows:

- Confirmation that the selection system was a viable product.
- Refinement of the selection system.
- Refinement of the project-specific selection system.
- Technology ratings of contribution to SHRP 2 Renewal objectives and degree of technology establishment should be in the system.
- Improve the documentation and output of the selection system.
- Cost spreadsheets should be provided for each technology, and not just a cost summary document.

Spring 2011: System Revision

The information and guidance system was revised based on the latest comments. Text on the website was reviewed and refined. A stand-alone column selection tool for column-supported embankments was drafted and added to the website. As of the date of this draft report, the column selection tool for column-supported embankments remains a work-in-progress.

April 2011, Ottawa, Canada: Presentation

A presentation to the Soils and Materials Standing Committee of the Transportation Association of Canada was made on April 17, 2011, in Ottawa, Ontario. The workshop was attended by approximately three dozen committee members and guests. Dr. James Bryant and Mr. Ryan Berg made presentations. Dr. Bryant's slide presentation was an update on the SHRP 2 Renewal program, and highlighted items of interest to this committee. This included construction QC, condition assessments tools, and long life pavements. Mr. Berg then made a two-part presentation. The first part was a slide presentation, with handout notes, on the R02 Geotechnical Solutions for Transportation Infrastructure project. This included project elements, project vision, project team, technologies addressed, and goal of the information and guidance system/website. The second part of the presentation was an interactive demonstration of the Geotechnical Solutions for Transportation Infrastructure website. The motivation for this workshop was to spur international technology transfer. This is particularly important in ground improvement technologies, where historically many new technologies have been developed outside of the United States. The main outcomes and feedback of this workshop are summarized as follows:

- A comprehensive website of tools for engineering with ground improvement methods was enthusiastically received.
- The case history summaries were well received.
- Response to question regarding case histories: Case histories would be accepted from outside the United States.
- Response to question on how new technologies could be added: No new technologies are being added at this stage of the project. However, addition of technologies is anticipated with website use, and the current project will document a systematic methodology for evaluating and adding a technology.

April 2011: Louisiana Workshop

A half-day workshop was held on April 14, 2011, in Baton Rouge, Louisiana. The workshop was attended by 20 engineers from the Louisiana Department of Transportation and Development (DOTD), the Louisiana Transportation Research Center (LTRC), Louisiana State University (LSU), and the FHWA. Mr. Caleb Douglas and Dr. Vern Schaefer conducted the workshop. The motivation for this workshop was to obtain user input during system development and then implement changes, revisions, and additions to the system resulting from the user input during final project development. The first portion of the workshop was introducing the system. The last portion of the workshop was allowing all 20 users to access the web-based system live. The system remained stable during the workshop and no occurrences of a slow site were observed. The main outcomes of this workshop are outlined as follows:

- Completely populate the downloadable products for each technology.
- Enable the user to back up a step during the technology selection process.
- Clearly describe process for determining the rating factors.
- Provide a smoother transition after completion of selection system to accessible list of potential technologies.
- Complete a quality check of live system considering potential technologies.
- Bring time of construction into the interactive selection system.
- Where possible, allow users the option to download Excel or Word files.

Summer 2011: System Revision

The major improvements to the system included refinement of the output from the selection system. New windows and ability to generate a PDF file were added. The text was refined and pages were visually enhanced. The selection system was revised in response to the latest comments. Programming for the column selection tool for column-supported embankments was added to the website. At this point, the "information and guidance system" terminology for the entire website was revised to the "web-based information and guidance system."

July–September 2011: Alpha Testing and System Revision

The project team conducted alpha testing of the web-based information and guidance system. Project team meetings were held at Iowa State University and at Virginia Polytechnic Institute and State University (Virginia Tech). The comments from the testing were incorporated into the system. Alpha testing was completed in preparation of submitting the beta version to the project sponsor for review.

The three main objectives of the development team were met during alpha testing.

- The system remained stable during testing with multiple users accessing the site simultaneously.
- Only minor issues with a wide range of wide browsers were identified and all of those issues have been corrected.
- The comments received for the interactive selection system were cosmetic in nature and no structural improvements to the system were suggested.

Programming

Programming the information and guidance system into a usable, stable website began in September 2010. Over the course of the year of development, all facets of the information and guidance system were also being revised. As the automated system was tested by the project team, further suggestions were implemented to increase the usability of the system. The structure of the information and guidance system is best described through a series of tables and figures. An overview of programming the website follows.

An individual, off-the-shelf shell software program for developing a knowledge-based system was not used. The website uses the following combination software: Adobe ColdFusion, JavaScript, and Microsoft Access.

The website platform was developed using Adobe ColdFusion. The programs are written in the ColdFusion Markup Language (CFML). This particular programming language offered the versatility to complete dynamic websites that query databases. The JavaScript programming language provided interactive site content and allowed for live page updates based on user actions. The knowledge to complete both dynamically developed web pages and the interactive selection system were contained in a Microsoft Access database.

The filename extensions found in the program files are shown in Table 3.1. The free, open-source JavaScript library called jQuery was used to simplify the program's JavaScript coding in some instances, extend its capabilities, and, as much as possible, ensure cross-browser compatibility. Each web page, along with the associated database table if the web page interacts with the database, is summarized in Table 3.2. The program directory tree is presented in Table 3.3.

Table 3.1. File Name Extensions

Extension	Description
.cfm	ColdFusion markup language file
.cfc	ColdFusion component file
.js	JavaScript file
.mdb	Microsoft Access database

Interactive Selection System

The interactive selection system was established from the flowcharts and tables developed to define the system and was coded as a nested "if . . . then" statement, with each selection by the user querying a column in the database. As subsequent selections are made by the user, additional columns are queried in the database. The list of potential technologies is determined by the technology(s) that satisfy all of the inputs selected by the user.

Figure 3.2 provides a conceptual view of sorting technologies in the interactive selection system.

Like most geotechnical analytical solutions, the results of the analysis must be measured against the opinion of an experienced geotechnical engineer practicing in the local area of the project. Although this section is titled "Approach to the Selection System," the following discussion also presents the approach to minimizing uncertainty or error in the system. Most of the uncertainty in the system can be attributed to either imperfect domain knowledge or imperfect case data (Jackson, 1999).

In maintaining the "keep the system simple" mandate from the advisory board, fuzzy logic and probability theory were not used in the development of the interactive selection system. The system developed for this project was addressed using two approaches. The first approach is that the system conservatively removes potential technologies during the process. The second approach is a common theme throughout the selection procedure—that is, the final selection of an appropriate technology will be the responsibility of the user. The system will lead the user to multiple technologies and provide the means for technology introduction, design, and cost estimating. The research team wants to emphasize that this system does not replace the project geotechnical engineer. The geotechnical engineer's "engineering judgment" should be the final selection process, which takes into consideration the following: construction cost, maintenance cost, design and QC issues, performance and safety (pavement smoothness; hazards caused by maintenance operations; potential failures), inconvenience (a tangible factor, especially for heavily traveled roadways or long detours); environmental aspects, and aesthetic aspects (appearance of completed work with respect to its surroundings) (Johnson, 1975; Holtz, 1989).

Table 3.2. Web Page, Programming, and Associated Database Summary

Web Page Name	Associated Programming Reference	Associated Database Table
Log In (to gain access to this site)	login/login_form.cfm	tblUsers
Home	index.cfm	
SHRP 2 R02 Project Background	background.cfm	
Technology Source Documents	catalogdocs.cfm	source_docs
Geotechnical Design Process	geodesign_steps.cfm	
Catalog of Technologies	techcatalog/index.cfm	techdisplay
Catalog of Technologies (with ratings)	techcatalog/withratings.cfm	techdisplay
Technology Information	tech_display/technology.cfm	techdisplay techdisplay_casehistory
Technology Selection System Disclaimer	selection_app/disclaimer_techselect.cfm	
Technology Selection	selection_app/index.cfm	
Technologies by Classification	selection_app/techclassification/	techclassification
Interactive Selection System	selection_app/techselect/	techselect
Interactive Selection System: Project-Specific Technology Selection for Construction over Unstable Soils	selection_app/techselect/ projectspecific/index.cfm	techadvanced_unstable
Glossary	glossary.cfm	
Abbreviations	abbreviations.cfm	
Frequently Asked Questions	faq.cfm	
Links	links.cfm	
Submit a Comment	comment.cfm	tblcomments
Submit Technology-Specific Information	submittechinfo/	submitttechinfo filetype
About this Website	about.cfm	

Table 3.3. Program Directory Tree

Folders	Subfolders Level 1	Subfolders Level 2
documents	ratingdocs	
	SHRP 2R02_reports	
images		
includes		
js		
login		
selection_app	techclassification	
	techselect	breadcrumbs
		projectspecific
		selection_includes
		selectionsummary
styles		
submittechinfo	Documents	
tech_display	CSEselectiontool	
techcatalog		

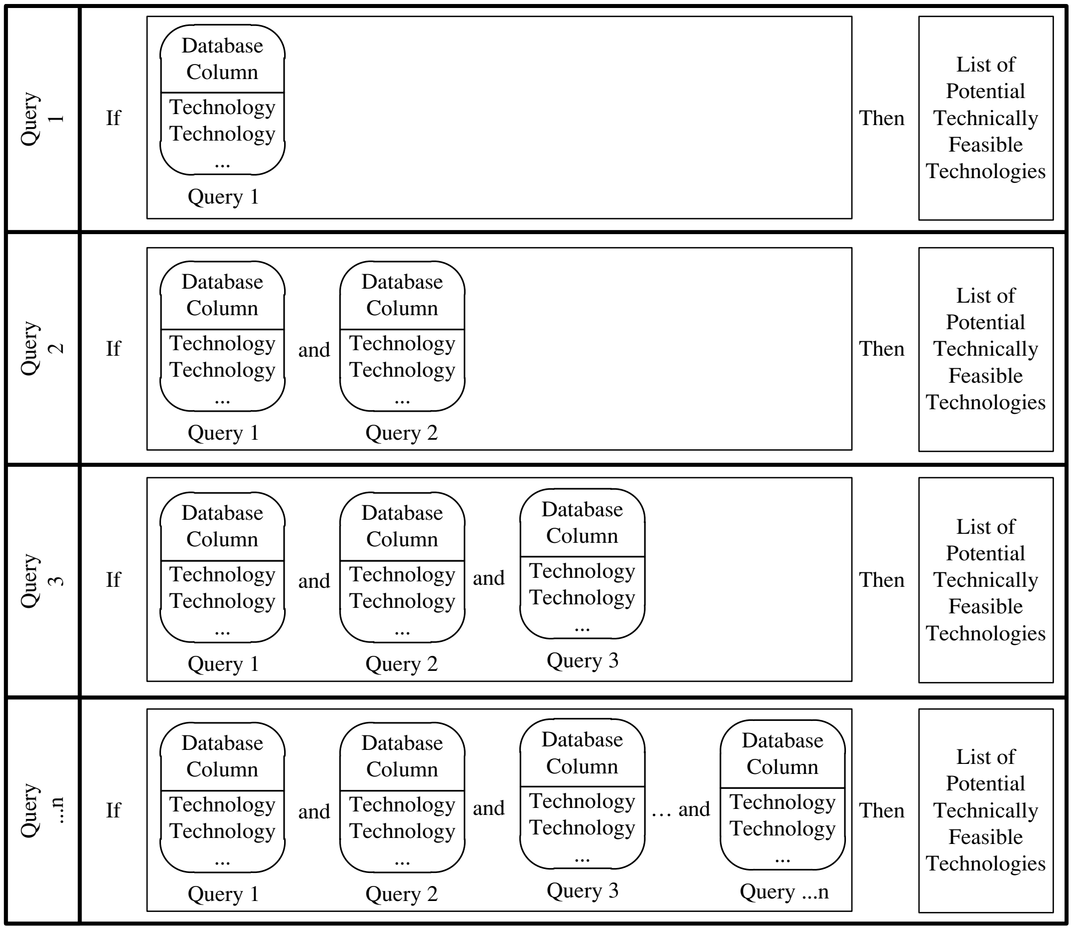


Figure 3.2. Conceptual of database sorting during interactive selection system.

CHAPTER 4

Web-Based Information and Guidance System

Introduction

The web-based information and guidance system contains the vital information for the 46 geoconstruction technologies previously identified under SHRP 2 R02 Project Background in Chapter 1. The vital information allows for selecting, applying, designing, cost estimating, specifying, and monitoring those geoconstruction technologies. The information and guidance system is a comprehensive toolkit of geotechnical information to address all phases of decision making, from planning to design to construction to allow transportation projects to be built faster, to be less expensive, and to last longer. Anyone involved in planning, design, and construction of transportation infrastructure will benefit from the information and resources available on the website. The target audience of the information and guidance system is public agency personnel at the local, state, and federal levels. Other users will include engineering consultants, contractors, architect/engineer groups, and academics/students.

The website allows immediate and automated access to the results of the SHRP 2 R02 research project. The overall concept of the information and guidance system is illustrated in Figure 4.1. The title for the website, Geotechnical Solutions for Transportation Infrastructure, comes from the objectives associated with the SHRP 2 R02 project. Programming for the guidance system is functionally complete. Internal review of the programming and documents has been completed. Minor revisions and additions are actively being incorporated with additional review and comment cycles.

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 avoided. The intent of the system is to offer a means of evaluating a particular geoconstruction technology. A thorough study of the information and guidance system should enable the user to determine where, when, and how a certain geoconstruction technology should be used (Terrel et al., 1979).

Reference to two systems will be found 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. A dynamic interactive selection system has been developed within the information and guidance system, as part of Technology Selection. It is a knowledge-based decision support system. The term *interactive selection system* refers to the dynamic portion of the system that assists in identifying candidate technologies.

Before detailing every aspect of the information and guidance system, the four primary components of the system, as illustrated in Figure 4.2, are described. The Catalog of Technologies provides a listing of all the technologies. The information included in the Catalog of Technologies facilitates the technology transfer from the research project to everyday practice. The web-based system allows this information to be easily accessed. For each technology, the following documents are available as downloadable PDF files:

- Technology fact sheet
- Photos
- Case histories
- Design guidance
- Quality control and quality assurance (QC/QA) procedures
- Cost information
- Specifications
- Bibliography

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

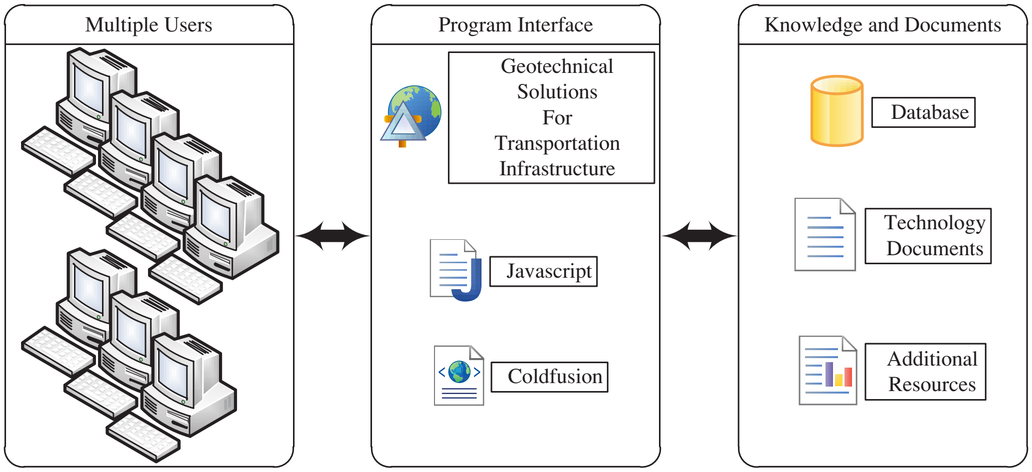


Figure 4.1. Information and guidance system overall concept.

evaluating site conditions and implementing a geoconstruction technology.

This website contains technical terms and industry specific jargon. Abbreviations and Glossary terms have been compiled to assist the user in understanding the acronyms and terminology used throughout this website and in its documents.

Website Structure

The interrelationship of the four primary components (see Figure 4.2) with the other features of the site is illustrated in Figure 4.3. The information on the individual Technology Information page forms the technology transfer to the user for a specific technology. One of the goals of the Technology Selection component is to refer the user to the appropriate individual Technology Information page, as shown in Figure 4.3. The other features of the website support the four primary components or usability of the website.

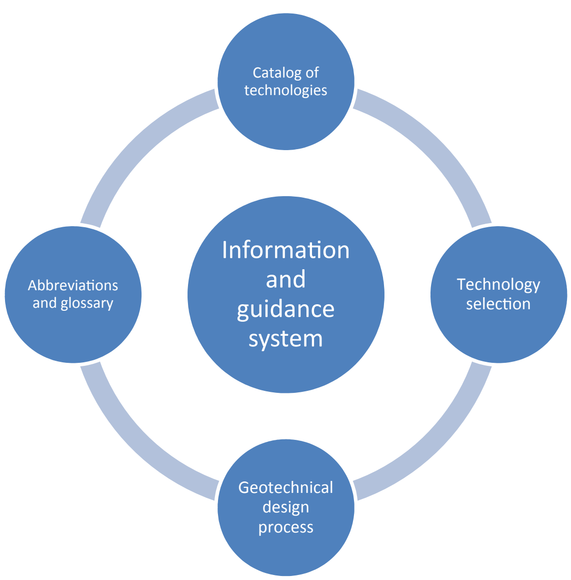


Figure 4.2. Relationship of the four primary components of the information and guidance system.

Information and Guidance System Website

The Geotechnical Solutions for Transportation Infrastructure information and guidance system website is currently housed in a server at the Iowa State University Institute for Transportation (www.geotechtools.org).

The site will remain password protected through the completion of beta testing and will be publicly released with approval by the project sponsors.

Homepage

The homepage for the web-based information and guidance system is shown in Figure 4.4. The title of the web page is shown across the top. Along the left side of the page are buttons to the pages, as shown in Figure 4.3, which include Home, Project Background, Geotechnical Design Process, Catalog of Technologies, Technology Selection, Glossary, Abbreviations, Frequently Asked Questions, Links, Submit a Comment, and About this Website, that are always available to the user. The homepage highlights the four main parts of the system: Geotechnical Design Process, Catalog of Technologies, Technology Selection, and Glossary. The entirety of the text included on the homepage is shown on Figure 4.4.

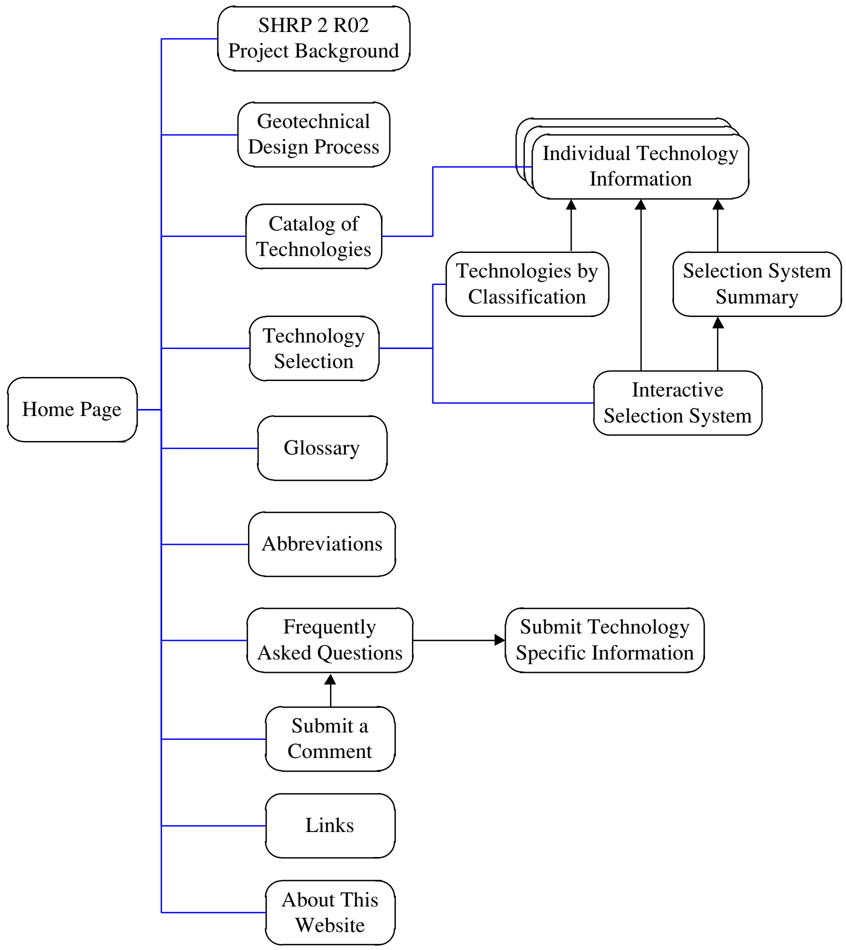


Figure 4.3. Information and guidance system website structure.

SHRP 2 R02 Project Background

The project background page contains an acknowledgement of sponsorship and provides a brief introduction to the SHRP 2 R02 project, the research team, and the tasks completed for the project.

Geotechnical Design Process

The Geotechnical Design Process web 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 R02 project encompassed such a wide range of possible projects and geoconstruction technologies that a detailed design process could not be developed to cover all the possibilities. This system provides tools for project-specific design engineering and does not replace an engineer's judgment. The process described does introduce the basic evaluation process for geoconstruction technologies. This page refers the user to the Links web page where additional information can be found to assist the user in the design process.

Catalog of Technologies

The Catalog of Technologies web page lists the 46 geoconstruction technologies in the system; a screenshot of this page is presented in Figure 4.5. The list of technologies in the catalog is shown under SHRP 2 R02 Project Background in Chapter 1. The name of each technology is a hot-link button on the website that takes the user to a web page for that technology, which is discussed in more detail in the next section. A link is provided on the page to view the Catalog of Technologies with SHRP 2 R02 ratings.

A Catalog of Technologies with Ratings web page was developed to assist the user in comparing similar technologies with regard to the SHRP 2 R02 ratings for degree of establishment, rapid renewal, minimum disruption of traffic, and production of long-lived facilities. The later three are the specific objectives of the SHRP 2 Renewal program.

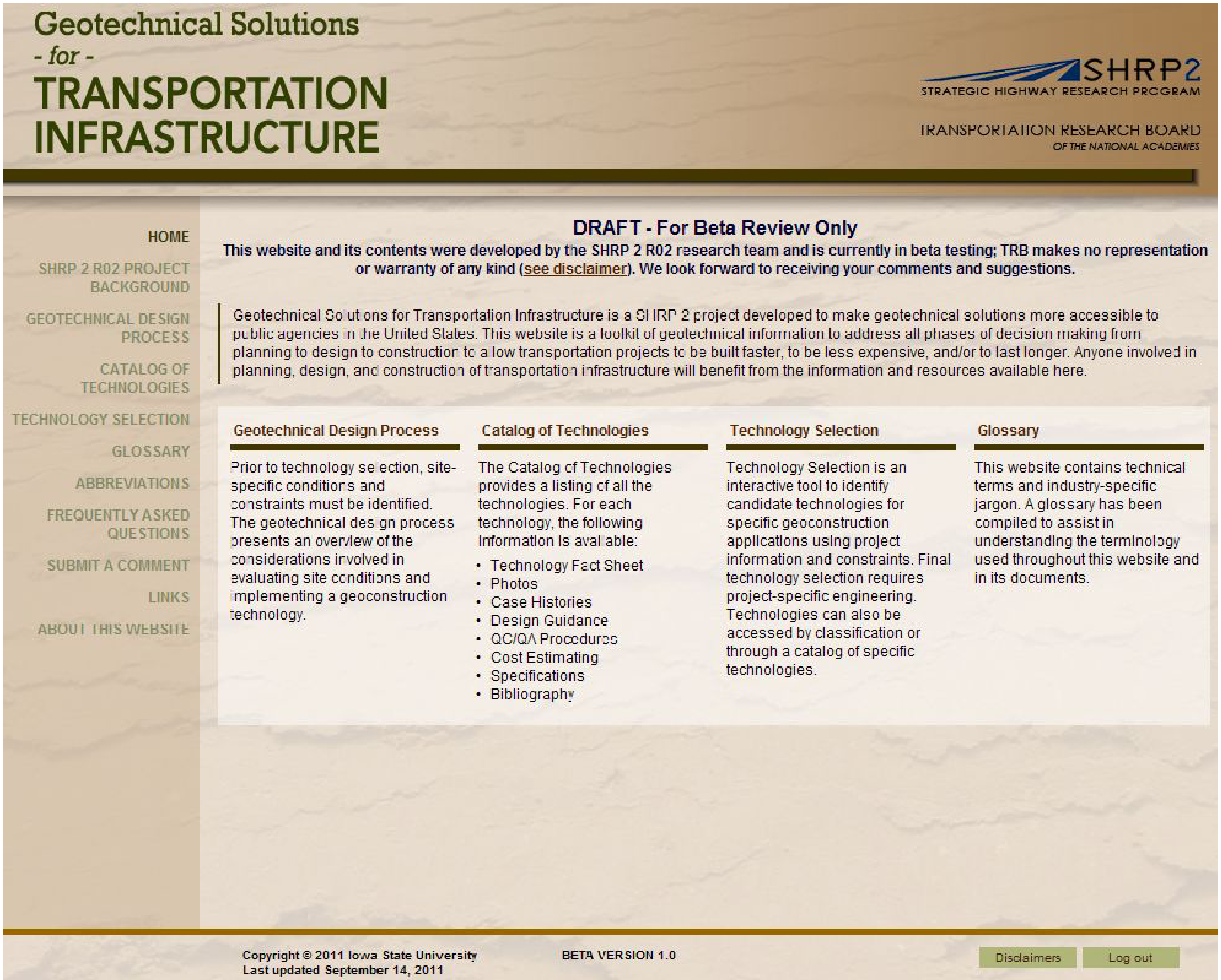


Figure 4.4. Information and guidance system homepage.

Individual Technology Information

The downloadable documents provided on the individual Technology Information web page for each technology provide the mechanism for technology transfer for the project. The intent of the entire information and guidance system is to guide the user to the information provided on this web page for each technology. An illustration of the structure of the downloadable documents is presented in Figure 4.6. An example of an individual Technology Information web page is shown in Figure 4.7.

The information documents are downloadable as Adobe PDF files. The 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. The photos show the 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), which were preferably conducted by a United States state transportation agency (STA), and contain project location, owner, and performance information, and STA project engineer contact information. The design guidance and QC/QA documents provide a summary of recommended procedures for the technology. The recommended design and QC/QA procedures come from an assessment of the current state of the practice of each technology. In cases where a

Figure 4.5. Catalog of Technologies web page.

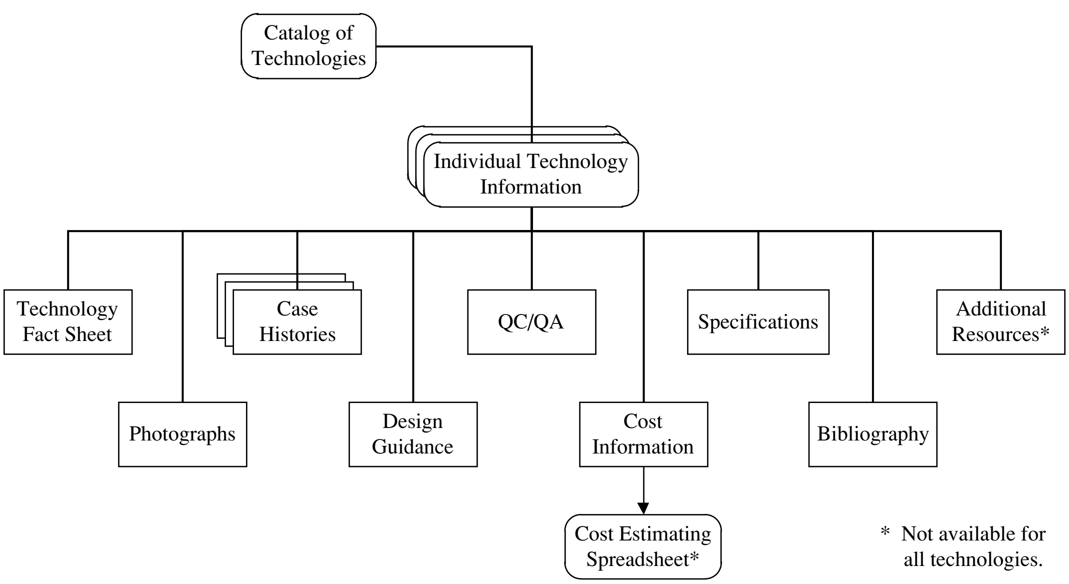


Figure 4.6. Concept of individual Technology Information web pages.

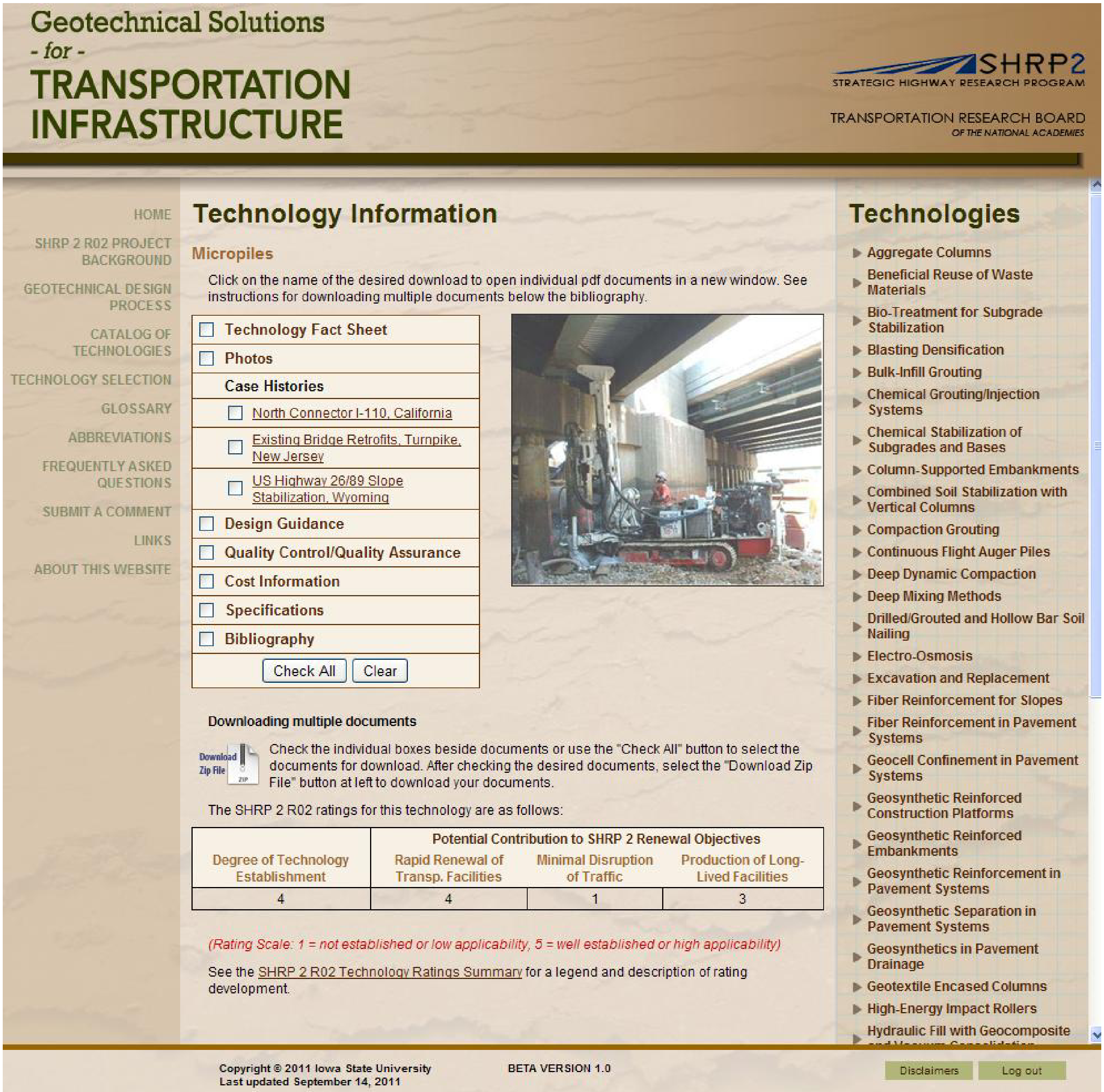


Figure 4.7. Example of an individual Technology Information page.

well-established procedure (e.g., an 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, there are two cost documents available. Cost information provides an explanation of the cost item specific to the technology, generally emanating from the pay methods contained in specifications. Available regional and state cost numbers, generally from DOT bid tabs or national databases, are compiled for each technology. The second document consists of an Excel spreadsheet developed to estimate costs for the use of the technology and lists items (e.g., mobilization cost) that must be quantified to estimate the cost of applying a particular technology. The spreadsheet can only be accessed as a link through the cost information document. The second document could not be prepared for a few 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. A specifications document is provided for each technology and provides a summary of example specifications identified during the project. The final document available for each technology is a bibliography compiled during the research project. It lists key references for that technology.

Technology Selection

A technology selection system was developed to aid the user in identifying potential geoconstruction technologies for a user-defined set of project conditions. The selection system contains both a listing of the technologies sorted by category and a dynamic interactive selection system. A schematic of the technology selection system and the interlink with the Technology Information web page is illustrated in Figure 4.8. The interactive selection system is entered after the user acknowledges the disclaimers and limitations of the interactive selection system. The start of the selection system is shown in Figure 4.9. In the classification system, the technologies are grouped into the following categories:

- Earthwork construction
- Densification of cohesionless soils
- Embankments over soft soils

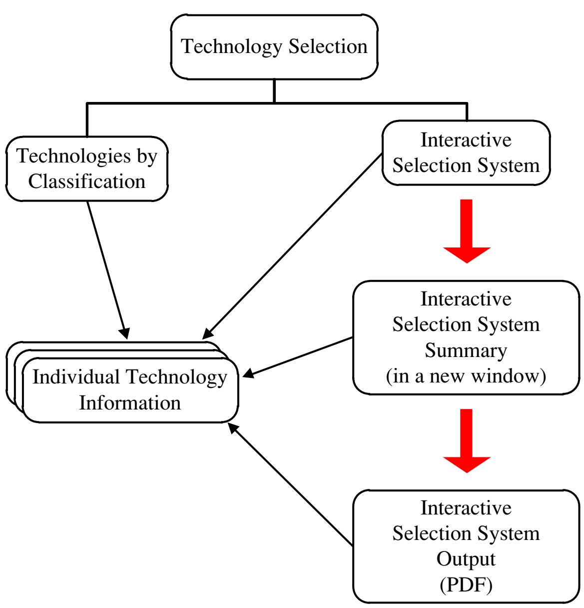


Figure 4.8. Conceptual layout of technology selection.

- Cutoff walls
- Increased pavement performance
- Sustainability
- Soft ground drainage and consolidation
- Construction of vertical support elements
- Lateral earth support
- Liquefaction mitigation
- Void filling

Thus an experienced engineer can access solutions according to particular categories of problems.

The interactive selection system provides the user the opportunity to access potential technologies based on four applications, as illustrated in Figure 4.10. After the user identifies potential technologies, the technology catalog can be accessed, which includes information necessary for additional screening (i.e., depth limits, applicability to different soil types, acceptable groundwater conditions, applicability to different project types, ability to deal with project-specific constraints, and general advantages and disadvantages). The interactive selection system points the user back to the technology-specific information found in the catalog. The interactive selection system is discussed in detail in Chapter 5.

Glossary and Abbreviations

Terms were identified during completion and review of the assessments for the 46 technologies. The term definitions provide reference to existing documents where possible. The Glossary page is provided in an alphabetical listing sentence with a hot-linked system of the letters for ease of use. Where a clear definition does not exist, the terms will be defined as used in this system. In addition to the glossary, a list of abbreviations was compiled to assist the user with the myriad of abbreviations used in the practice of applying geoconstruction technologies.

Frequently Asked Questions

To assist the user, a Frequently Asked Questions (FAQ) web page was developed. The questions shown in Figure 4.11 are answered on the FAQ web page. Responses to the questions have been written for use with the website and contain links to various pages on the website.

Submit a Comment

A Submit a Comment web page was developed to capture comments. The need for a mechanism to capture comments was repeatedly confirmed after presenting the system to user groups during its development. The Submit a Comment system captures each input in a database, which will allow comment

Figure 4.9. Technology Selection web page.

sorting during comment review. Additionally, as a supplement to the Submit a Comment system, a mechanism to allow users to upload technology-specific information was developed. The submission of files is captured in the database for future sorting. An addition to this submission feature is the requirement for the user to add a statement discussing why the information being submitted should be considered for inclusion in the system.

Links

Many state and federal departments have developed technical information that provides additional information regarding selecting, implementing, and designing projects with geoconstruction technologies. Some organizations that support geoconstruction technologies are also shown on this page. Proprietary or for-profit links were not considered for inclusion. Users wishing to suggest additional links can do so with the Submit a Comment form.

About This Website

An About This Website page was developed to provide an introduction to the purpose of the website, which is to disseminate the research results developed for SHRP 2 R02, Geotechnical Solutions for Soil Improvement, Rapid Embankment Construction, and Stabilization of the Pavement Working Platform.

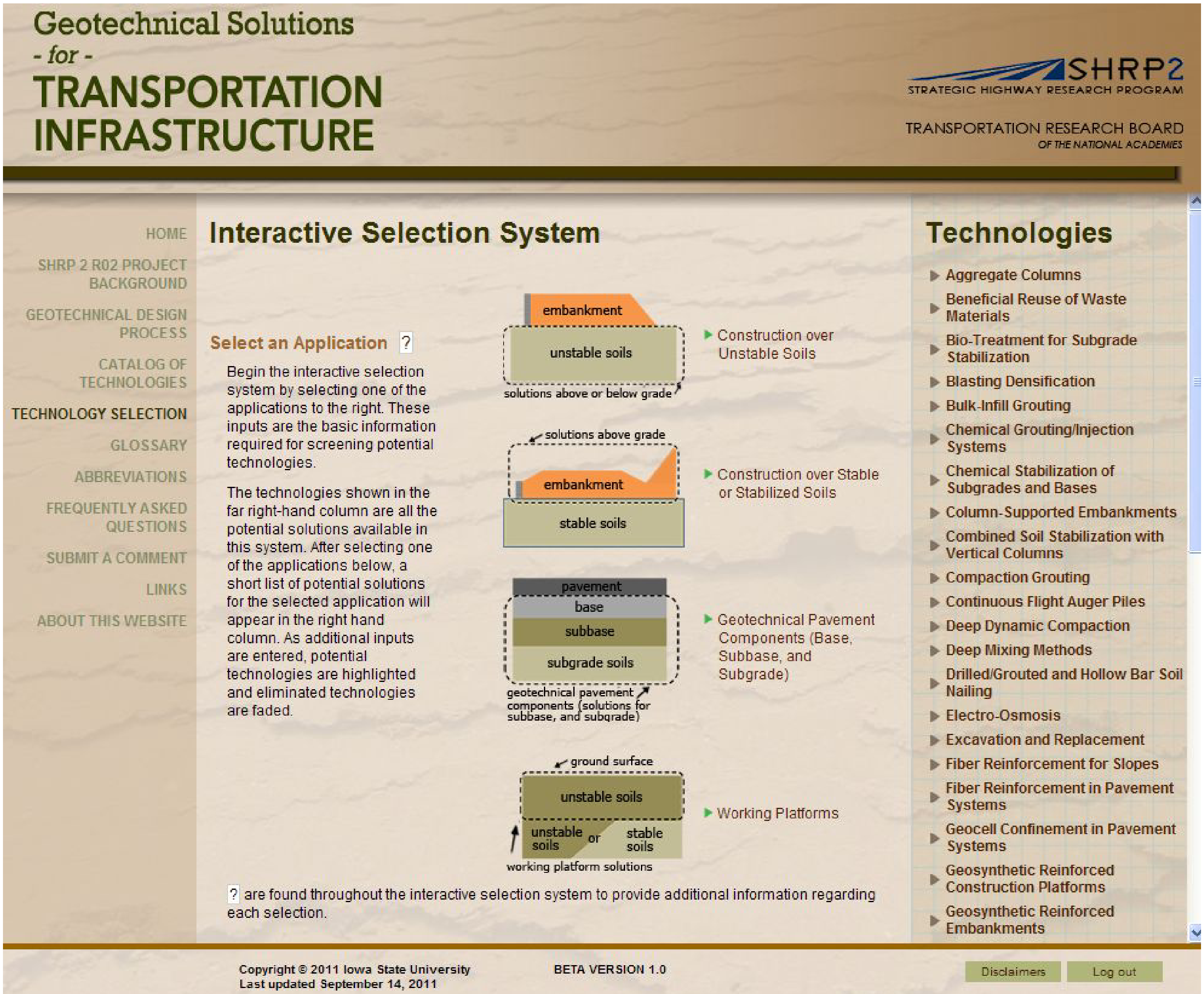


Figure 4.10. Interactive Selection System web page.

Additional Resources

Additional resources are provided throughout the website as hot links in the area(s) where the resources could benefit the user. Three additional resources are described in the following paragraphs.

A User's Guide to the Information and Guidance System was prepared and is included as Appendix A. The User's Guide to the Information and Guidance System provides a brief introduction to the website and examples of how to use the website. The User's Guide to the Information and Guidance System will be available at the website.

A White Paper on Integrated Technologies for Embankments was developed to assist users in identifying possible combinations of geoconstruction technologies, which was required because the selection system leads users only to individual technologies. The White Paper on Integrated Technologies for Embankments will be available throughout the interactive selection system.

A White Paper for Reinforced Soil Slope Facing details was prepared to assist users with implementation of facing options for the reinforced soil slope technology. The White Paper for Reinforced Soil Slope Facing will be available through the Reinforced Soil Slope Technology Information web page.

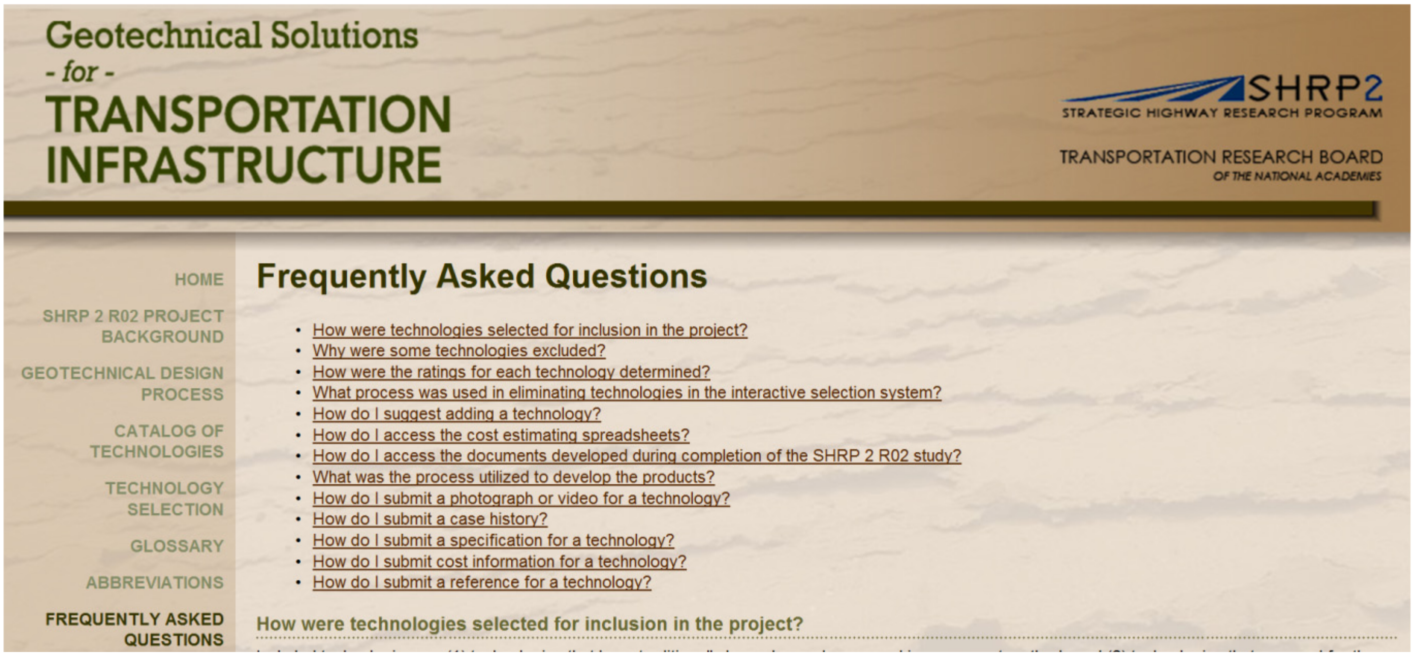


Figure 4.11. Frequently Asked Questions web page.

CHAPTER 5

Interactive Selection System

Introduction

An interactive selection system was developed to aid the user in identifying potential geoconstruction technologies for a user-defined set of project conditions. The interactive selection system is a qualitative tool to assist the engineer in completing a project-specific quantitative analysis and comparison of potential technologies. Quick solutions in geotechnical engineering are generally not found, and this system does not shortcut the proper formulation of a problem and assess the alternatives. This system does assist the user in identifying and sorting possible alternatives or geoconstruction technologies. The comparison and final selection of the geoconstruction technology(s) will require judgment of an experienced engineer on a project-by-project basis.

The scope of the interactive selection system is limited to technologies applicable to one or more of the three elements of the project: new embankment and roadway construction over unstable soils, roadway and embankment widening, and stabilization of pavement working platforms. The system was initially developed along the lines of these three elements. However, the final system was developed for four transportation applications, as noted under the first item in the following list. The objectives of this interactive selection system are:

- Identify potential technologies for design and construction for the following transportation applications:
  - Construction over unstable soils
  - Construction over stable or stabilized soils
  - Geotechnical pavement components (base, subbase, and subgrade)
  - Working platforms.
- Provide assistance to develop a short list of applicable technologies.
- Provide guidance for detailed project-specific screening of technologies with consideration of SHRP 2 R02 objectives.
- Provide an interactive, programmed system.
- Provide current, up-to-date information in technology products and tools.

The interactive selection system is represented in hard copy form through a series of flowcharts and tables. The flowchart layout allows user-defined inputs, which lead to a series of tables. At points along the system, tables are listed that identify potential technologies. Thus, the "knowledge" of the appropriate technologies is contained in the tables and the "reasoning" or inference engine is formed through the user inputs, as outlined in the flowcharts. The method of flowcharts and tables facilitated the programming of a rule-based, automated system.

The interactive selection system is a knowledge-based system. The simplest knowledge-based systems have two modules: the knowledge base and the inference engine (Hopgood, 1993). The knowledge base is contained in the tables and the inference engine is shown graphically through flowcharts.

Strategies for Development

To support the goals and objectives of the R02 project, strategies for development of the selection procedure were established. The system was developed with input from the advisory panel, outside experts, and SHRP 2. Meetings were conducted throughout the project to bring together state agency transportation personnel; practitioners; contractors; and academics who work with the relevant geotechnical materials, systems, and technology areas. The following guiding principles were established as a result of these meetings for the development of the selection system:

- The procedure should be simple.
- The process used for decision making should be transparent.
- The system will conservatively remove potential technologies.

- The system will lead the user to a list of potential, unranked technologies.
- The final selection of the appropriate technology will be the responsibility of the user.
- The knowledge for potentially applicable technologies comes from the comprehensive technology summaries and Task 10 documents. The knowledge was supplemented with expert input from the project team and advisory board.

The Knowledge

"The most important process in a knowledge-based system is knowledge acquisition. How the knowledge is obtained and where it is obtained determines the usefulness of the system" (Fredlund et al., 1996). Knowledge for identifying potentially applicable technologies to a set of geotechnical and loading conditions (the selection system) comes from two sources: from the result of the research team's work products and from experts on the research team and advisory board.

Research Team Work Products

The research team's work efforts included the development of comprehensive technology summaries (CTSs), design method assessments, and quality control and quality assurance (QC/QA) procedure assessments for each of the technologies listed under SHRP 2 R02 Project Background in Chapter 1. CTS development entailed an in-depth technology overview that included advantages, potential disadvantages, applicable soil types, depth/height limits, groundwater conditions, material properties, project-specific constraints, equipment needs, and environmental considerations. Additionally, for each technology, case histories, design procedures, QC/QA procedures, and specifications were collected. The assessment efforts then quantitatively and qualitatively assessed the current design methods and QC/QA procedures.

The development of these CTS and assessment documents provided significant technical information related to each technology and the application of that technology with regard to geotechnical and loading conditions. FHWA manuals and guidance documents were identified in the CTS and assessment work efforts. These sources and other available information on the technologies were incorporated into the work products.

Expert Input from Research Team and Advisory Board

After developing the selection system, comprised of flowcharts and tables, the system was reviewed by the research team and advisory board members to obtain their expert input as to the applicability of certain technologies to certain conditions. Research team members had multiple opportunities to comment on the selection system. The advisory board had one opportunity to comment on the selection system on November 9, 2010. (The advisory board members are part of the proposed beta testing group, and will have an additional opportunity to comment then.) Comments from both the research team and advisory board have been tracked through the use of comment logs, which include the action taken on the comments.

Elimination of Technologies

In describing the process of the elimination of technologies during the selection procedure, the selection system should be considered a heuristic program. Intuition, experience, and judgment can be used to develop heuristic rules (Ignizio, 1991). Heuristics such as "Do you know a related problem?" require the recollection of previous projects (Baron, 1988). These recollections from the experts were used to form the knowledge base for the selection system. Chameau and Santamarina (1989) found that a geotechnical expert's comprehension of a problem is affected by a large number of factors, including those that are case-specific, context-dependent, and subjective. Geotechnical experts make decisions based upon the recollection of previous cases, which is relevant in geotechnical engineering where an emphasis is placed on experience (Chameau and Santamarina, 1989).

An acceptable solution(s) is generally sought, rather than the optimal solution. Heuristic programs are used to identify acceptable solutions. A general characteristic of many heuristics is the focus on screening, filtering, or pruning (Ignizio, 1991). Heuristics can be used to reduce the number of alternatives that are considered. An expert typically learns through time and experience which solutions tend to work well and which solutions tend to work poorly. Thus, even though it is possible that a better solution might be missed, the apparently less-attractive solutions are eliminated in the selection process (Ignizio, 1991). The crux of viewing the selection system as a heuristic program is that the solution(s) identified as a result of using the selection system may or may not be the best or optimal solution. The best or optimal solution requires consideration of both technical and nontechnical project issues and constraints.

In recognition of the ultimate responsibility for final technology selection resting with the user, the following disclaimer was developed for the selection system:

> The application of this selection system is the responsibility of the user. It is imperative that the responsible engineer understand the potential accuracy limitations of the program results, independently cross checks those results with other methods, and examines the reasonableness of the results with engineering knowledge and experience.

The research team, advisory board, and other stakeholders supported the development of a system that does not define the "best" or "most applicable" geotechnical technology or technologies for a particular set of input parameters, but rather provides a short list of potential technologies. Then the system leads the user to the catalog of technologies to provide the information for the user to complete a project-specific analysis.

Fuzzy logic and probability theory were considered for use in the development of the interactive selection system. However, a simpler rule-based system was chosen for the interactive selection system to allow the system to be used by a wide range of technical and nontechnical users.

Initial Inputs into Selection System

As noted, the system was initially developed along the three R02 elements. A list of potential questions was generated initially and shown as follows as an indication of all the factors that may influence the selection of a geoconstruction technology.

- What type of project is being constructed?
- What is the size of the area needing improvement?
- Are there any project constraints to be considered in selecting a possible technology?
- What is the soil type that needs to be improved?
- To what depth do to the unstable soils extend?
- At what depth do the unstable soils start?
- Is there a "crust" at the ground surface?
- What is the depth to the water table?
- How much does the water table fluctuate?
- What is the desired improvement? (i.e., decrease settlement, decrease construction time, or increase bearing capacity)
- With what technologies does the user already have experience?
- What is the geologic setting of the project?

As the project progressed, other potential, nontechnical queries were also identified, such as:

- Experience with geoconstruction technology?
- Experienced contractors available in project area?
- What materials are available for use on the project?
- What is the schedule?

Many meetings and discussions were held to discuss the first few steps of the interactive selection system. From these meetings, the initial input into the system will be through the selection of one of the four applications shown in Figure 5.1. Each application resulted in a unique set of inputs. A separate selection procedure has been developed for each application.

Application 1, Construction over Unstable Soils, leads to a decision process for foundation soil improvement, reinforcement of the embankment, or reduction in load. Application 1

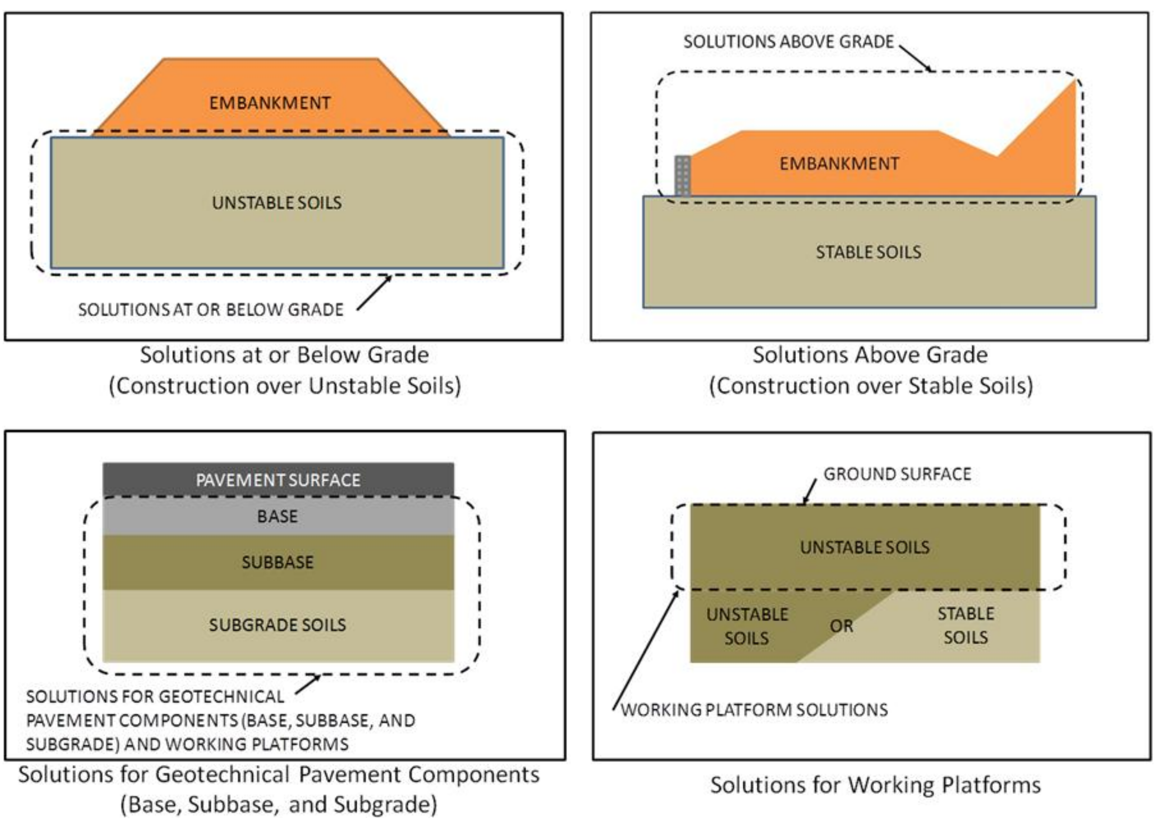


Figure 5.1. Illustration of four application areas for technologies.

includes ground improvement technologies to support embankments of any height over unstable soils. Application 2, Construction over Stable or Stabilized Soils, leads to a decision process for construction over stable or stabilized soils. Application 2 is focused on topics pertaining to embankment construction. Application 3, Geotechnical Pavement Components, leads to a decision process for improving materials directly supporting the surface pavement. Application 4, Working Platforms, leads to technologies that can provide working platforms.

Interactive Selection System

The system operates in a step-by-step process through the answers to preset questions. The system was intentionally developed such that users must be able to answer the current question before proceeding to the next question. The initial questions and order of the questions along each application represent the minimum information required to sort the geoconstruction technologies. Examples of using the selection system are provided in Appendix A, User's Guide to the Information and Guidance System.

To begin the interactive selection system, the user selects one of the four application areas, as illustrated in Figure 5.2. In the selection system, the list of potentially applicable technologies is shown on the right side of the page (see Figure 5.2), all of which are hot-linked to the respective technology pages. At the start of the selection process, as shown in Figure 5.2, all of the technologies in the system are shown in the right column. Upon selection of an application, the list of technologies in the right column will shorten to just a list of technologies that could potentially be used for that application. As additional decisions

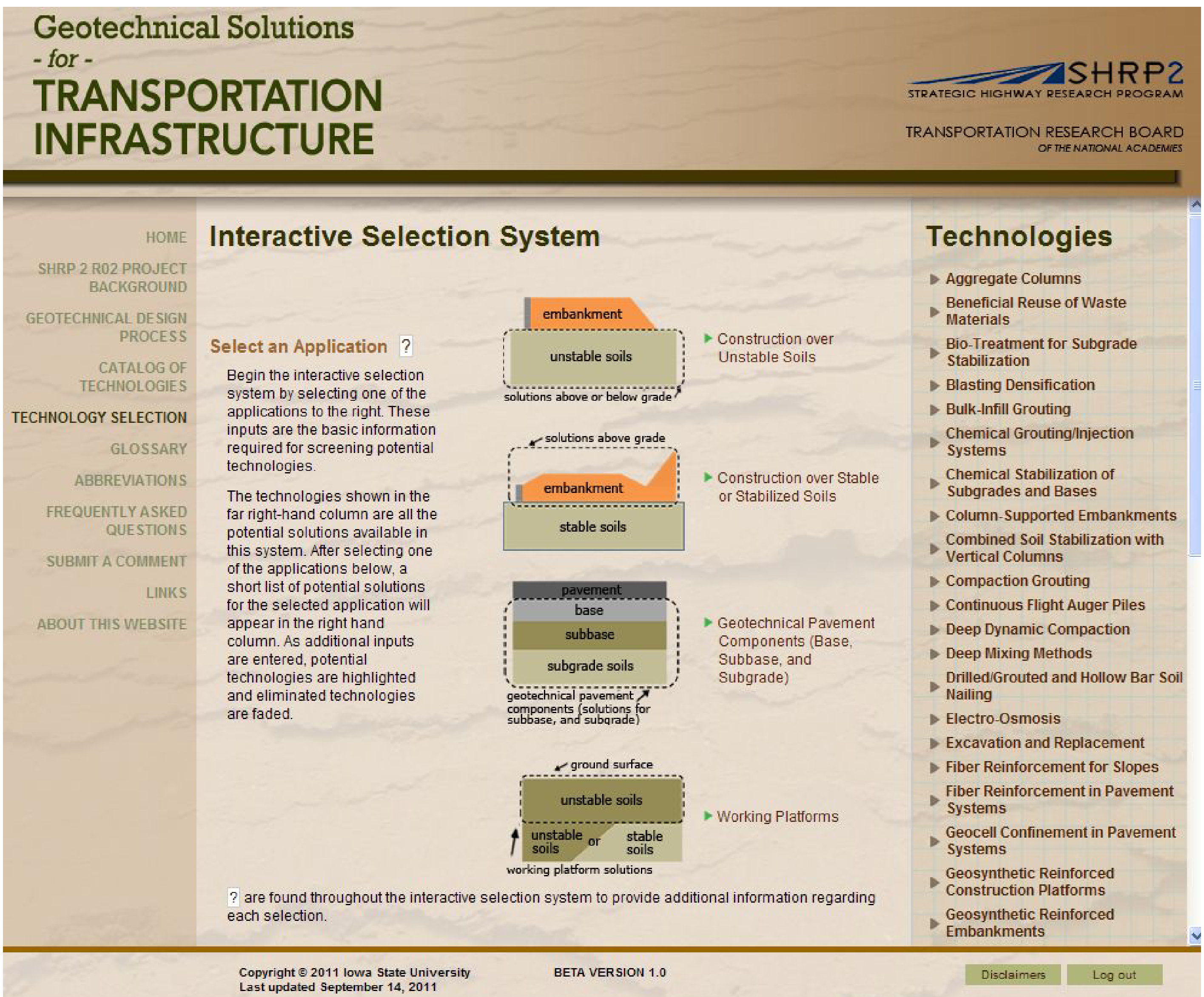


Figure 5.2. Interactive Selection System web page.

are made, nonapplicable technologies are grayed out (fade). Both the remaining technologies and the grayed technologies on the right side are linked to their respective Technology Information web pages.

After completion of the interactive selection system for any of the four applications, the user has the option to select Go to Selection Summary. This will open a new window that lists the user inputs, the potential technologies with the SHRP 2 R02 ratings, and provides a space to enter user-specific information. Within this window, the user will have the option to Create PDF, which generates a PDF documenting the interactive selection system choices. The individual technologies shown as potential technologies within both the Selection System Summary window and the PDF are linked to the individual Technology Information pages on the Information and Guidance System website. A date stamp is automatically generated at the time of PDF generation.

Project-Specific Technology Selection for Construction over Unstable Soils

During project development, many possible queries were developed that provide further sorting of technologies. The flowchart and table system quickly became inefficient with the addition for further selections. To address this, the project-specific technology selection for construction over unstable soils tool was developed. The potential project-specific technology selection inputs include the following:

- Purpose of improvement(s).
- Select project type.
- Site characteristics.
- Size of area to be improved.
- Project constraint(s).
- Select the best description of the construction or implementation schedule.
- Select unstable soil condition that best describes site.
- Are sufficiently thick peat layers present that will affect construction and settlement?
- If unstable fine-grained soils are present, do the unstable soils have a shear strength less than 500 psf?
- Are water-bearing sands present in the soil to be improved?
- Are any subsurface obstructions that would cause drilling difficulty, such as cobbles, boulders, buried tree trunks, or construction debris, present?

This tool queries a large table with no associated flowcharts. This tool is an example of how the interactive selection system can be further refined.

CHAPTER 6

Limitations of the Information and Guidance Website

Understanding the limitations of the Information and Guidance website are critical to its proper implementation and use in practice. Some of the limitations of the information and guidance system include the number of technologies considered in the system, the difficulty in measuring the results of the selection system against the opinion of an experienced geotechnical engineer, and the difficulty of anticipating possible project-specific scenarios, as discussed in more detail in this chapter. This information and guidance system provides tools for engineering of geotechnical solutions. It does not "engineer" solutions, because that must be performed on a project-by-project specific basis.

Information and Guidance System Limitations

At present, the United States lacks a comprehensive, integrated system that provides critical data relating to geoconstruction technologies. The information and guidance system described in this report represents the first significant attempt at developing a useful tool to promote the widespread use of geoconstruction technologies in transportation infrastructure projects. The user must recognize this system is the initial attempt and fully understand and accept the limitations of the system.

Inappropriate Application of System by Inexperienced Personnel

The Geotechnical Solutions for Transportation Infrastructure system is not a "black box" that provides solutions that can be blindly implemented. During the development stage, every review group expressed concern that the potential exists for inexperienced users to inappropriately apply the information provided on the website. The structure and availability of documents were developed with the intent to minimize this potential. For example, many reviewers suggested that the cost-estimating spreadsheets be made available directly on the Technology Information web pages. However, the spreadsheets can only be accessed through the cost information product, which forces the user to access the critical information required to complete a meaningful cost estimate.

The use and application of this system is the responsibility of the user. It is imperative that the responsible user understands the potential accuracy limitations of the program results, independently cross checks those results with other methods, and examines the reasonableness of the results with engineering knowledge and experience.

Limitation recapitulation: The information and guidance system is not a "black box."

Limited Number of Technologies in System

Although a large number of technologies are included, the technologies were limited to the defined scope of the SHRP 2 R02. The information and guidance system summarizes 46 geoconstruction technologies. The system contains two traditional solutions, which are excavation and replacement, and traditional compaction. Other traditional solutions were beyond the scope of the project, such as piles, shafts, sheetpiles, and cast-in-place retaining walls. Additionally, some emerging technologies that could also provide viable solutions for projects in the United States were excluded from the system.

Limitation recapitulation: The information and guidance system contains a limited number of geoconstruction technologies.

Technology-Specific Information

The information provided in the information and guidance system is current as of the time of report and system/website release. During the 3 years that the information and guidance system was being developed, technology-specific information was continually being updated. As emerging technologies become more established, updating of technology-specific information is necessary. One of the primary reasons to provide a web-based system is that is it updatable.

Limitation recapitulation: The information and guidance system information is current as of the date of development (or future update).

Selection System Limitations

The selection system outlined in this report presents the first attempt at an automated, publicly available system to assist in the selection of a geoconstruction technology for transportation applications. The selection system has a unique set of limitations.

Selection System Does Not Replace Engineering Judgment

The selection of an appropriate technology is the responsibility of the user. The users that access the system will have greatly varying degrees of education, experience, and position. Regardless of a user's background, all users must recognize the value of a local, experienced engineer's judgment. The website is not intended to be a "black box" for users. Rather, the website is intended to assist the user in reaching a decision regarding the use of a geoconstruction technology. Marr (2006) developed five "take-home messages" concerning geotechnical engineering and judgment in the information age that should be considered by the users using the information and guidance system.

- Engineering judgment without relevant experience is weak.
- Engineering judgment without relevant data is foolish.
- Good judgment needs good data and evaluated experience.
- Good judgment is essential for the effective use of information technology tools.
- Good judgment is central to geotechnical engineering, even in the information age.

Limitation recapitulation: The information and guidance system does not replace engineering judgment.

Selection System Leads to Single Technologies

The selection system leads the user to a list of unranked, technically feasible geoconstruction technologies. In practice, a combination of geoconstruction technologies may be used. To assist the user in evaluating possible combinations of technologies, a White Paper on Integrated Technologies for Embankments on Unstable Ground was prepared and made available on the website.

Limitation recapitulation: The selection system leads the user to individual geoconstruction technologies, where combinations of technologies may be used on some projects.

Selection System Uncertainty

Although several cycles of review and revision have evaluated the selection system, a certain project may use a geoconstruction technology that the system has eliminated. Considering the wide-ranging geologic conditions across the United States, combined with the wide-ranging project types, there exist solutions to projects outside of the solutions proposed by the selection system. The intent of the system is for the user to use engineering judgment to evaluate the set of candidate technologies. Additionally, the field of geoconstruction technologies is continually evolving with the application of new and existing technologies to a wider range of project conditions.

Limitation recapitulation: Other technically viable solutions may likely exist for a project beyond the list of geoconstruction technologies output by the selection system.

CHAPTER 7

Conclusions and Recommendations

Introduction

A web-based information and guidance system for 46 geoconstruction technologies has been developed as part of the SHRP 2 R02 project. The information and guidance system contains an introduction to the geotechnical design process, catalog of technologies, selection system, and glossary. Detailed information for a geoconstruction technology is found in the catalog where, for each individual technology, the following information can be found: technology fact sheets, photographs, case histories, design guidance, quality control and quality assurance procedures, specification guidance, cost information, and bibliography. A selection system was developed to aid the user in identifying potential geoconstruction technologies for a user-defined set of project conditions. The selection system contains both a listing of the technologies and a dynamic, interactive selection tool. The selection system leads the user to the technical information for each geoconstruction technology.

Experienced engineers will benefit from the design, construction, cost, and specification information provided in the catalog. Less experienced engineers, planners, and owners will benefit from the introductory material for each geoconstruction technology and the technology selection assistance portion of the system to assess the feasibility of technologies to address project requirements and constraints. The information and guidance system will be a valuable tool for engineers, planners, and transportation officials to use when evaluating potential technologies. No system like this existed, either in hard-copy form or automated, before the development of the Geotechnical Solutions for Transportation Infrastructure system. Providing critical path guidance for emerging technologies will decrease the time required for promising solutions to be used in future infrastructure projects.

In concluding this development report, recommendations follow for the public release of the site, final technology selection, and additional research.

Public Release of Site

The Geotechnical Solutions for Transportation Infrastructure system should not be released to general users until beta testing has been completed. Until completion of beta testing, all documents contained within the information and guidance system will carry a DRAFT watermark. The website will be password protected until the completion of beta testing.

Final Technology Selection

Selection of a geoconstruction technology is a major theme throughout this development report and the system. The information and guidance system provides a tool to assist the user in selecting and applying geoconstruction technologies. The selection system guides a user to a short list of unranked, candidate technologies. The information in the catalog provides the material for the completion of a comparable, quantifiable, project-specific analysis. The cost information produced as part of this project is intended to provide the user with a means for understanding what variables may impact the cost of a given geotechnical solution as well as developing a preliminary cost estimate for a given technology on a project-specific basis. There are many factors that can affect cost for a specific project (i.e., soil type, labor rates, and utility conflicts); identifying and understanding how these variables impact 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.

The process used by each user to compare technologies should be completed on a case-by-case method. The research team wants to emphasize that this system does not replace the project geotechnical engineer. The geotechnical engineer's judgment should be the final selection process. The selection process should include: construction cost, maintenance cost, design and QC issues, performance and safety (pavement smoothness, hazards caused by maintenance operations, potential failures), inconvenience (a tangible factor, especially for heavily traveled roadways or long detours), environmental aspects, and aesthetic aspects (appearance of completed work with respect to its surroundings) (Holtz, 1989). Alternatively, Raju (2010) indicated the choice of technique that should consider the suitability of method, technical compliance, availability of QC/QA methods, availability of material, time, cost, convenience, and protection of the environment.

Recommendations for Additional Research

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 that could be added to the system to provide complete one-stop shopping for geotechnical solutions for transportation infrastructure.

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APPENDIX A

User's Guide to the Information and Guidance System

Introduction

The Geotechnical Solutions for Transportation Infrastructure system provides a means for transportation engineers, geologists, planners, officials, engineering consultants, and others to access critical information for geoconstruction technologies. The primary value of the web-based information and guidance system is that it collects, synthesizes, integrates, and organizes a vast amount of critically important information about geoconstruction technologies in a system that makes the information readily accessible to the transportation agency personnel who need it most. The homepage is shown in Figure A.1. The system was developed with the intent that both nontechnical and technical personnel would use the system, albeit at different levels. This user's guide provides a brief introduction to the system and some examples of how different users can use the available tools. Users wanting detailed information are referred to the second Strategic Highway Research Renewal Project R02 (SHRP 2 R02) project reports, which describe the development of the system and available documents.

Responsibilities of the User

The Geotechnical Solutions for Transportation Infrastructure system is not a "black box" that provides solutions that can be blindly implemented. During the development stage, every review group expressed concern that the potential exists for inexperienced users to inappropriately apply the information provided on the website.

The application of this system is the responsibility of the user. It is imperative that the responsible user understands the potential accuracy limitations of the program results, independently cross checks those results with other methods, and examines the reasonableness of the results with engineering knowledge and experience. Marr (2006) developed the following five take-home messages concerning geotechnical engineering and judgment in the information age:

- Engineering judgment without relevant experience is weak.
- Engineering judgment without relevant data is foolish.
- Good judgment needs good data and evaluated experience.
- Good judgment is essential for the effective use of information technology tools.
- Good judgment is central to geotechnical engineering, even in the information age.

Site Disclaimer

The opinions and conclusions expressed or implied on this system are those of the research agency. They are not necessarily those of the Transportation Research Board, the National Academies, or the program sponsors.

This system and the information provided are offered as is, without warranty or promise of support of any kind either expressed or implied. Under no circumstance will the National Academy of Sciences or the Transportation Research Board (collectively, "TRB") or will the R02 project team (individually or universities or firms) (collectively, "project team") be liable for any loss or damage caused by the installation, use, or operation of this product. TRB and the project team make no representation or warranty of any kind, expressed or implied, in fact or in law, including without limitation, the warranty of merchantability or the warranty of fitness for a particular purpose, and shall not in any case be liable for any consequential or special damages.

Technology-Specific Information

The individual technology information is accessed through the Catalog of Technologies through selection of a specific technology, as shown in Figure A.2. The downloadable documents

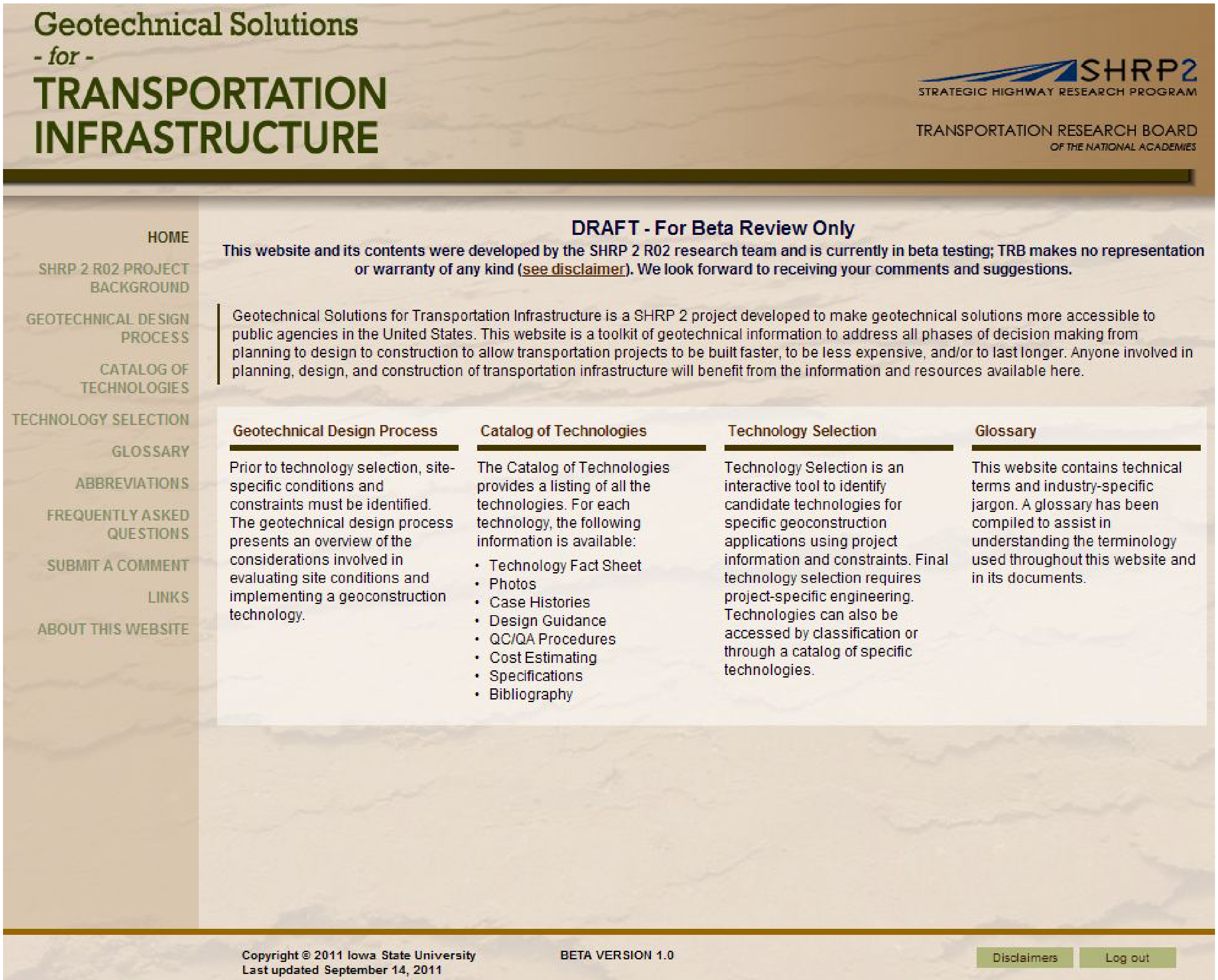

Figure A.1. Geotechnical Solutions for Transportation Infrastructure homepage.

provided on the individual Technology Information web page for each technology provide the mechanism for the user to access technology-specific information. The intent of all the website features surrounding the Catalog of Technologies is to aid the user in understanding the technical information or aid in the selection and application of the technology. An illustration of the structure of the downloadable documents is presented in Figure A.3.

Also included on the Technology Information page are the R02 ratings for each technology. The location of the ratings on the page is circled in red in Figure A.2. Some specific studies were completed for a few technologies, and links to these special studies are provided on this page as well, when appropriate.

Options for Technology Selection Assistance

The Technology Selection page provides the means of accessing technology-specific information through a classification system and through an interactive selection system. A schematic of the technology selection system and its interlink with the Technology Information web pages is illustrated in Figure A.4. The flow of the technology selection system is illustrated in Figure A.5. In the classification system, the technologies are grouped into categories that allow an experienced engineer to access solutions according to a particular category of problems. The interactive selection system provides the user the opportunity to access potential technologies

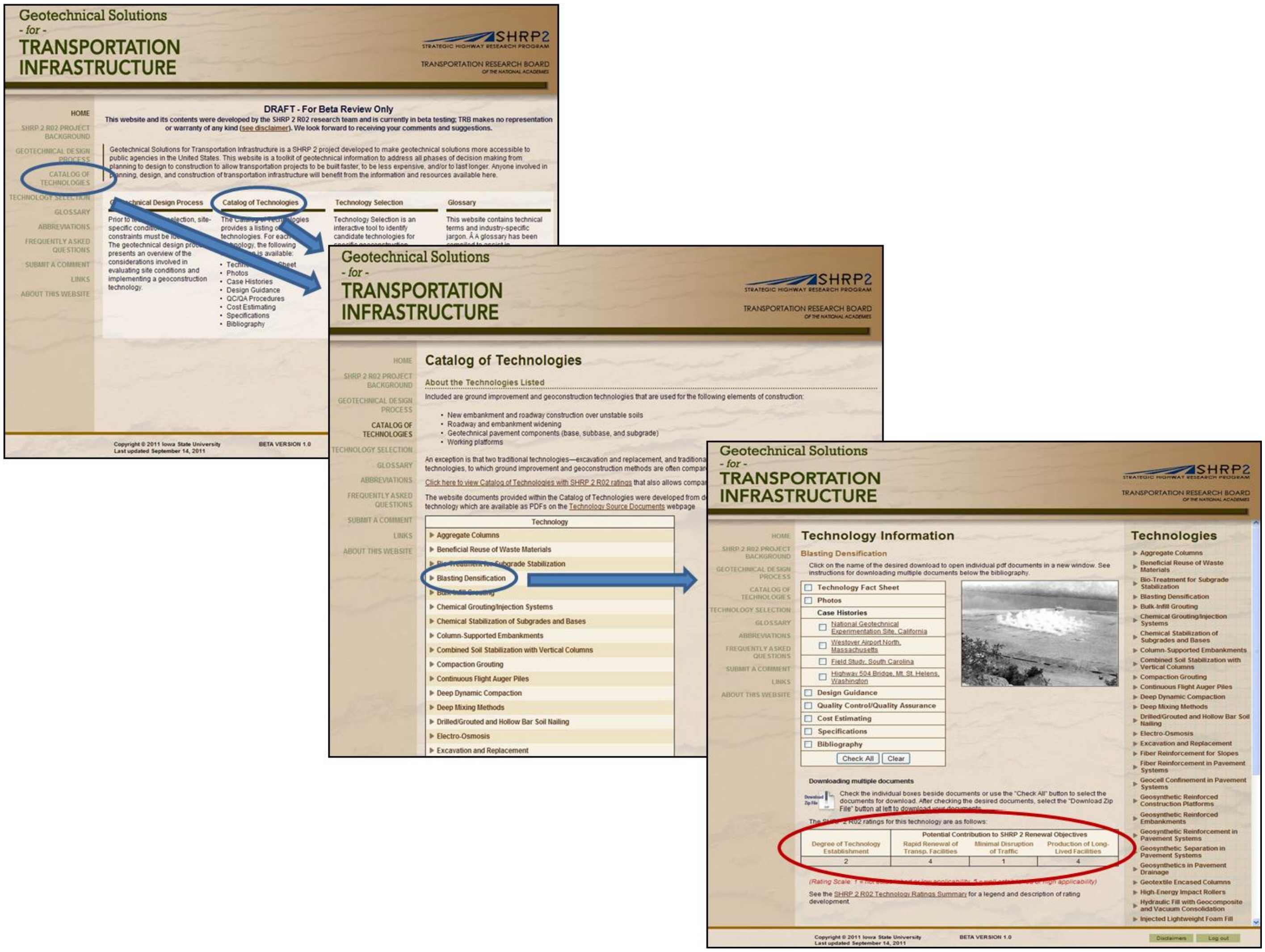

Figure A.2. How to access individual Technology Information page.

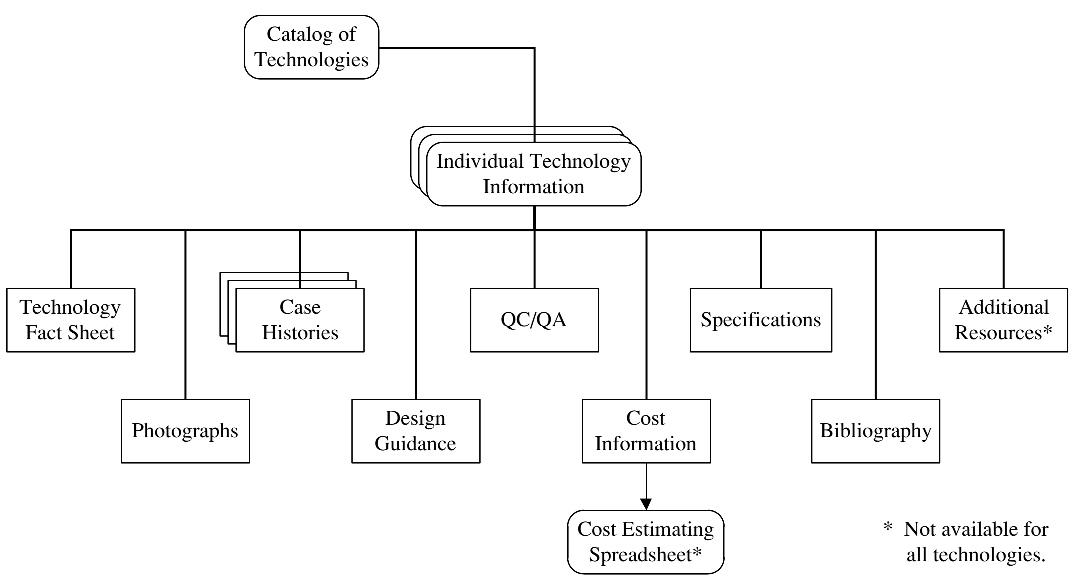

Figure A.3. Concept of individual Technology Information page.

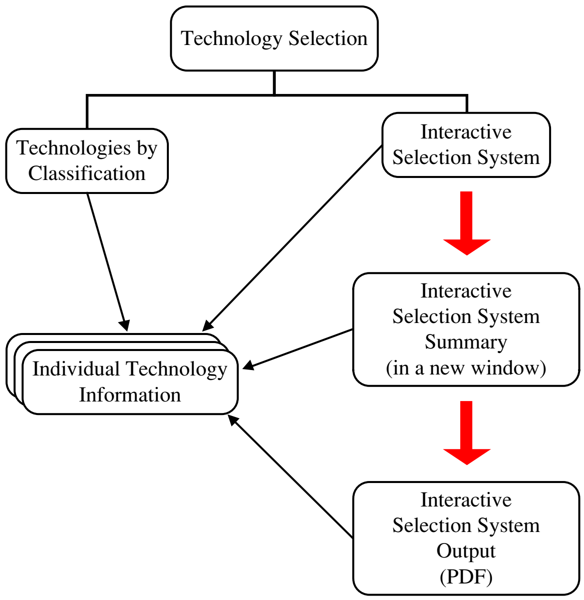

Figure A.4. Conceptual layout of technology selection.

based on several applications. The inner workings of the interactive selection system are described in detail in the R02 project Web-Based Information and Guidance System Development (Douglas et al., 2012).

Decision help notes have been developed for each decision encountered in the interactive selection system. These notes are available on all the Interactive Selection System web pages to assist both experienced and inexperienced users with decisions. On the website, these notes are appropriately placed and are accessed by clicking on a help link that appears as a boxed question mark (?).

After completion of the interactive selection system, the user has the option to select Go to Selection Summary, which opens a new window that documents the user inputs, shows the potential technologies with the SHRP 2 R02 ratings, and provides a space to enter user-specific information. Within this window, the user has the option to Create PDF, which generates a PDF documenting the results of the interactive selection system. The individual technologies within the Selection Summary window and the PDF are linked to the individual technology information for ease of use.

A limitation of the interactive selection system is that only singular technologies appear as potential solutions. To assist the user in identifying possible combinations of technologies for the construction over unstable soils application, a document titled White Paper on Integrated Technologies for Embankments on Unstable Ground was developed and is available for download throughout the selection system, as shown by the red oval in Figure A.5.

Introduction to System Through Examples

To provide a further introduction to the system, several examples have been developed to illustrate both information provided in the system and the use of the website. The examples consider different user backgrounds and a wide range of projects.

Example 1: State Transportation Official Question Regarding Micropiles

Example Intent

Illustrate an example where an upper-level transportation official is requesting additional information to understand a proposed solution.

Project Information

- Application: existing bridge retrofit.
- Project site: existing bridge over river.
- Subsurface conditions
  - Moderately weak, intermixed, sandy, and clayey soils from surface to depth of 40 ft; and
  - Hard clay below 40 ft.
- The State Transportation geotechnical department developed a plan to underpin the existing foundations with micropiles.

Problem

Identify introductory material for micropiles and similar applications by other transportation departments.

Discussion

The Technology Information page for micropiles can be accessed through the Catalog of Technologies and is shown in Figure A.6. The circled area in Figure A.6 highlights the downloadable products that can be used to provide an introduction to the technology. The 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. The photos show the 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), which were preferably conducted in the United States by a state department of transportation (DOT),

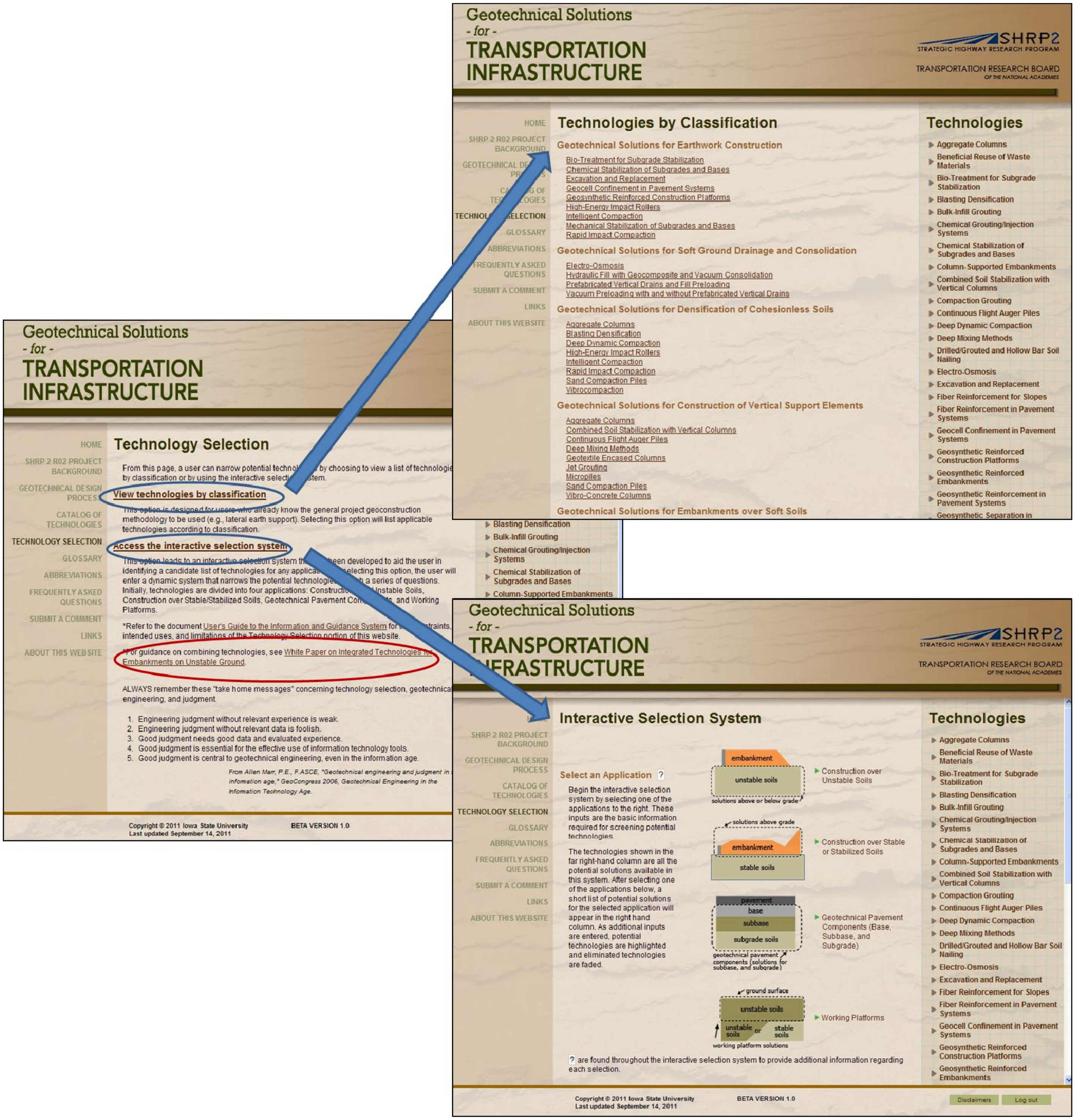

Figure A.5. Technology selection assistance.

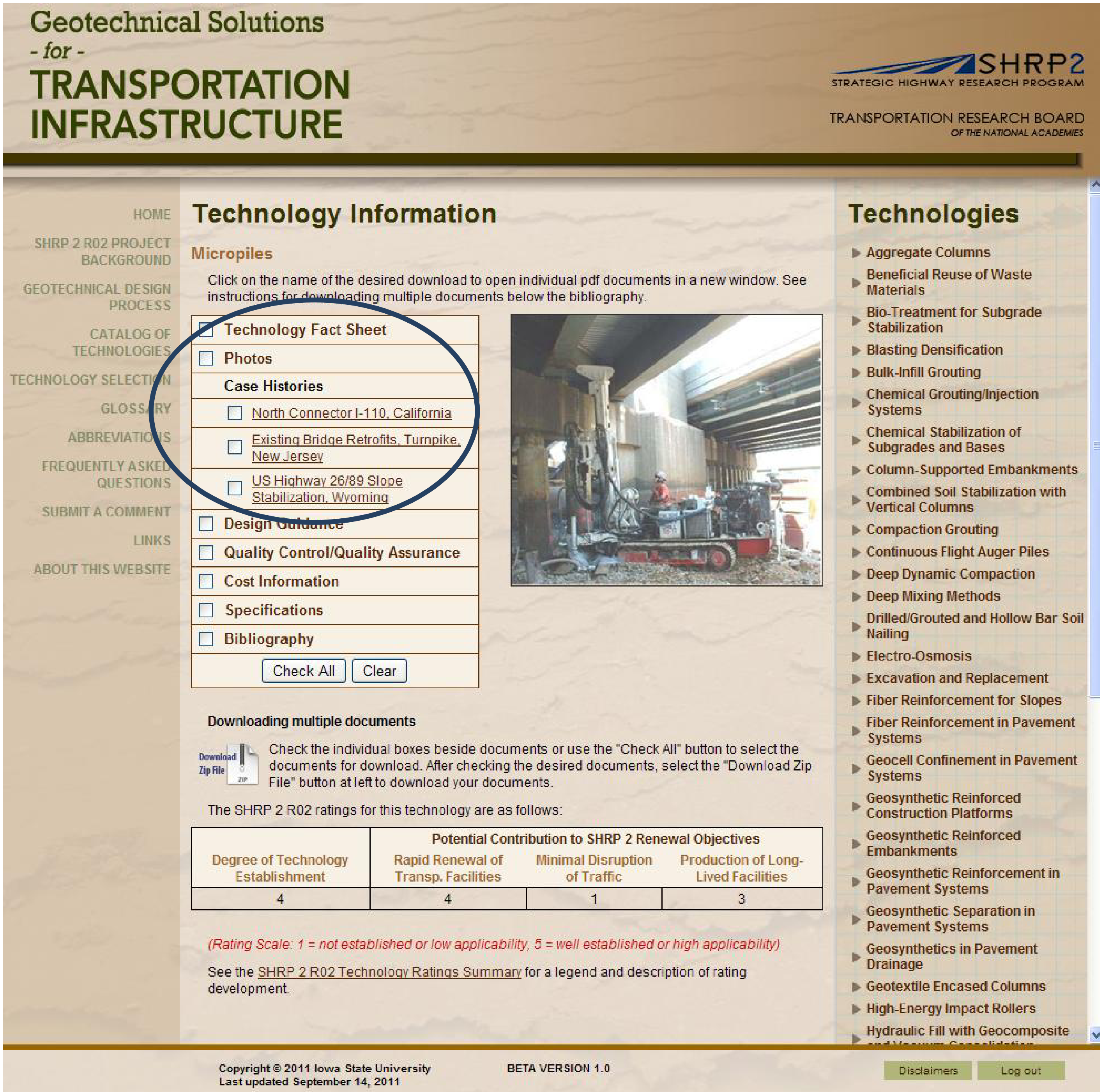

Figure A.6. Technology Information web page for micropiles.

and contain project location, owner, a project summary, performance, and contact information.

Example 2: Experienced DOT Engineer/ Geologist with Known Solution

Example Intent

Illustrate an example where an experienced engineer/geologist has a desired solution and is attempting to locate current technical information for a technology.

Project Information

- Application: new embankment through a swamp.
- Project site: wooded and undeveloped.
- Subsurface conditions
  - Wet and weak clayey soils from surface to depth of 70 ft; and
  - Dense sand below 70 ft.
- Experience, availability of materials, and schedule allow DOT personnel to select geosynthetic reinforced embankment.

Problem

Identify up-to-date information for design, cost estimate, specifications, and quality control and quality assurance (QC/QA).

Discussion

The Technology Information page for geosynthetic reinforced embankments can be accessed through the Catalog of Technologies and is shown in Figure A.7. The circled area in Figure A.6 highlights the downloadable products that can be used to provide the technical information for the technology. The design guidance and QC/QA documents provide a summary of recommended procedures for the technology. Cost information provides an explanation of the cost item specific to the technology, generally emanating from the pay methods contained in specifications. Available regional and cost numbers, generally from DOT bid tabs or national data bases, are compiled for each technology. A second cost document consists of an Excel spreadsheet developed to estimate costs for the use of the technology and can only be accessed as a link through the cost information document. The user can modify the spreadsheet to estimate specific project cost based on either a preliminary or final design. The spreadsheet identifies pay items by line and serves to assist an estimator for overlooking a particular pay item for a technology. A specifications document is provided for each technology and offers a summary of example specifications identified during the project. Guide specifications are provided for each technology as a PDF file, if available.

Example 3: Densification of Liquefiable Granular Soil

Example Intent

Illustrate options in the system to assist a user in identifying potential technologies to mitigate liquefiable granular soils.

Project Information

- Application: bridge approach embankment.
- Project site
  - Open and undeveloped; and
  - Total area = 30,000 ft^2.
- Subsurface conditions
  - Saturated, loose sand from surface to depth of 25 ft; and
  - Dense sand below 25 ft.
- Factors of safety adequate under static loading.
- Potential liquefaction of loose sand is a concern.

Problem

Identify potential technologies to mitigate liquefiable granular soils.

Discussion

Two options exist to identify potential technologies for this example. A listing of potential technologies can be found in Technologies by Classification, as depicted in Figure A.8. A more refined listing of potential technologies can be developed with the interactive selection system and user-input project-specific information, shown in Figure A.9. In Figure A.9, the lower right illustration is the result of a new window being opened after selecting Go to Selection Summary at the end of the Interactive Selection System. From this new window, a PDF can be generated with a user name, organization, and project name to provide documentation of the system results. Additionally, in Figure A.9, the lower right illustration shows the Project-Specific Technology Selection for Construction over Unstable Soils. This project-specific selection system is intended for experienced users and was developed only for the fine-grained and granular soil conditions within the construction over unstable soils application.

Example 4: Embankment on Soft Clay

Example Intent

Illustrate comparison of technologies for a project.

Figure A.7. Technology Information web page for geosynthetic reinforced embankments.

Figure A.8. Technologies by Classification for mitigating liquefiable granular soils.

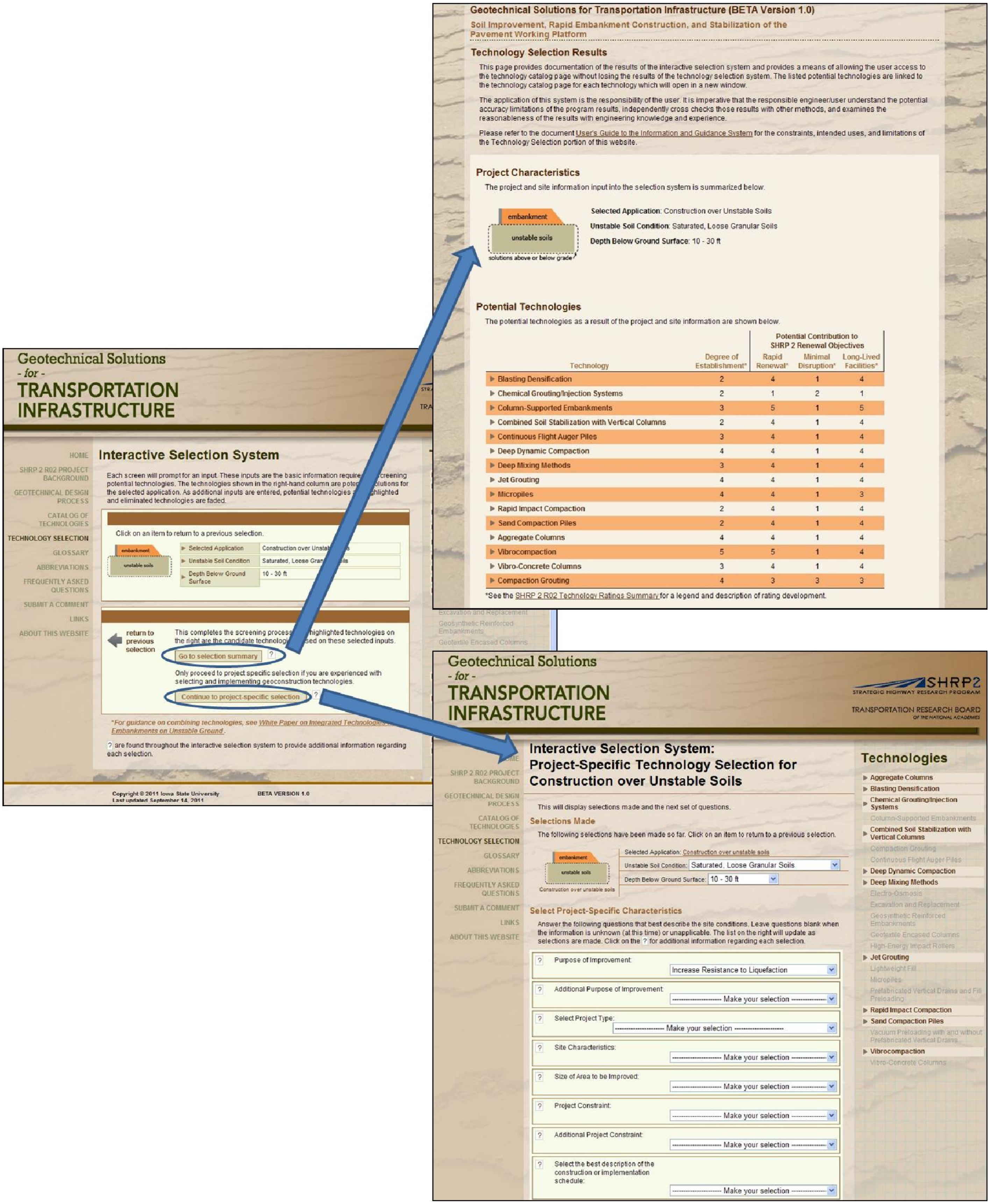

Figure A.9. Interactive Selection System for mitigating liquefiable granular soils.

Project Information

- Application: bridge approach embankment.
- Embankment requirements
  - Length = 1,000 ft;
  - Height = 20 ft;
  - Width at crest = 50 ft; and
  - Width at base = 130 ft (2H:1V side slopes).
- Subsurface conditions
  - Soft clay layer from subgrade to depth of 45 ft; and
  - Dense sand at depth 45 ft.
- Global stability and settlement are concerns.

Problem

Compare potential technologies identified through the selection system.

Discussion

Through completion of the interactive selection system, the selection summary presented in Figure A.10 was developed. The project-specific selection system could also have been used for further refinement. From the list of potential technologies, the following four technologies were selected for further evaluation: aggregate columns, column-supported embankments, geosynthetic reinforced embankments, and prefabricated vertical drains and fill preloading. After completing a preliminary design for each technology, a cost estimate can be prepared to compare the technologies, or SHRP 2 Renewal ratings can be compared, as applicable.

The process of getting to the cost estimate tool is presented in Figure A.11. The tool can only be accessed through the cost information document available on the Technology Information web page. The cost information document contains critical information required to complete a representative cost estimate for a technology. A preliminary design must be completed to develop a preliminary cost estimate.

For this example and not included with this guide, a preliminary cost estimate was completed for each of the four technologies selected for further evaluation. The results of the cost analysis and other information gathered from the available documents enabled the development of Table A.1. The comparison shown in Table A.1 is provided as an example only; the system does not produce this table. A project-specific design and comparison of technologies is required to complete a comparison, and other factors can be incorporated into the comparison as appropriate.

The cost information produced as a part of this project is intended to provide the user with a means for understanding what variables may impact the cost of a given geotechnical solution, as well as for developing a preliminary cost estimate for a given technology on a project-specific basis. There are many factors that can affect cost for a specific project (i.e., soil type, labor rates, utility conflicts); identifying and understanding how these variables impact cost can be beneficial when evaluating the applicability of a geotechnical solution. It is important to note that while 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 geoconstruction technologies.

Comments on Selection of Final Technology

The selection system guides a user to a short list of unranked, candidate technologies. Guidance for the completion of a comparable, quantifiable analysis to aid the user in the final selection remains to be developed. However, the information provided for each technology will allow the user to complete a preliminary design and subsequently compare technologies. The final selection of the geoconstruction technology to use is the responsibility of the user.

Holtz (1989) indicated that each of the following elements must be carefully examined when selecting a geoconstruction technology:

- Construction cost
- Maintenance cost
- Performance and safety (pavement smoothness; hazards caused by maintenance operations; potential failures)
- Inconvenience (a tangible factor, especially for heavily traveled roadways or long detours)
- Environmental aspects
- Aesthetic aspects (appearance of completed work with respect to its surrounding)

References

Douglas, S. C., V. R. Schaefer, and R. R. Berg. 2012. *SHRP 2 Report R02: Web-Based Information and Guidance System Development Report,* prepared for The Strategic Highway Research Program 2, Transportation Research Board of the National Academies, Washington, D.C.

Holtz, R. D. 1989. *NCHRP Synthesis of Highway Practice 147: Treatment of Problem Foundations for Highway Embankments.* TRB, National Research Council, Washington, D.C.

Marr, W. A. 2006. Geotechnical Engineering and Judgment in the Information Age. In Proc. *GeoCongress 2006: Geotechnical Engineering in the Information Technology Age,* Feb. 26–March 1, ASCE, Reston, Va., pp. 1–17.

Geotechnical Solutions for Transportation Infrastructure (BETA Version 1.0)

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

Technology Selection Results

This page provides documentation of the results of the interactive selection system and provides a means of allowing the user access to the technology catalog page without losing the results of the technology selection system. The listed potential technologies are linked to the technology catalog page for each technology which will open in a new window.

The application of this system is the responsibility of the user. It is imperative that the responsible engineer/user understand the potential accuracy limitations of the program results, independently cross checks those results with other methods, and examines the reasonableness of the results with engineering knowledge and experience.

Please refer to the document User's Guide to the Information and Guidance System for the constraints, intended uses, and limitations of the Technology Selection portion of this website.

Project Characteristics

The project and site information input into the selection system is summarized below.

Selected Application: Construction over Unstable Soils

Unstable Soil Condition: Unsaturated and Saturated, Fine Grained Soil

Depth Below Ground Surface: 30 - 50 ft

Potential Technologies

The potential technologies as a result of the project and site information are shown below.

Technology	Degree of Establishment*	Potential Contribution to SHRP 2 Renewal Objectives: Rapid Renewal*	Minimal Disruption*	Long-Lived Facilities*
▶ Column-Supported Embankments	3	5	1	5
▶ Combined Soil Stabilization with Vertical Columns	2	4	1	4
▶ Continuous Flight Auger Piles	3	4	1	4
▶ Deep Mixing Methods	3	4	1	4
▶ Geosynthetic Reinforced Embankments	5	4	2	3
▶ Geotextile Encased Columns	2	3	1	3
▶ Jet Grouting	4	4	1	4
▶ Lightweight Fill	5	5	3	3
▶ Micropiles	4	4	1	3
▶ Prefabricated Vertical Drains and Fill Preloading	5	2	1	4
▶ Sand Compaction Piles	2	4	1	4
▶ Aggregate Columns	4	4	1	4
▶ Vacuum Preloading with and without Prefabricated Vertical Drains	2	3	1	4
▶ Vibro-Concrete Columns	3	4	1	4

*See the SHRP 2 R02 Technology Ratings Summary for a legend and description of rating development.

Figure A.10. Interactive selection system summary for Example 4.

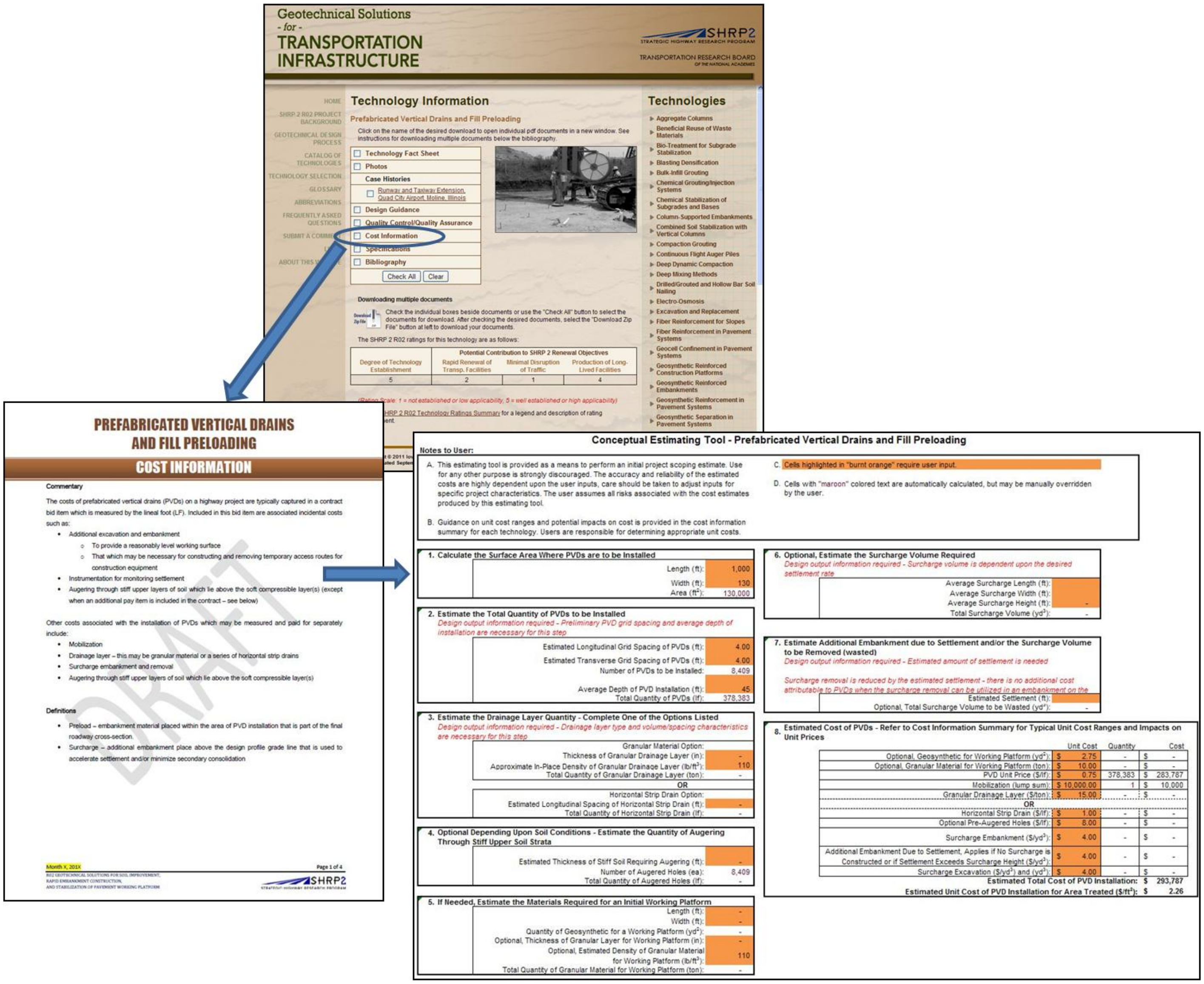

Figure A.11. Process of getting to conceptual estimating tool.

Table A.1. Example Comparison of Geoconstruction Technologies

Technology	Cost Estimate	Time Delay	Total Settlement	Other Considerations
Aggregate columns (stone columns)	$5.0M	Less than 0.5 yr	30% to 40% of total settlement for unimproved case	Risk of insufficient lateral confinement if soil is too soft, instrumentation and monitoring may be required.
Column-supported embankments	$3.5M	None	Less than 3 in.	Instrumentation and monitoring may be useful, minimizes damage to adjacent facilities, higher performance achievable.
Geosynthetic reinforced embankments	$286K	Years without PVDs	No reduction in total settlement over unimproved case	Instrumentation required, risk of additional settlement if soil is softer than expected, staged construction possibly required.
Prefabricated vertical drains (PVDs) and fill preloading	$294K	0.5 to 1 yr	Low settlements after 0.5 to 1 yr	Secondary compression settlements.

Related SHRP 2 Research

Innovative Bridge Designs for Rapid Renewal (R04)
Precast Concrete Pavement Technology (R05)
Performance Specifications for Rapid Highway Renewal (R07)
Process of Managing Risk on Rapid Renewal Projects (R09)
Project Management Strategies for Complex Projects (R10)
Using Existing Pavement in Place and Achieving Long Life (R23)