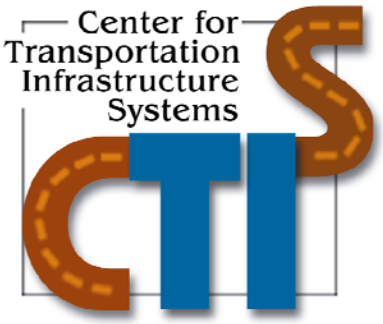

Expert System for Pavement Remediation Strategies (ExSPRS) User's Manual

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Conducted for:
Texas Department of Transportation

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Center for Transportation Infrastructure Systems
The University of Texas at El Paso
El Paso, TX 79968
(915) 747-6925
http://ctis.utep.edu

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by

Yaqi Wanyan, MSCE
Enrique Portillo,
Imad Abdallah, MSCE
and
Soheil Nazarian, PhD, PE

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Yaqi Wanyan, MSCE
Enrique Portillo,
Imad Abdallah, MSCE
Soheil Nazarian, PhD, PE (66495)

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CHAPTER 1 - INTRODUCTION

Rural, low-volume, farm-to-market access roads, roads connecting communities, and roads for logging or mining are commonly referred as low-volume roads. Low-volume roads commonly have an average daily traffic (ADT) of less than 400 vehicles per day, and usually have design speeds less than 50 mph (80 kph) (AASHTO, 2002).

This research project was focused on low-volume roads over expansive clayey soils in Texas. In spite of the over conservative pavement designs recommended and widely used in Texas for roads in high PI clay areas, these costly pavements often fail prematurely. This failure occurs primarily because of the highly variable properties of the clay throughout the year due to moisture fluctuations. A significant amount of work is required to maintain and rehabilitate these roads. The expansive nature of high PI clays, despite the fact that they are considered in the design, is also of concern since they contribute to the roughness of the road, and as such the loss of the functional serviceability of the roads. Therefore, it is imperative to improve the design and laboratory procedures to address expansive subsoil conditions and then design pavements accordingly to extend the life expectancy of these roads. The intent of this research project was to cultivate the vital features of strategies for improving low-volume flexible pavement design and thus improving the overall low-volume road performance. These include:

1). Identify the shortcomings of current design and construction practices associated with the less than desirable performance of pavements in low-volume roads constructed on high PI clays;
2). Identify the most significant soil parameters directly related to the performance of these types of roads;
3). Propose practical and dependable laboratory test methods and analyzing models to address the problem of premature failure of low-volume roads on high PI expansive subgrade;
4). Qualify and quantify current remediation procedures, climatic effects and road condition assessment (both successful and unsuccessful) used to mitigate the shrink-swell problems;
5). Develop a user-friendly expert system design tool to guide the designers through the process for more realistic designs and rehabilitations.

The results from this study offered a new design procedure that provides the following information:

- Identify most relevant soil properties and corresponding test procedures to characterize and address highly expansive subgrade problems;
- Propose quantitative analyzing models to predict flexible pavements failure on expansive subgrade, specifically for low-volume roads;
- Create an interactive expert system program to guide the user through design procedures and provide realistic layer thicknesses for low volume roads;
- Rank feasible design alternatives for rehabilitation and maintenance to minimize the cost without compromise performance.

The design guideline for low classification roads over high PI clays developed to address the issues summarized above is referred to as Expert System for Pavement Remediation Strategies (ExSPRS). This program can be used to evaluate the structural and performance adequacy of low-volume flexible pavement designs and to achieve cost-effective designs with appropriate modifications. The program mimics human expert decision making process for this purpose. Finally, cost-benefit comparisons are made between possible alternative modifications based on modified inputs for each strategy. The goal is to help pavement engineers to design low-volume roads that avoid costly over-designed yet underperforming roads over expansive subgrade.

This document provides a user's guide to Version 1.0 of ExSPRS. Although the focus of this research is for Texas, the new design guidelines will be helpful to other states with similar problems. It is highly recommended to review research report 0-5430-1 and 2 before going any further and using this program. The report provides a solid foundation regarding the theory, models and processes used to develop this program.

1.1 - SYSTEM REQUIREMENT AND INSTALLATION

The program will work on a typical computer with Windows 9x, 2000, XP, Vista or NT operating system. To install the program, execute the setup file ***ExSPRS.EXE*** and follow the onscreen instructions. After installation, double click on the program icon on your desktop to execute the program.

1.2 - DESCRIPTION OF PROGRAM

The **Ex**pert **S**ystem for **P**avement **R**emediation **S**trategies (ExSPRS) program has four main modules: Input, Evaluation, Remediation and Cost-Benefit. Figure 1.1 shows the flowchart of the program. ExSPRS uses an expert system approach which manages and incorporates concepts derived from our study and uses structured knowledge to provide analysis to the user as an expert would do. This program is specially developed for low-volume roads build over expansive clayey subgrade.

The user needs to provide an initial pavement structure as an input. This pavement structure can be obtained using common design software such as FPS19W. ExSPRS will check the candidate pavement structure for several potential structural or functional distresses using its evaluation models. If the input section experience premature distress, ExSPRS will use the expert system approach to recommend feasible remediation strategies. Based on the remediation selected, the modified pavement structure is re-evaluated. The cost-benefit analysis module will provide the agency cost estimation of the original pavement section along with the additional agency costs

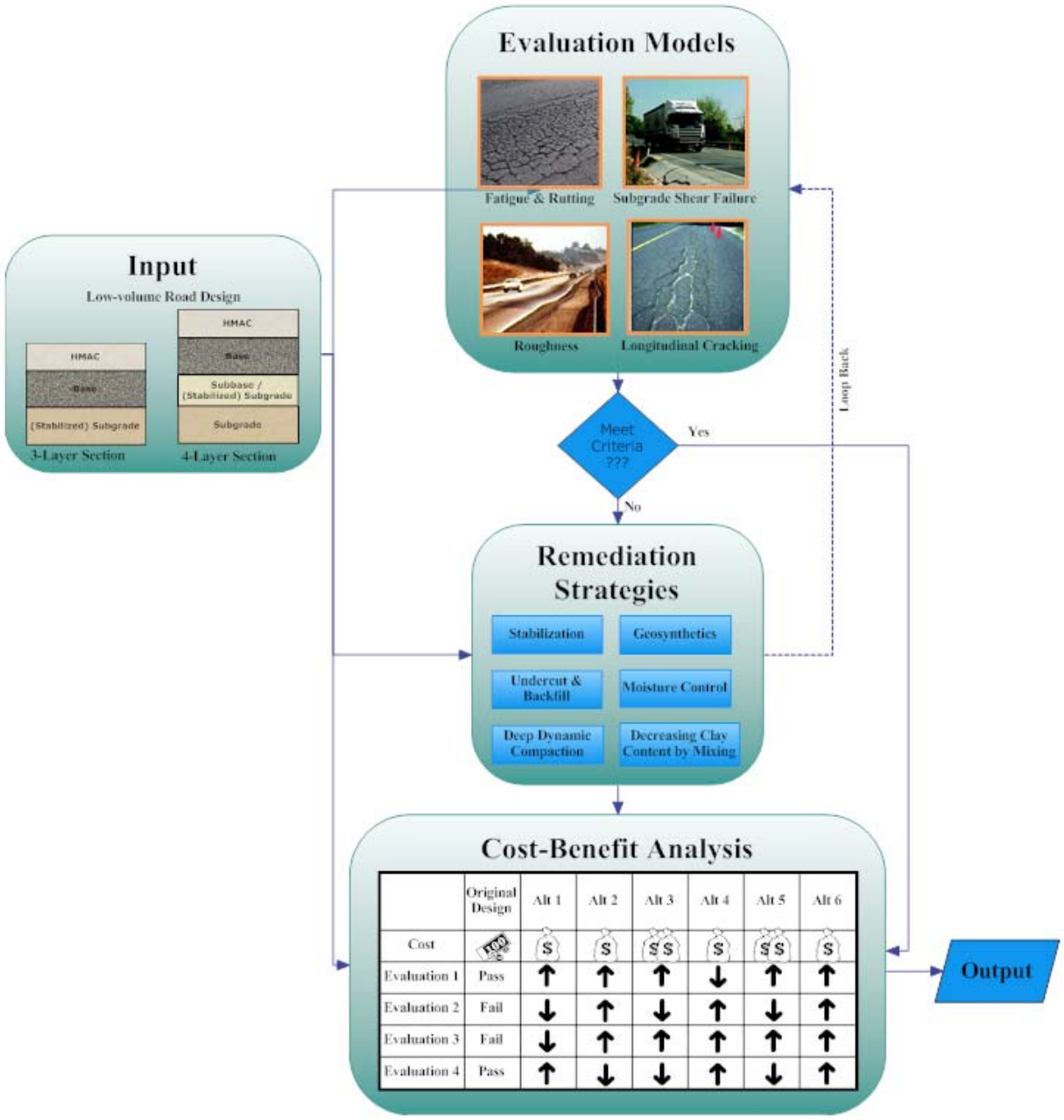


Figure 1.1—ExSPRS Flowchart

for each of the recommended remediation strategies so that the user can judge the cost-benefit of each modification selected. The user can then decide which of the remediation strategies to use that fits his/her requirements and constrains.

In order to use ExSPRS, the user just needs to follow the program and answer different questions to their best of knowledge. Some evaluation models require laboratory characteristic test results such as gradation (Tex-110-E), Atterberg limits (Tex-104-E and Tex-105-E), moisture density tests (Tex-114-E), unconfined compressive strength (UCS, Tex-117-E) tests to quantify the properties of the clayey subgrade material.

Upon execution, ExSPRS brings-up the ***INPUT*** module as shown in Figure 1.2. Before going any further, four basic guidelines should be kept in mind when navigating through the program:

- The user should always start from ***INPUT*** module and follow the program steps through other modules. It is best not to navigate to the next module before completing the information on the current one.
- To select a particular option with check box or radio button, move the pointer to it and then click with the left mouse button. To select a particular option from a drop-down list, move the pointer to the downward arrow and click once, while scrolling through the choices, click with left mouse button when the desired answer is highlighted.
- To enter data for a particular variable, move the cursor to the field or cell. Then type in the required data. To position the cursor to an input field, move the pointer to the field and click on it.
- Hints are provided for all sections of the program that require interaction with the user (as shown in Figure 1.2)

Table 1.1 provides a list of all required inputs in order to execute the program. A default value is provided in the program for each input. A case study will be followed as an example to demonstrate the program.

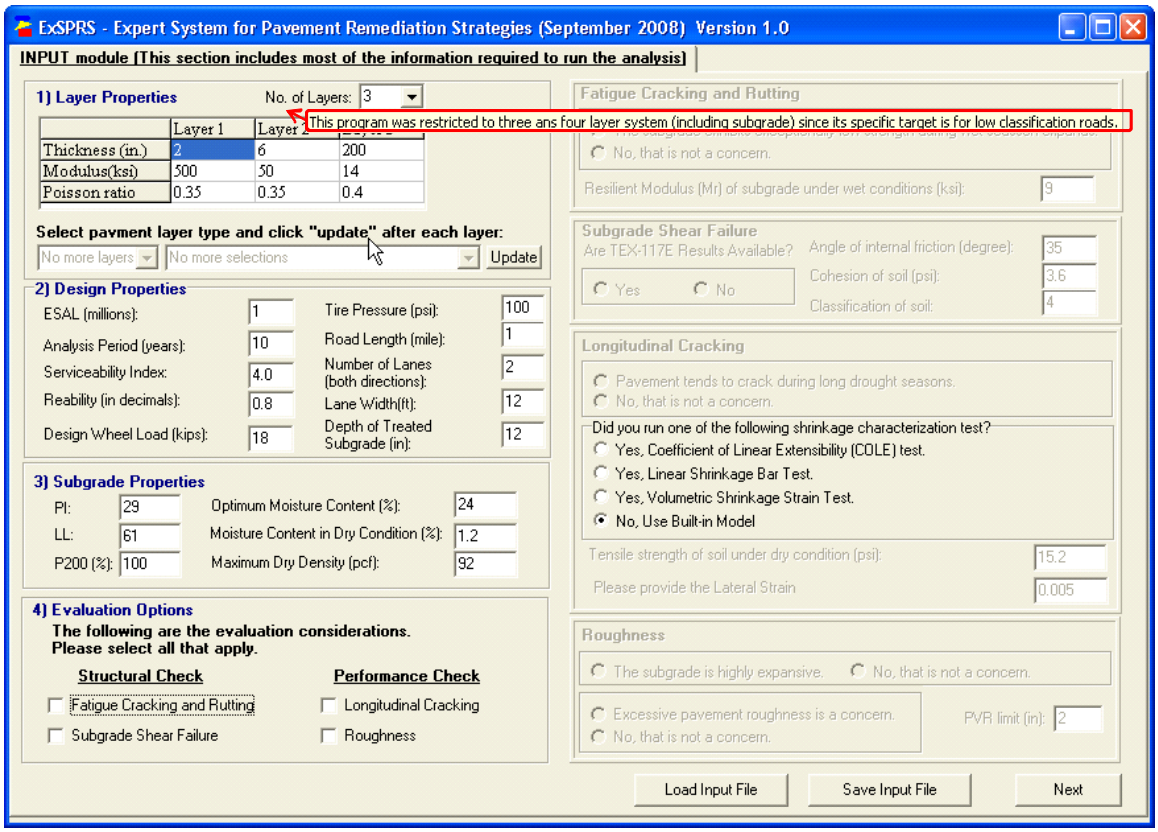


Figure 1.2—ExSPRS Start-up User Interface

Table 1.1—List of Input Parameters Required in ExSPRS

Layer Properties	Number of Layers
	Description of layers (Layer Type)
	Thickness (in.)
	Modulus (ksi)
	Poisson's ratio
Design Properties	Design ESALs (millions)
	Analysis period (years)
	Initial Serviceability index
	Reliability (in decimal)
	Design wheel load (kips)
	Tire pressure (psi)
	Road length (mile)
	Total number of lanes
	Lane width (ft)
	Depth of treated subgrade (in.)
	Percent of time pavement is exposed to saturation moisture level (%)
	Pavement drainage quality
Soil Properties	Subgrade Modulus during wet season (ksi)
	PI
	LL
	P200
	Optimum moisture content (%)
	Maximum dry density(pcf)
	Angle of internal friction from Triaxial tests (degrees)
	Cohesion of soil from Triaxial Test (psi)
	Texas Triaxial Classification of soil
	IDT at dry (psi)
	PVR Limit (in.)
	Sulfate Content (ppm)

CHAPTER 2 - INPUT MODULE

In this chapter, the following items are discussed as used in the *INPUT* module:

- Layer properties
- Design properties
- Soil properties
- Preliminary information regarding structural and performance evaluations

The ExSPRS ***INPUT*** module is developed through an interactive screen, which allows the user to rapidly create the input data. The default values for a typical low-volume road build over high PI clayey subgrade in Texas are displayed in the screen data input fields at the time the program starts. These default values can be used as a starting point for the user to edit or use as desired.

At the bottom of the screen, two buttons are provided to recall data from an existing file or save the input in a file for future use.

The "Load Input File" button is used to load a previously saved input file.

The "Save Input File", allows the user to type in a file name "***with no spaces***", and save the current input file under the default program folder.

The ***INPUT*** module has four sections as shown in the left portion of the input screen. The right part of the input screen is grayed out. That section is related to the evaluation options and is activated when the required information is provided in the right hand portion. The following section will discuss the ***INPUT*** module in detail.

2.1 - BASIC INPUT

Basic input includes layer properties, design properties and subgrade properties. A brief description of the basic design inputs are given below.

1). Layer Properties

- Number of layers: This program is restricted to ***three and four layer pavement systems*** (including subgrade) since its specific target is the lower classification roads.

- Layer Property Table: Layer thickness in in., layer modulus in ksi and Poisson's ratio for each layer should be input. The representative moduli of materials can be obtained either from the Falling Weight Deflectometer tests or laboratory tests. The user is advised to make a reasonable input for each modulus because of the effects these values have on the final solution.
- Layer Description: The type of layer being HMA, base or subgrade should be identified for each layer. The first layer is HMAC by default. For surface-treatment a thickness of 0.5 in. and a modulus of 300 ksi are recommended. After the layer type is selected from the drop-down list for each layer, the user needs to click "Update" button.

2). Design Properties

- ESAL: One direction cumulative 18-kip (80-kN) equivalent single axle load (ESAL) applications in millions at the end of the design period (10 years in this case). This value can be obtained from the Transportation Planning & Programming Division.
- Analysis Period: Length of analysis period in years, usually 10 years for low-volume roads.
- Serviceability Index: This input pertains to the initial pavement serviceability index, which is a function of pavement type and construction quality. Typical value ranges between 4.0 and 4.2.
- Reliability: It is a means of incorporating some degree of certainty into the design process. The level of reliability to be used for design of low-volume roads ranges from 50% to 80%. ***This number should be entered in decimal format.***
- Design Wheel Load: Load on one single axle or a set of tandem axles in kips.
- Tire Pressure: Default value is 100 psi. Higher tire pressure is one of the reasons for higher tensile strains and stresses within pavement.
- Road Length: This value is used to estimate cost. Unit length of 1 mile is recommended.
- Number of Lanes for both directions: This refers to the total number of lanes in both directions. For low-volume roads, it is usually 2 or 4.
- Lane Width: This input is also used to estimate cost. The standard 12-ft lane is used as default.
- Depth of Treated Subgrade: This is the thickness of the stabilized layer between the base and subgrade in in.

3). Subgrade Properties

- PI: Plastic index in percentage (Tex-106-E). It is a measure of the range of water contents where the soil exhibits plastic properties. The PI is the difference between the liquid limit and the plastic limit. $PI = LL - PL$
- LL: Liquid limit in percentage (Tex-104-E).The liquid limit (LL) is the water content where a soil changes from liquid to plastic behavior.
- P200: Percentage of materials passing the 75 μm (No 200) sieve. (Tex-110-E)

- OMC: Optimum moisture content is the water content in percentage at which the soil can be compacted to the maximum dry density. This value is used as the upper limit of moisture variation.
- MC under dry condition: This constant moisture content value in percentage under dry condition (No further weight loss in 24-hr in 104°F oven) is used as the lower limit of moisture variation.
- MDD: Maximum dry density is the maximum value obtained by the compaction curve using the specified compactive effort.

Once the basic inputs are provided, the user can select the performance evaluation options.

2.2 - EVALUATION OPTIONS INPUT

Four evaluation options as depicted in the input screen are provided: 1) Structural checks that consider fatigue cracking and rutting, as well as subgrade shear failure; 2) Performance checks that consider longitudinal cracking and roughness. The user can deactivate any or all of the options except the ***fatigue cracking and rutting check***. Based on the user's selections, additional input based on lab testing data and/or his/her subjective judgments are required. The appropriate modules in the right hand side of the ***INPUT*** module will be activated depending on the evaluation options selected, as shown in Figure 2.1.

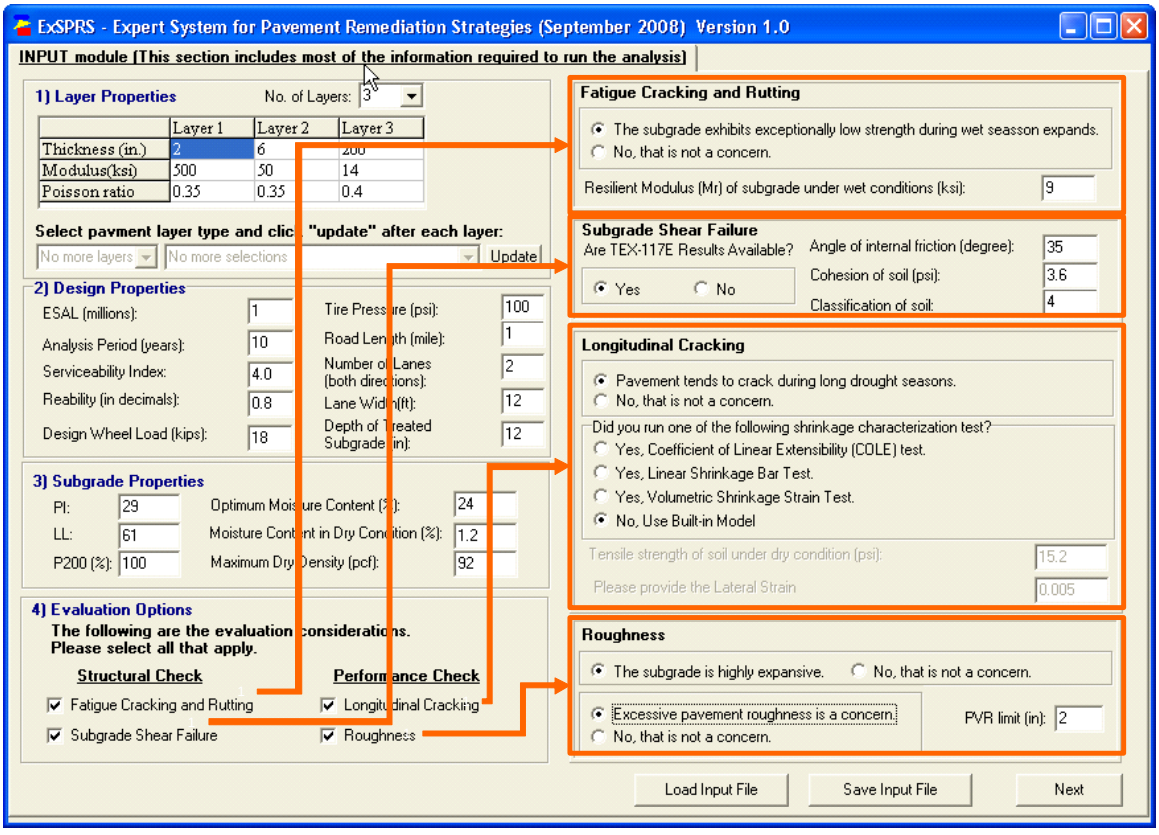


Figure 2.1—Selection of Evaluation Models

Fatigue Cracking and Rutting

A layered linear elastic model that computes pavement responses under static loads is incorporated in the software to check for the pavement fatigue cracking and subgrade rutting. The Asphalt Institute (1982) and Shell (1978) design methods, which relate the strains to the allowable number of load repetitions as shown in the following equations are used:

$$N_f = f_1(\varepsilon_t)^{-f_2}(E_1)^{-f_3} \quad (2.1)$$

$$N_d = f_4(\varepsilon_c)^{-f_5} \quad (2.2)$$

where N_f and N_d is the allowable number of load repetitions for fatigue cracking and rutting respectively, ε_c is the horizontal tensile strain at the bottom of the HMA, ε_t is the vertical compressive strain on top of the subgrade, E_1 is the HMA modulus, f_1 to f_5 are empirical coefficients.

If the loss of stiffness during wet season is a concern, the user is prompted to provide the saturated subgrade modulus in ksi. This modulus will be used in the check to account for the worst case scenario.

Subgrade Shear Failure

This option utilizes the Texas Triaxial Design method and LoadGage to check the subgrade shear failure. If the user desires to check for the subgrade shear failure, the Texas Triaxial Test (Tex-117-E) results will be required. However, if the test data is not available, default values are assigned by the program based on some general questions. ***The user is strongly encouraged to minimize the use of the default values for this purpose as much as possible.***

Longitudinal Shrinkage Cracking

The longitudinal shrinkage cracking is believed to be initiated in the subgrade as a "bottom-up" crack. The subgrade cracks under the combined action of shrinkage by drying and the resistance to shrinkage due to base layer on one hand, and to the deeper, constant-moisture layers of the clay, on the other hand. Resistance to the shrinkage results in shear stresses at the interface of subgrade and base which in turn produce compression stress in the granular courses and tension stress in the clay. When the tensile stress equals the tensile strength, cracking is initiated. Upon further drying, the crack propagates through the base course towards the asphalt layer. If the tensile strength of the asphalt layer is also inadequate, the crack may propagate through to the surface, after which another new cracking cycle begins. (Uzan, *et al*., 1972; Bell and Wright, 1991)

During a dry weather cycle, subgrade shrinkage will cause lateral forces which may exceed its tensile strength. The increase in the lateral shrinkage stress of soil is the main reason for the development of longitudinal cracks. A finite element model is incorporated in ExSPRS to estimate the threshold moisture contents for the initiation (MC_I) and propagation (MC_P) of the longitudinal cracks in the pavement structure. This model also estimates the most likely location for such cracking.

A thorough description of the theory and the model used in ExSPRS is provided in TxDOT Research Report TX-0-5430-2.

To utilize this model, the user needs to either provide laboratory results of the shrinkage strain or use the shrinkage strain vs. moisture content relationships (later referred to as shrinkage strain model) developed under this research project. If the information regarding the shrinkage strain is available and the user selects any of the first three test options, two inputs are required: 1) the tensile stress under dry condition, and 2) the shrinkage strain value that can be obtained from a shrinkage strain characterization test such as linear shrinkage bar test or the volumetric shrinkage strain test. Means of estimating the tensile strength is provided in Research Report 0-5430-2.

If the user decides to use the built-in shrinkage strain model, no extra inputs are required as they were already provided under the soil properties section.

Roughness

Environmental changes cause subgrade volume change induced by swelling and/or shrinking. The roughness of pavement is the result of the cumulative deformation and differential volumetric change of the problematic subgrade soils. The roughness model checks the potential vertical rise (PVR) of subgrade and evaluates the international roughness index (IRI) of low volume roads surface.

If the user reports the subgrade as highly expansive (Roughness portion on the bottom right panel), PVR check will be evoked. The limit of tolerable PVR is also required. This value typically varies between 1 to 2 inches. Also, if excessive roughness is known to be a concern in the area, IRI check will be activated to estimate the expected IRI at the end of the design period.

2.3 - EXAMPLE

To understand the steps and modules in ExSPRS, an example is provided for the user to follow. This also serves as a training exercise. Table 3.1 gives an example of summarized input information to input into the program. This example will be used in the description of the remaining modules so the user can use this manual to follow along for the remaining chapters.

Once the required data for all the evaluation checks are completed, the user may click the “Next” button (at the bottom-right hand side of the ***INPUT*** module) to proceed to the ***EVALUATION*** module.

Table 3.1—Summary of Example Input Data (Fort Worth Case Study)

Layer Properties	Number of Layers			3
	Description of layers	HMAC	Flexible Base	Compacted Subgrade
	Thickness (in.)	2	6	200
	Modulus (ksi)	500	50	14
	Poisson's ratio	0.35	0.35	0.4
Design Properties	Design ESALs (millions)			1
	Analysis period (years)			10
	Initial Serviceability index			4.0
	Reliability (in decimal)			0.8
	Design wheel load (kips)			18
	Tire pressure (psi)			100
	Road length (mile)			1
	Total number of lanes			2
	Lane width (ft)			12
	Depth of treated subgrade (in)			12
	Percent of time pavement is exposed to saturation moisture level (%)			1 to 5
	Pavement drainage quality			Good
Soil Properties	Subgrade Modulus during wet season (ksi)			9
	PI			29
	LL			61
	P200			100
	OMC (%)			24
	Dry MC (%)			1.2
	MDD (pcf)			92
	Angle of internal friction (◦)			35
	Cohesion of soil (psi)			3.6
	Classification of soil			4
	IDT at dry (psi)			15
	PVR Limit (in)			2
	Sulfate Content (ppm)			1000

CHAPTER 3 - EVALUATION MODULE

In this chapter, the following items are discussed as used in the ***EVALUATION*** module:

- Information regarding evaluation models
- Outcome of possible distresses and failures of the design being evaluated

Based on the district survey and literature review conducted under research project TX-0-5430, the most prevailing distresses for low volume flexible pavements are longitudinal cracking, rutting, shoving and excessive roughness. The main causes for these distress problems can be categorized into two areas: 1) Inadequate support, which is caused by inadequate layer thicknesses, poor constructions and improper stabilization; 2) Problematic soils susceptible to moisture variation, which include subgrade volume change, shoulder problems, poor drainage or other combined effects. The ***EVALUATION*** module is used to determine whether the user-defined pavement structure meets these criteria. The outcome from ***EVALUATION*** module provides the user with the option to either modify the original design (use different cross-sections or materials) and restart the analysis over or proceed to the ***REMEDIATION*** module to determine suitable remediation alternatives.

3.1 - EVALUATION OPTIONS

In addition to the preliminary inputs required in the ***INPUT*** module, several specific questions are also asked in the ***EVALUATION*** module window as shown in Figure 3.1. The details for each type of evaluation are presented next.

Longitudinal Shrinkage Cracking Model

If the user selects to provide the shrinkage strain in the ***INPUT*** module, no additional information is required. If the user decides to use the built-in shrinkage strain model, he/she needs to select the index parameters to be used to estimate the shrinkage strain with the built-in model. Figure 3.1 depicts the selection of soil parameters for inclusion under the top panel. The development and validation of the shrinkage strain model used in ExSPRS is provided in TxDOT Research Report TX-0-5430-1.

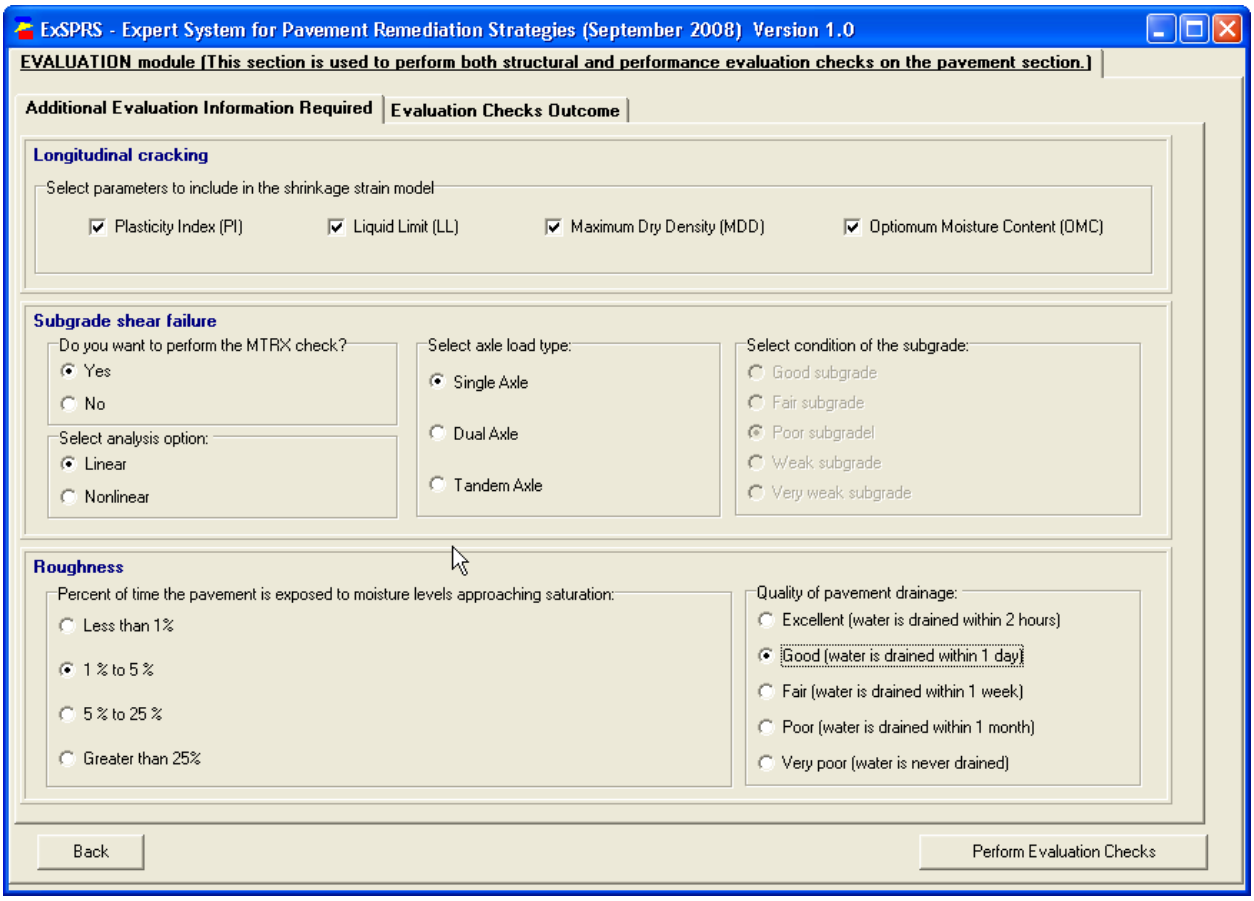


Figure 3.1—Evaluation Options

Subgrade Shear Failure Model

Figure 3.2 depicts the input structure for subgrade shear failure check. By default, the Texas Triaxial method is used. The required cover depth from this method may be over-conservative in districts where the climate is drier, or where the soils are not as moisture susceptible (Fernando, *et al.*, 2001). To account for this conservatism, the modified triaxial design method (MTRX) is also provided as a choice to double-check the cases when the pavement structure fails the Texas triaxial check. If triaxial test results are provided in the ***INPUT*** module, no further information is required and the rightmost question in the ***EVALUATION*** module under the Subgrade Shear Failure model is grayed. If on the contrary, the triaxial test results are not available, the subgrade condition is used to estimate these parameters. The user also needs to select the analysis option and axle load type in order to execute the MTRX (also known as LoadGage) check. By default, the LoadGage program runs a linear analysis to predict the stresses. However, for the advanced user, a nonlinear option is included to permit modeling of the stress-dependency. The nonlinear analysis option will provide a more realistic prediction of the stresses induced under loading (Jooste and Fernando, 1995) for thin pavements. This analysis in MTRX uses equation with k_1, k_2 and k_3 material constants determined from resilient modulus testing (Uzan, 1985).

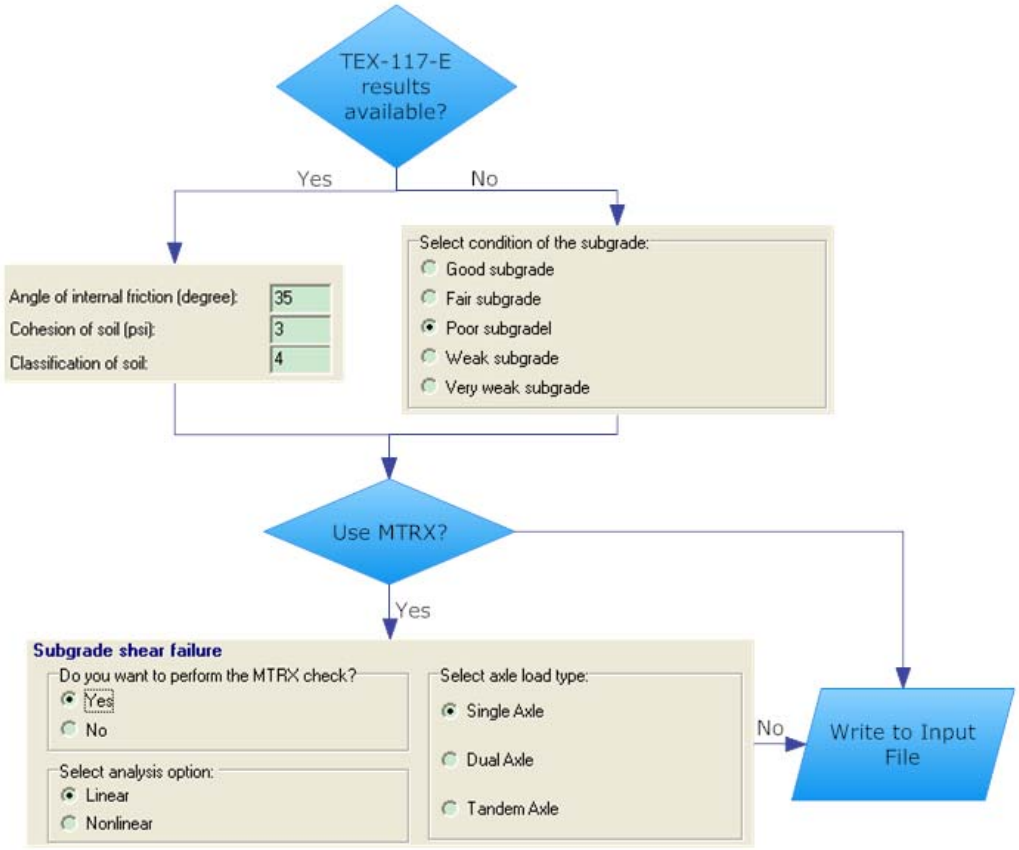


Figure 3.2—Subgrade Shear Failure Check Input Structure

Roughness Model

In order to estimate IRI and PVR more accurately, two environmental-related questions are asked:

1). What is the percentage of time within a typical year that the pavement is exposed to wet season (moisture level approaching saturation)?
2). What is the quality of the pavement drainage system?

The user needs to make appropriate selections according to his/her experience. Once all the relevant information for the ***EVALUATION*** module is provided, the user can proceed to view the ***Evaluation Outcome*** by clicking the "Perform Evaluation Checks" button at the bottom-right hand side of the window.

3.2 - EVALUATION CHECKS OUTCOME

The "Evaluation Checks Outcome" window is divided into four panels to present the results for the four Evaluation Options (see Figure 3.3). The top left portion presents the outcome of the fatigue cracking and rutting check, the top right section presents the results for the subgrade shear failure check, the bottom left section is for the roughness check results and finally the bottom right portion shows the results for the longitudinal shrinkage cracking (LSC) check

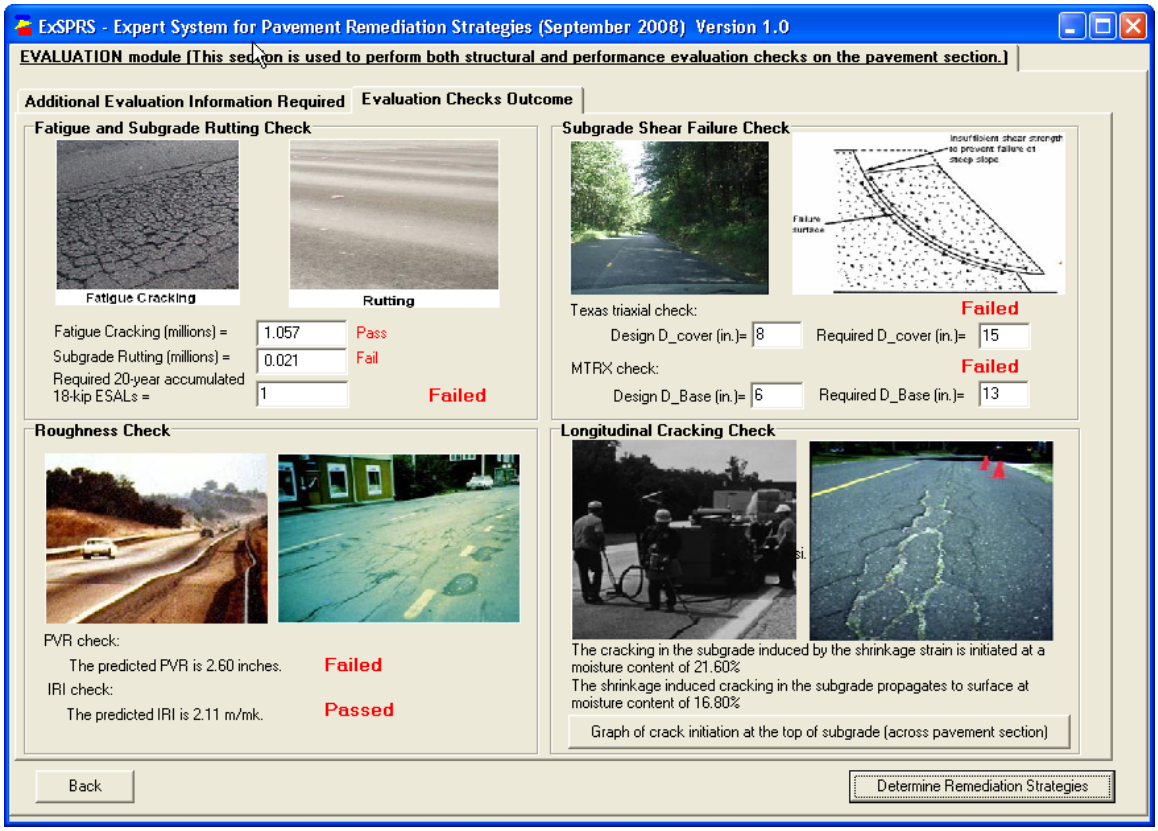


Figure 3.3—Evaluation Checks Outcome

results. If an evaluation was not selected in the ***INPUT*** module, the designated results panel will be blank.

For the fatigue cracking and rutting check, the corresponding allowable load repetitions are reported in million ESALs. Fail/Pass flags are also shown for each one. The design traffic provided by the user in the ***INPUT*** module is also reported here for comparison. An overall Fail/Pass flag is also reported for this evaluation check. In the example used in this manual for illustration, the section passed the fatigue cracking performance and failed the rutting. The overall evaluation check is considered as failed, and therefore, remediation to prevent rutting is required.

In this example, both the Texas triaxial (Tex-117-E) method and MTRX method were used. The Texas triaxial check proposed a required cover depth of 15 in. MTRX check required a base thickness of 13 in. The original design failed both checks.

Under the roughness check results, the total PVR was estimated to be 2.6 in. Since in this example the acceptable PVR limit of 2 in. was provided, the PVR check also failed. The IRI check gave 2.1 m/km, which passed the criteria for farm to market roads. Details of IRI criteria can be found in Research Report TX-0-5430-2.

The longitudinal shrinkage cracking check estimated that at a moisture content of 21.6%, the shrinkage cracking initiates, and at 16.8%, the longitudinal crack propagates up to surface. At

the bottom-right of the LSC results panel, there is a button "Graph of crack initiation at the top of subgrade (across pavement section)" that provides the user with the location and distribution of stresses. The user can click to see the distribution of critical points along a 12-ft lane (144 inches in x-axis) cross-section view (depth of inches along y-axis) as shown in Figure 3.4. The critical locations are near the 42 ± 18 in. (3.5 ± 1.5 ft) range from the pavement edge.

To proceed to the ***REMEDIATION*** module, the user needs to click the "***Determine Remediation Strategies***" button in the bottom right of the screen. The ***REMEDIATION*** module is presented in Chapter 4.

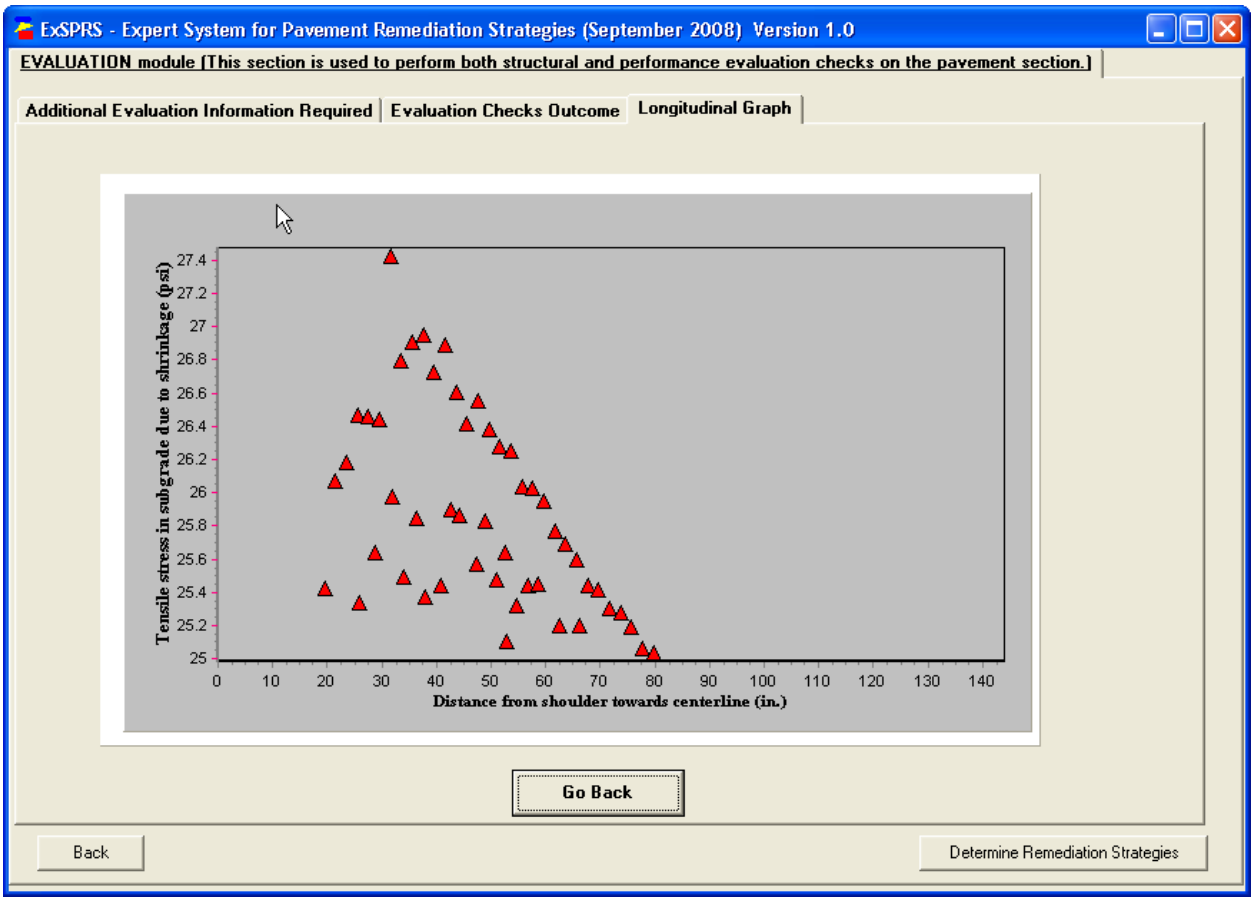


Figure 3.4—Longitudinal Cracking Check Graphical Result

CHAPTER 4 - REMEDIATION MODULE

In this chapter, the following items are discussed as used in the *REMEDIATION* module:

- Alternative ways to consider for overcoming structural inadequacy and performance problems
- Description of each alternative on how to improve the pavement system

In the ***REMEDIATION*** module, six modification strategies grouped into two categories are available for consideration: 1) To improve subgrade strength and stiffness; and 2) To minimize moisture variation induced swell/shrink problems. ExSPRS will recommend appropriate methods to consider from either or both categories following the logic flowchart shown in Figure 4.1 based on the evaluation results.

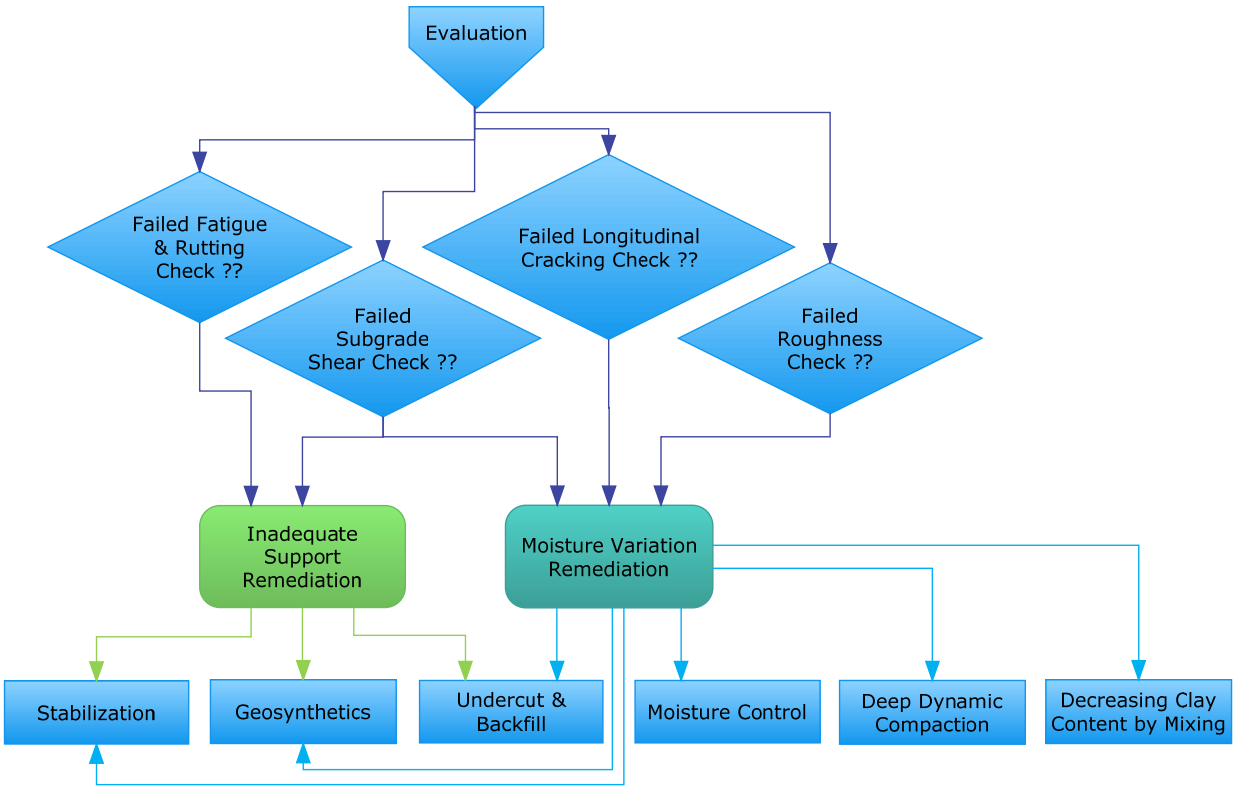


Figure 4.1— Logic Flowchart of Recommended Remediation Strategies

4.1 - REMEDIATION STRATEGIES FOR CONSIDERATION

Figure 4.2 shows the selection of remediation strategies. The user has the choice to decide which one(s) out of the recommended modifications to be considered and analyzed for the original candidate design. When a specific strategy is selected, the user will notice that a new tab is activated. Figure 4.2 shows where both Stabilization and Undercut-Backfill are selected and thereby their tabs are activated (see Figure 4.2). For demonstration purpose and the example provided in this manual, all recommended remediation strategies are selected for further illustration. This module shows the remediation strategies that resulted from the evaluation check results. Once the user determines and selects which of the remediation strategies might be suitable for consideration, the user can proceed to the ***COST-BENEFIT*** module where a cost analysis is performed and the benefits of the selected remediation strategies are provided for comparison.

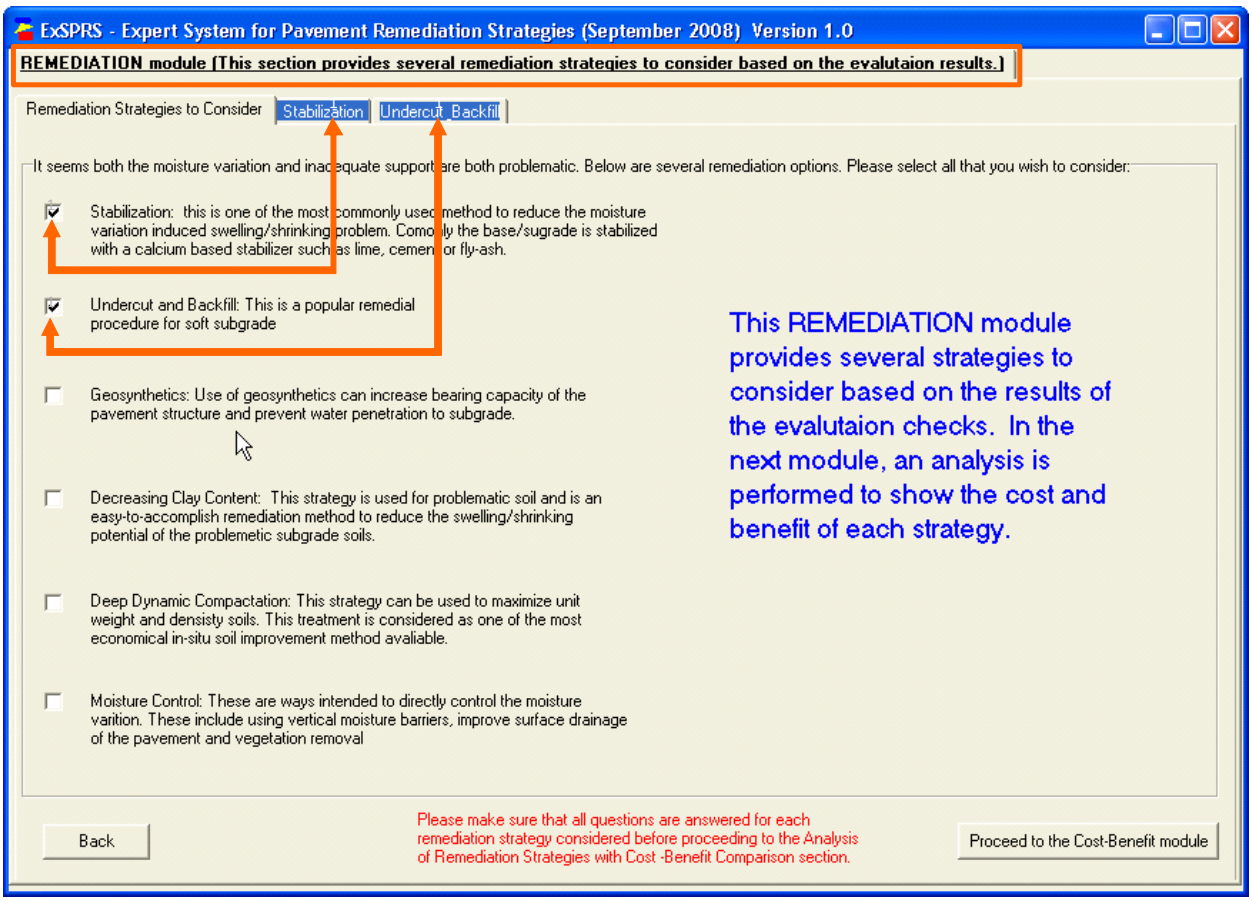


Figure 4.2—Selection of Remediation Strategies

4.2 - DETAILS OF REMEDIATION STRATEGIES TO CONSIDER

To explore the details of each modification method, the user can click on the corresponding highlighted tab. All activated remediation strategy tabs are parallel, and the user can explore any of the solutions in any order.

Stabilization

Clayey soils are often stabilized with calcium based stabilizers to improve their engineering properties including strength, volumetric change potential and permeability. Figure 4.3 depicts the screenshot of stabilization window. Three questions are asked in this module. First, the user is asked to locate their project using the map provided (see Figure 4.3) to decide whether the location is susceptible to sulfate heave problem, which is one of the main factors that affects the final stabilization method and stabilizer recommended. Second, the user is asked to provide the laboratory tested sulfate concentration in ppm. (Tex-145-E). The default value for this question will be set to no sulfate concentration, if the user answer for the first question is "Neither", or Tex-145-E is not carried out. Finally, the user should indicate whether the subgrade is an organic-rich subgrade. To facilitate the responses to these questions, the user can take advantage of the specially treatment recommendations, references and the recommended stabilizers provided at the bottom-left part (see Figure 4.3).

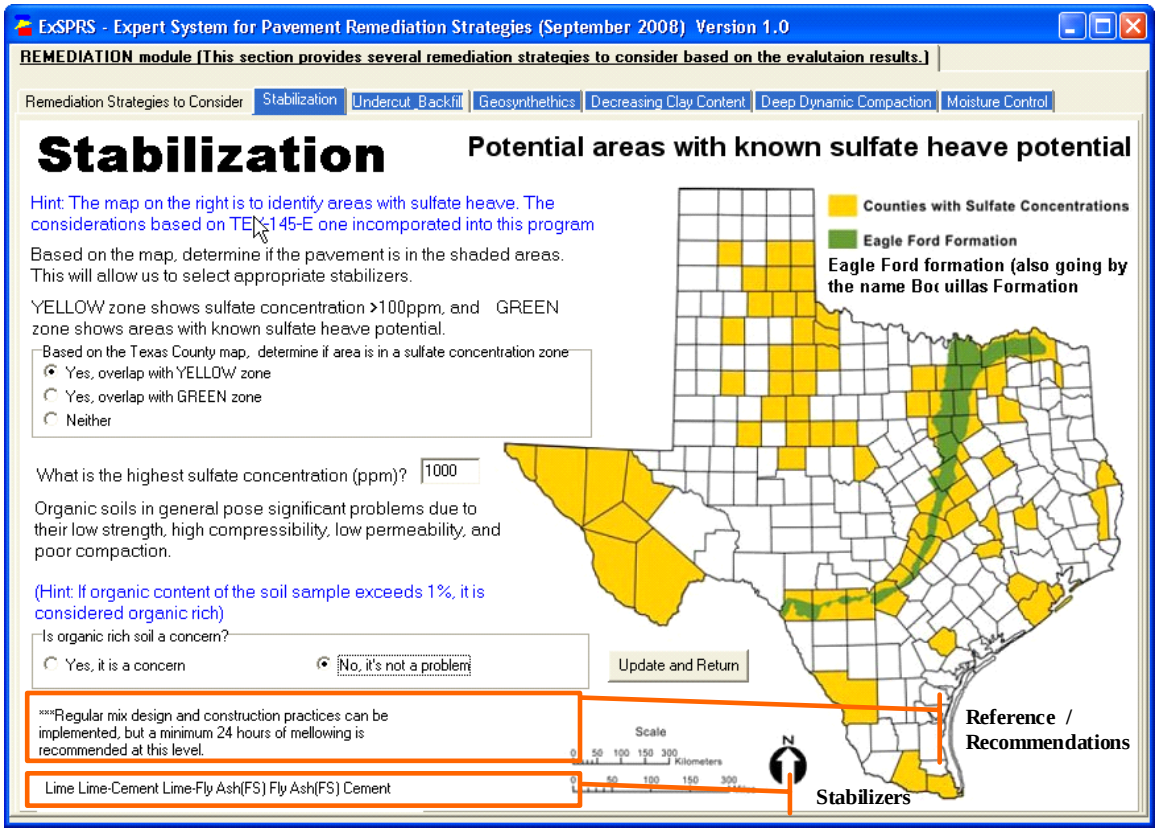


Figure 4.3—Stabilization Window of Remediation Module

Geosynthetics

For the scope of this research, the geosynthetic reinforcement is assumed to be targeted for subgrade improvements. The reinforcement is placed at the interface between base/subbase and the subgrade. Figure 4.4 illustrates the usage of the geosynthetic reinforcement with some additional references. At the bottom half of the window there are three questions regarding the subgrade quality. These questions are used to decide the required depth of the pavement above

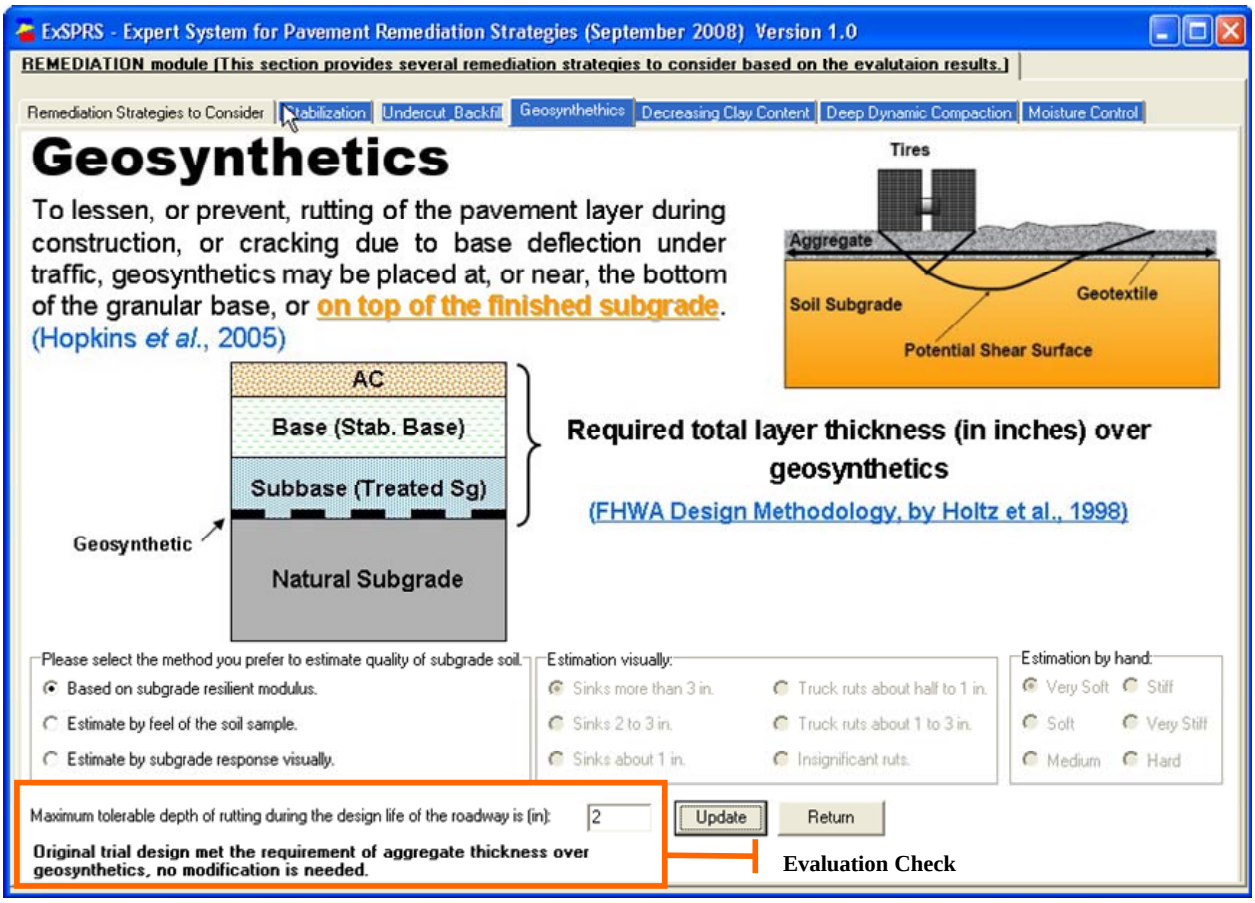


Figure 4.4—Use of Geosynthetics

the placement of the geosynthetic material. If has chosen to select this option as a remediation strategy to consider, then the user should answer those questions. One option is to use the subgrade resilient modulus, which requires no further action since that value was already provided in the ***INPUT*** module. Further questions are only required if the user decides to use the other two very approximate methods (***the use of these two options is discouraged for project level studies***). Upon selecting one of the two lower radio buttons, the appropriate menu will be activated.

To ensure that the geosynthetic material can be place at the recommended depth (middle graph in Figure 4.4) directly without further construction modifications, the user needs to provide maximum tolerable depth of rutting during the design life of the roadway in inches. Commonly used value of 2-inch was provided as default. The "Update" button needs to be selected. The program will show whether thicker layers above subgrade are required for the section with the geosynthetic to be fully functional without losing it's anchorage strength. To return to the main remediation tab, select the "Return" button or directly click on the tab.

Moisture Control

Many pavement distress problems are caused by moisture variation and migration. The moisture control remediation methods are offered in a hierarchical style as shown in Figure 4.5. This remediation strategy focuses on measures that directly deal with minimizing moisture change in the subgrade. These remediation strategies are grouped into three main categories: 1) use of vertical moisture barriers, 2) improve drainage and 3) treat nearby vegetations.

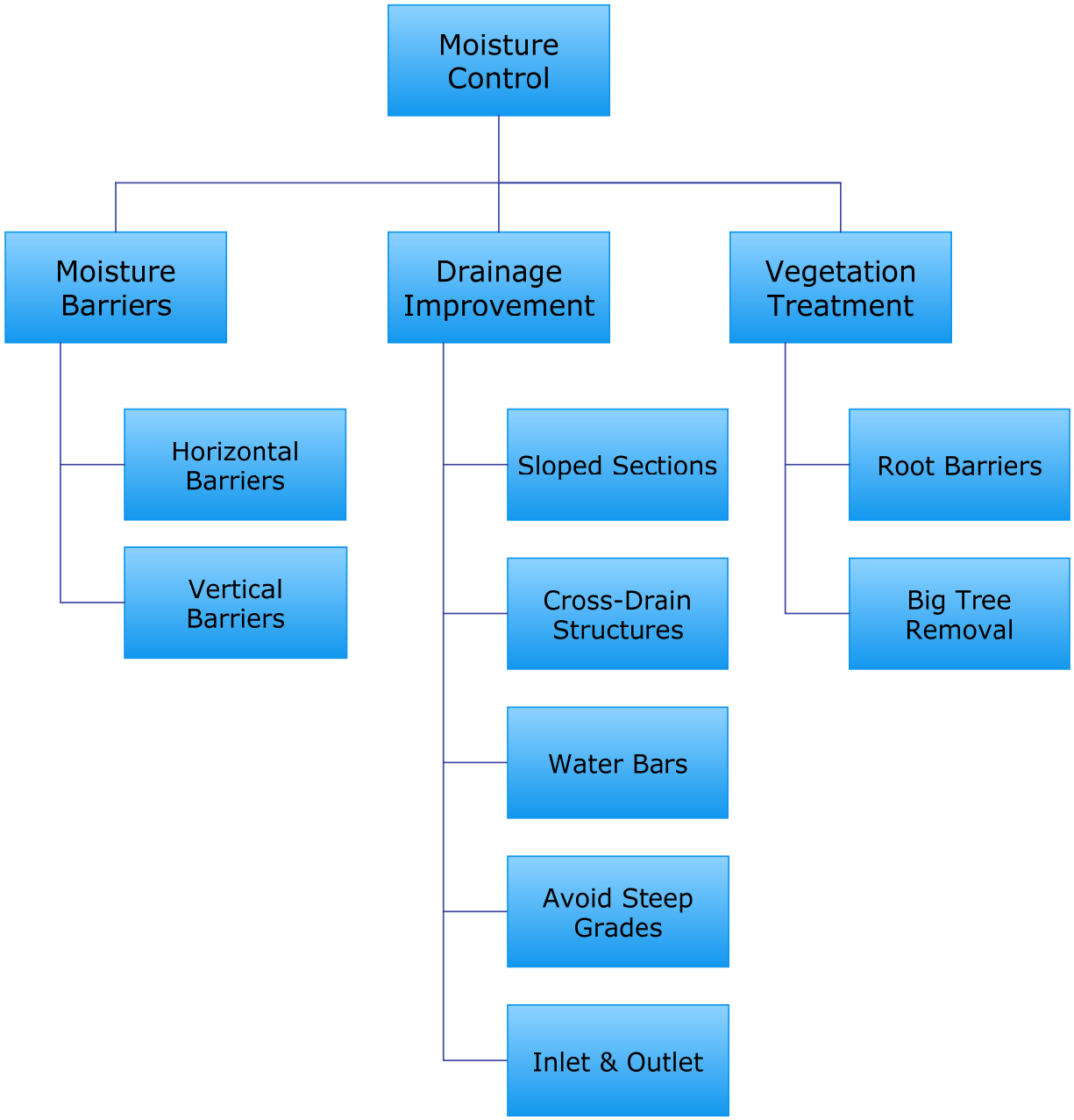


Figure 4.5—Hierarchy of Moisture Control Methods

This portion of the program is illustrative rather than analytical. The user can explore useful information, design methods and references for different methods by first selecting one of the three moisture control groups, then further specifying a method if selection question shows up. Figure 4.6 shows an example informational screen of using moisture barriers. The user can click "Next Picture" button to read more. As presented in the flowchart in Figure 4.5, there are five methods to improve the drainage. They are: use sloped sections, cross-drain structure, water bars, inlets and outlets and to avoid steep grades. Figures 4.7 to 4.11 show example informational screens of these drainage improvement methods. Figure 4.12 and 4.13 depicts example informational screens of vegetation treatments.

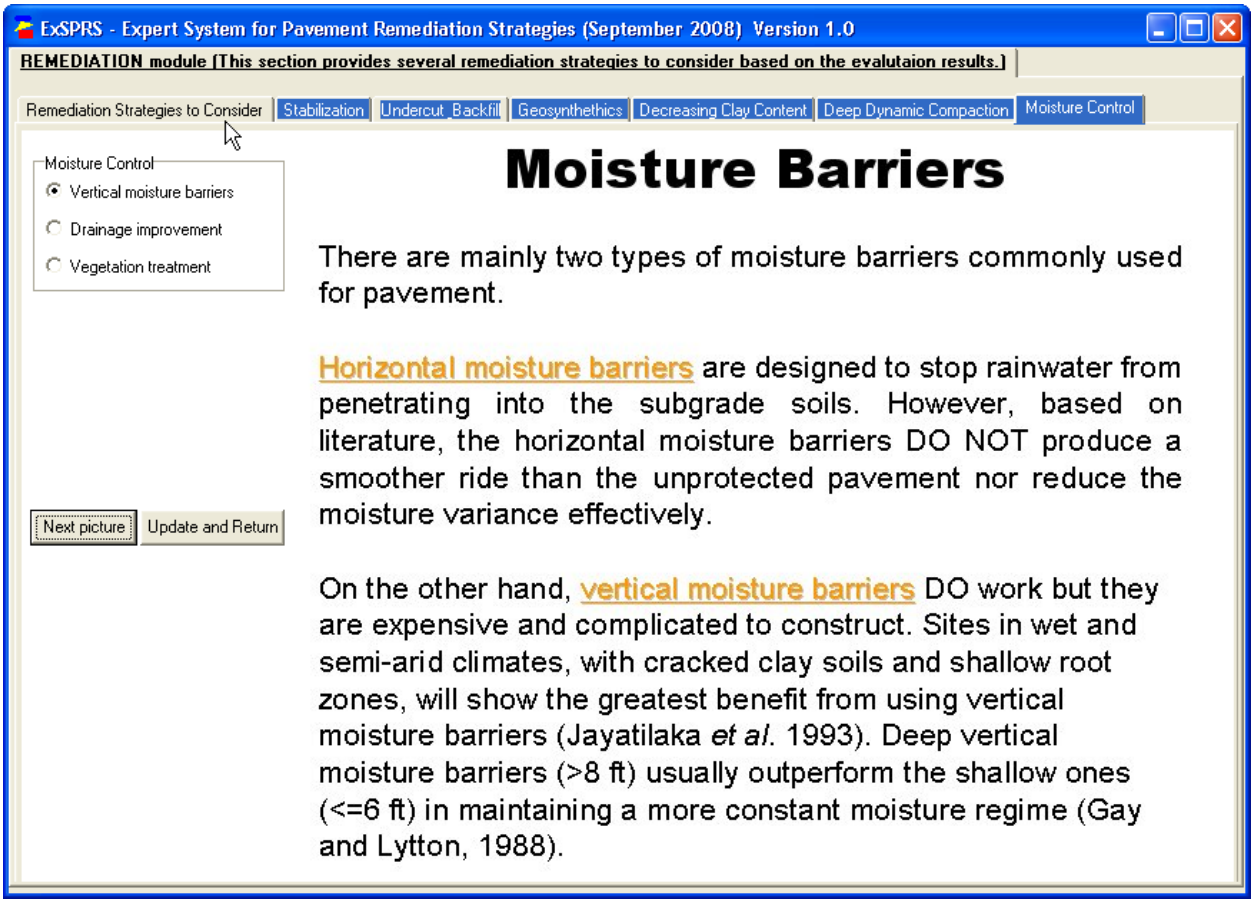


Figure 4.6—Moisture Control Method of Using Moisture Barriers

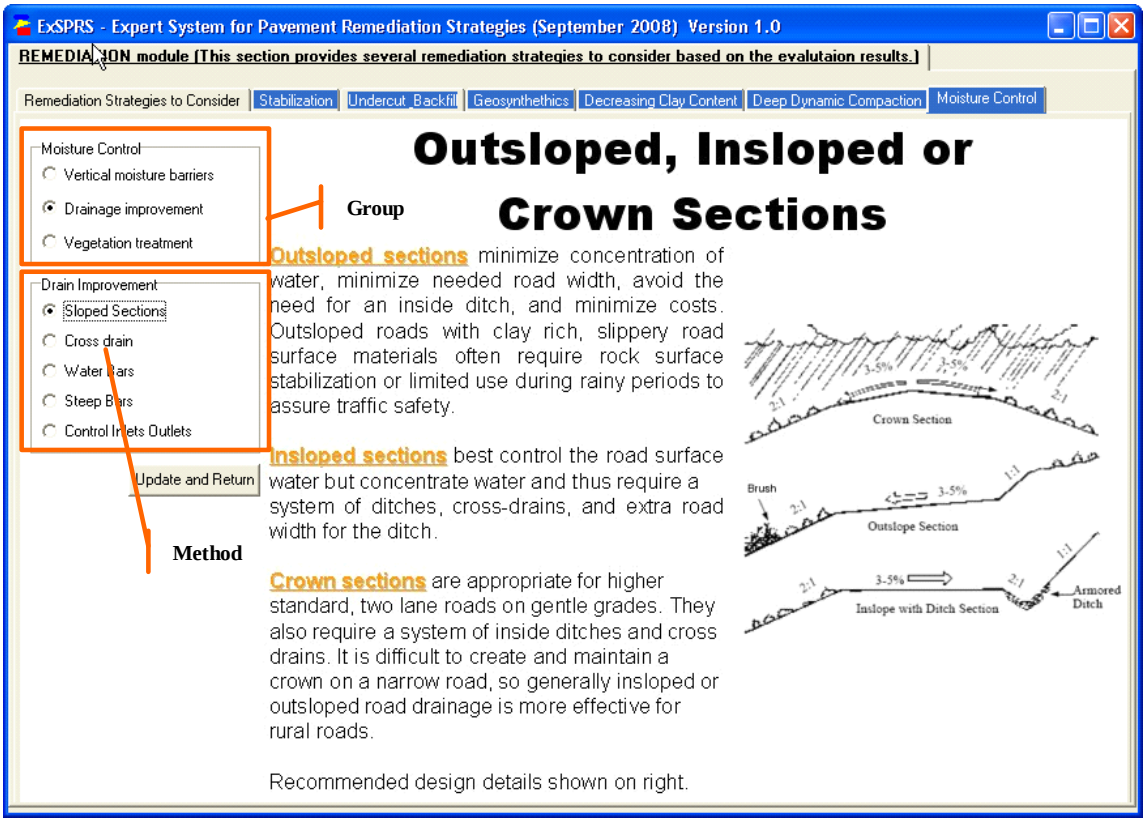


Figure 4.7—Moisture Control Method of Using Sloped Sections

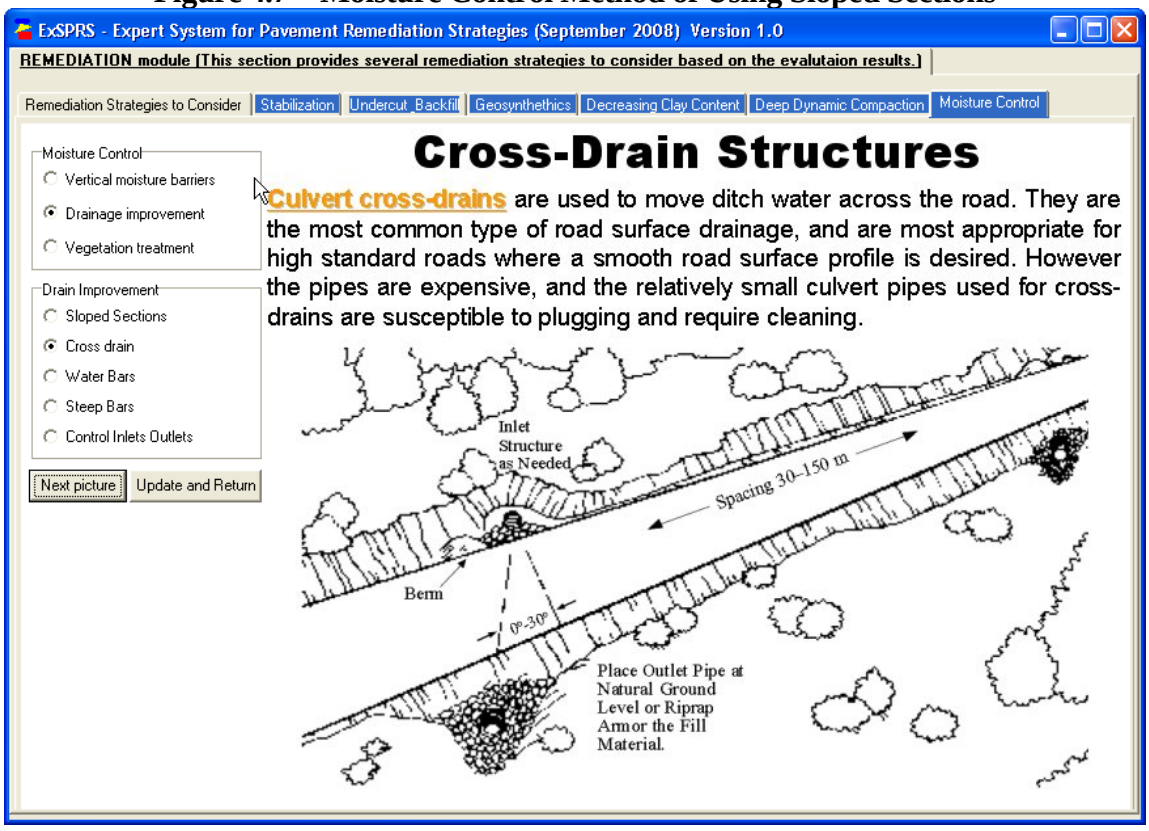


Figure 4.8—Moisture Control Method of Using Cross Drain Structures

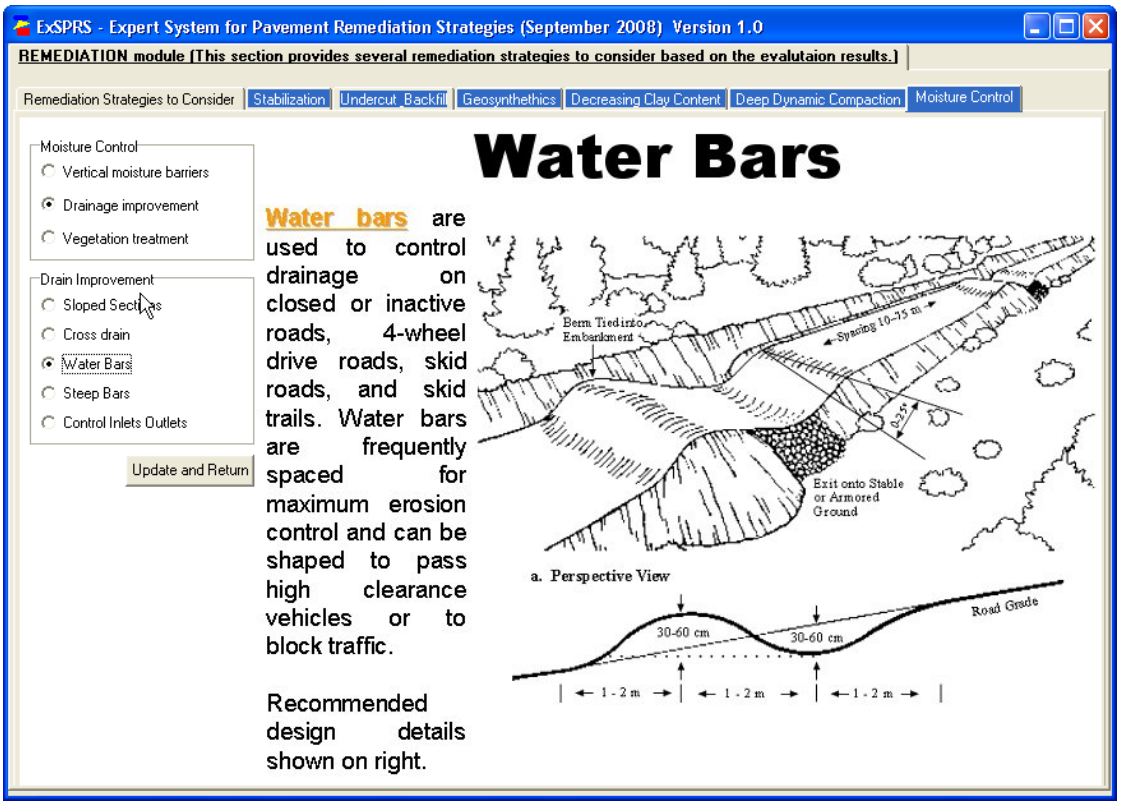


Figure 4.9—Moisture Control Method of Using Water Bars

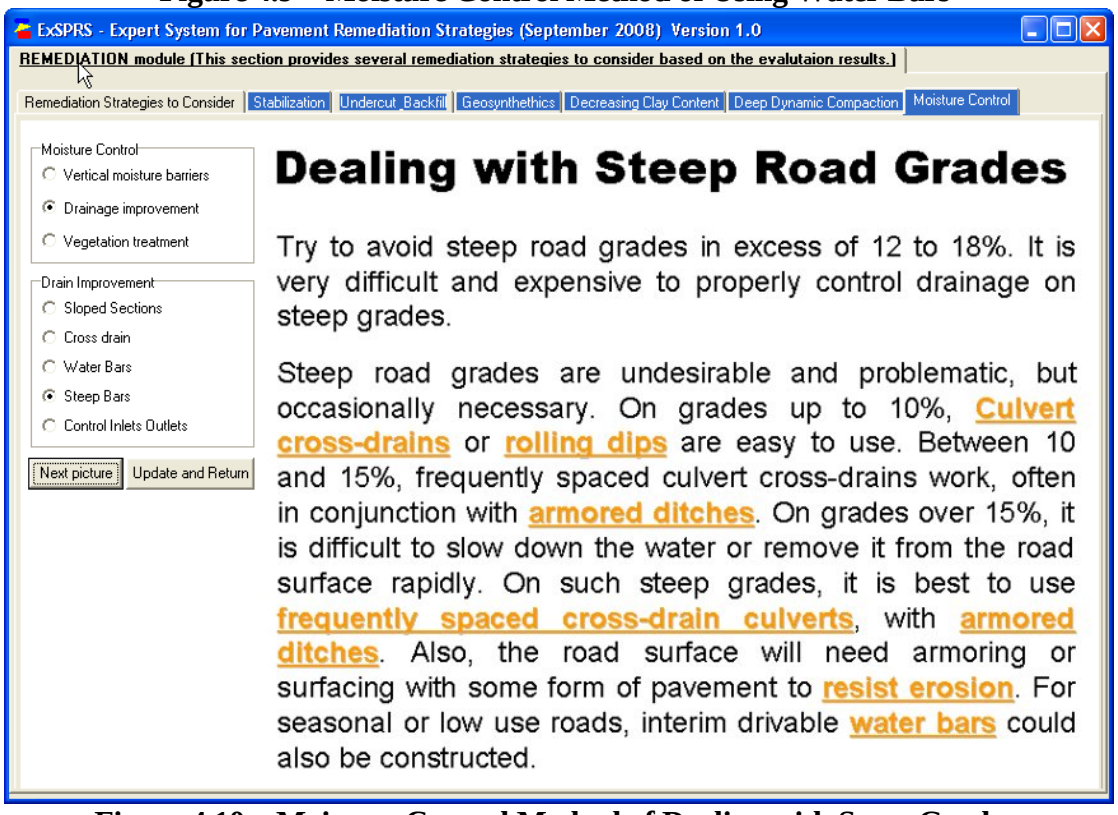


Figure 4.10—Moisture Control Method of Dealing with Steep Grades

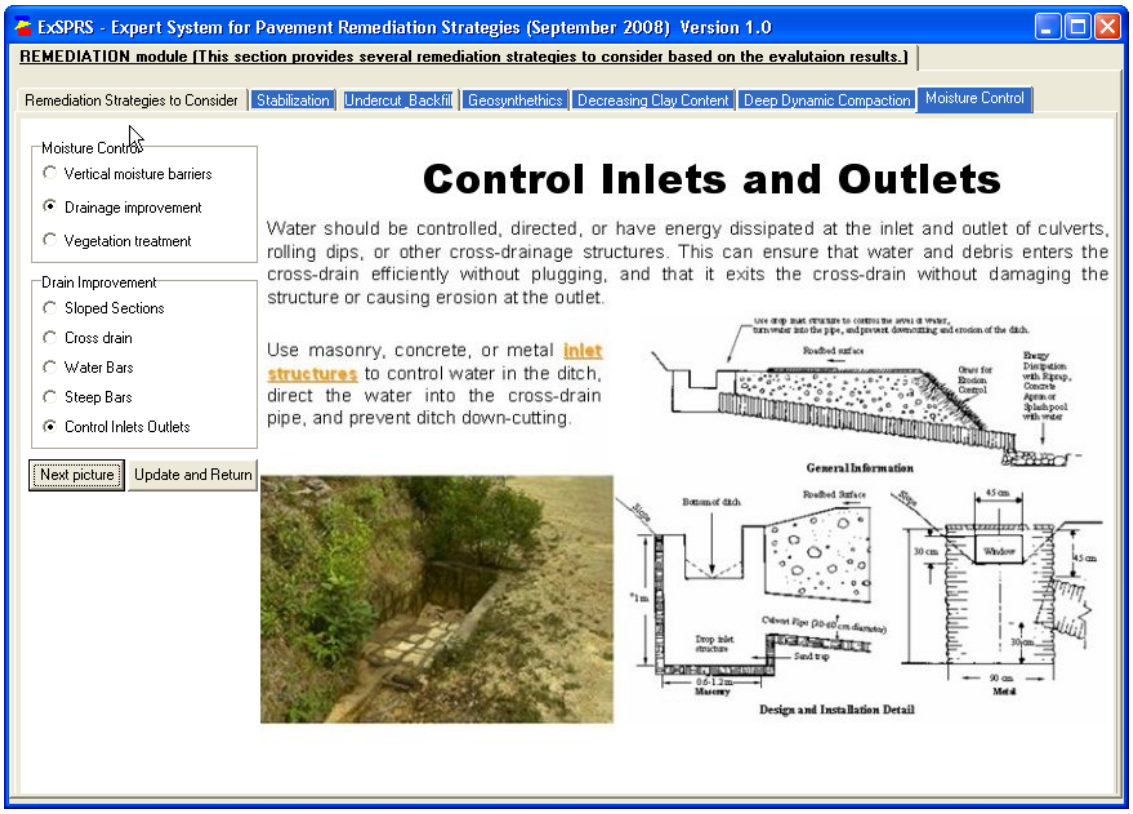


Figure 4.11—Moisture Control Method of Using Inlets and Outlets

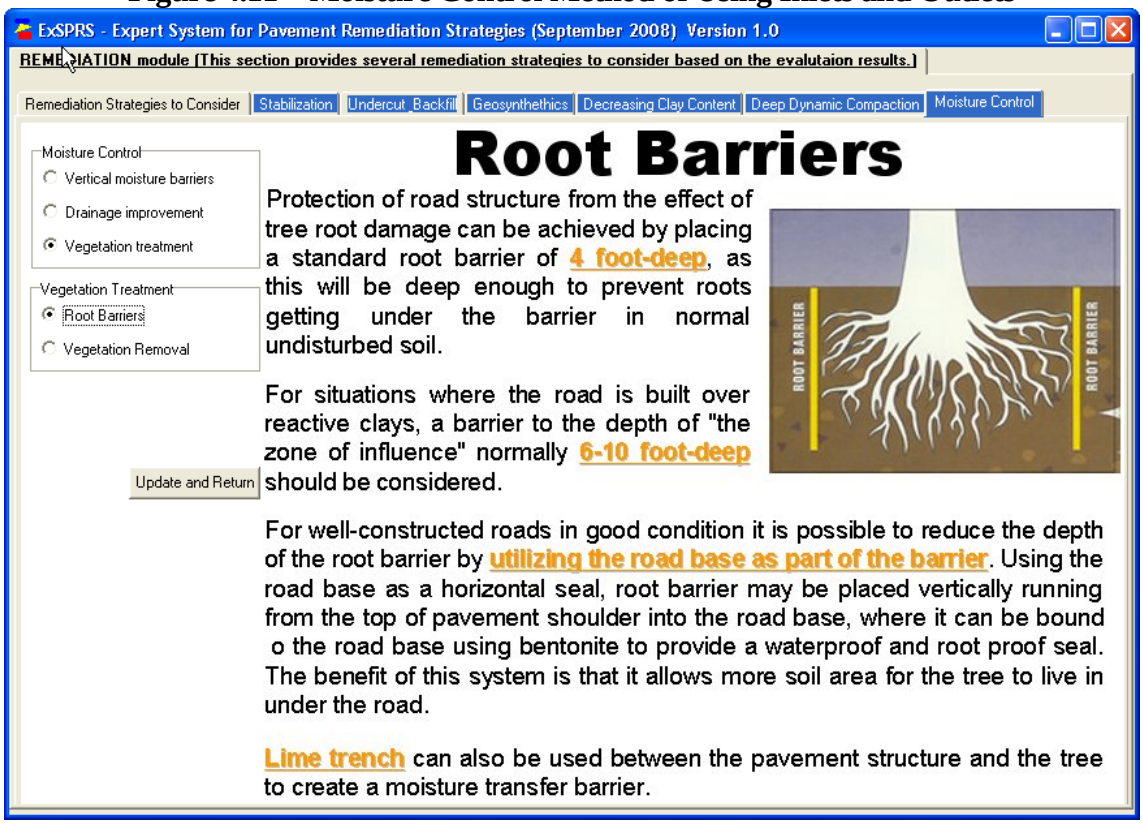


Figure 4.12—Moisture Control Method of Using Root Barriers

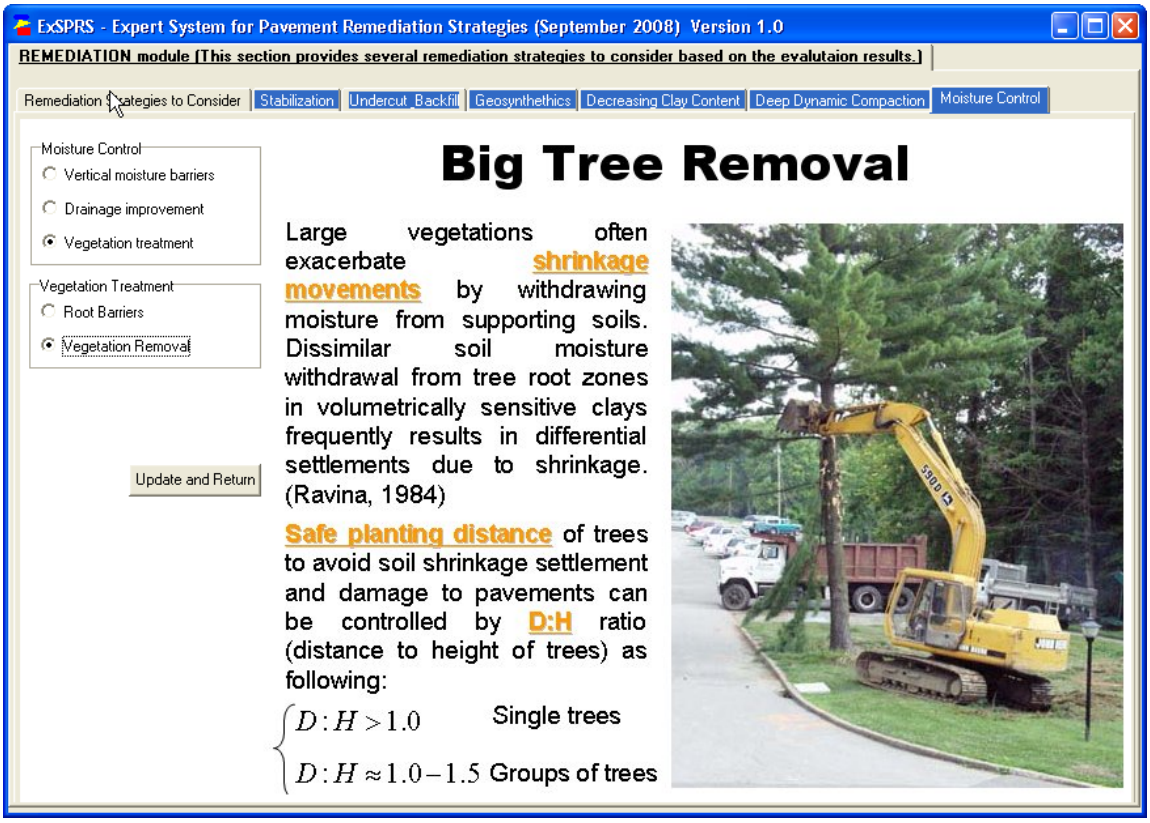


Figure 4.13—Moisture Control Method of Removing Vegetations

Undercut and Backfill

Poor subgrade soil can simply be removed and replaced with high quality fill. This method, which is also called undercut and backfill, is a simple procedure that does not require any specialized equipment. However, unless a suitable backfill material is available near the job site, removal and replacement is generally a much more expensive operation than the use of additives. For this reason, removal and replacement is mostly used in urban areas, where dust and environmental impacts make the use of additives less desirable. Removal and replacement may also be the best option in areas where deep deposits of peat and muck cannot be treated with the use of additives. For lower classification roads, economic constrains have to be taken into account. If this remediation is selected, the program calculates the recommended replacement depth. Figure 4.14 provides an example of the calculated undercut and backfill depth in inches provided by the program.

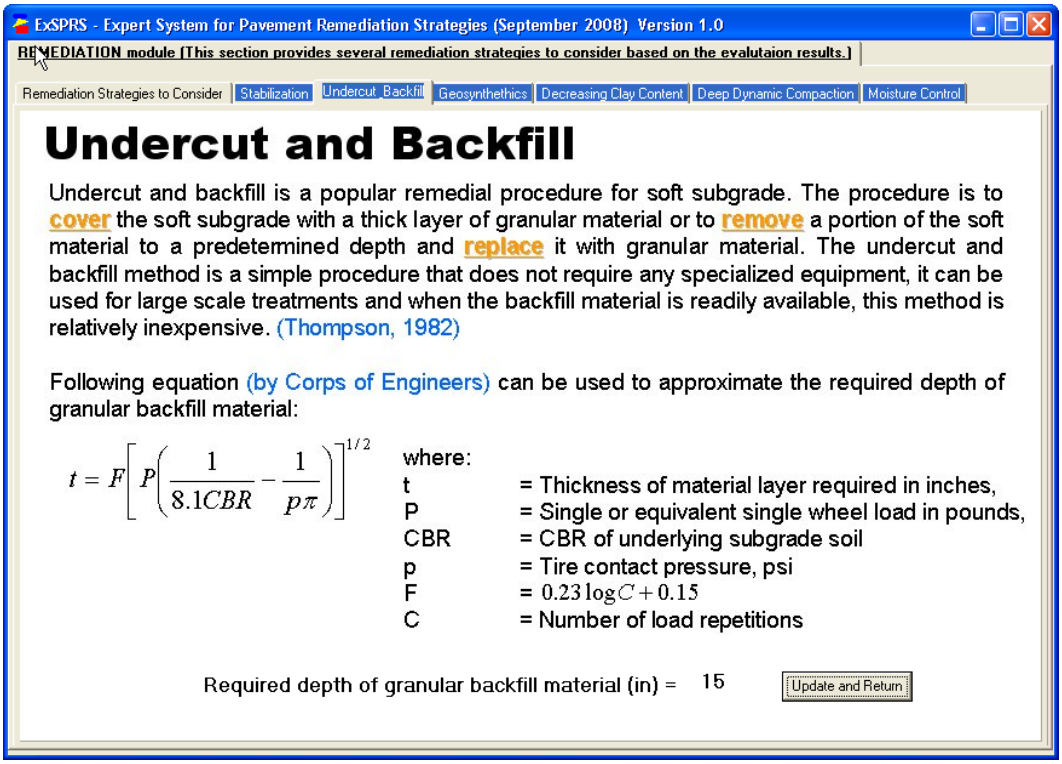


Figure 4.14—Undercut and Backfill

Deep Dynamic Compaction

Deep dynamic compaction (DDC) is an economical ground modification method (Figure 4.15). This technique involves repeatedly raising and dropping a large weight in a prescribed pattern to densify the potentially unstable or weak underlying materials with high-energy impacts. The weight may range from 6 to 25 tons and the drop height typically varies from 30 to 60 ft. The degree of densification achieved is a function of the energy input (i.e., weight and drop height) as well as the saturation level, fines content and permeability of the material. As mentioned by several researchers, (Mowafy *et al.*, 1985; Rollins and Christie, 2002), this method is not appropriate for saturated clayey soils and the solution may be temporary due to water infiltration.

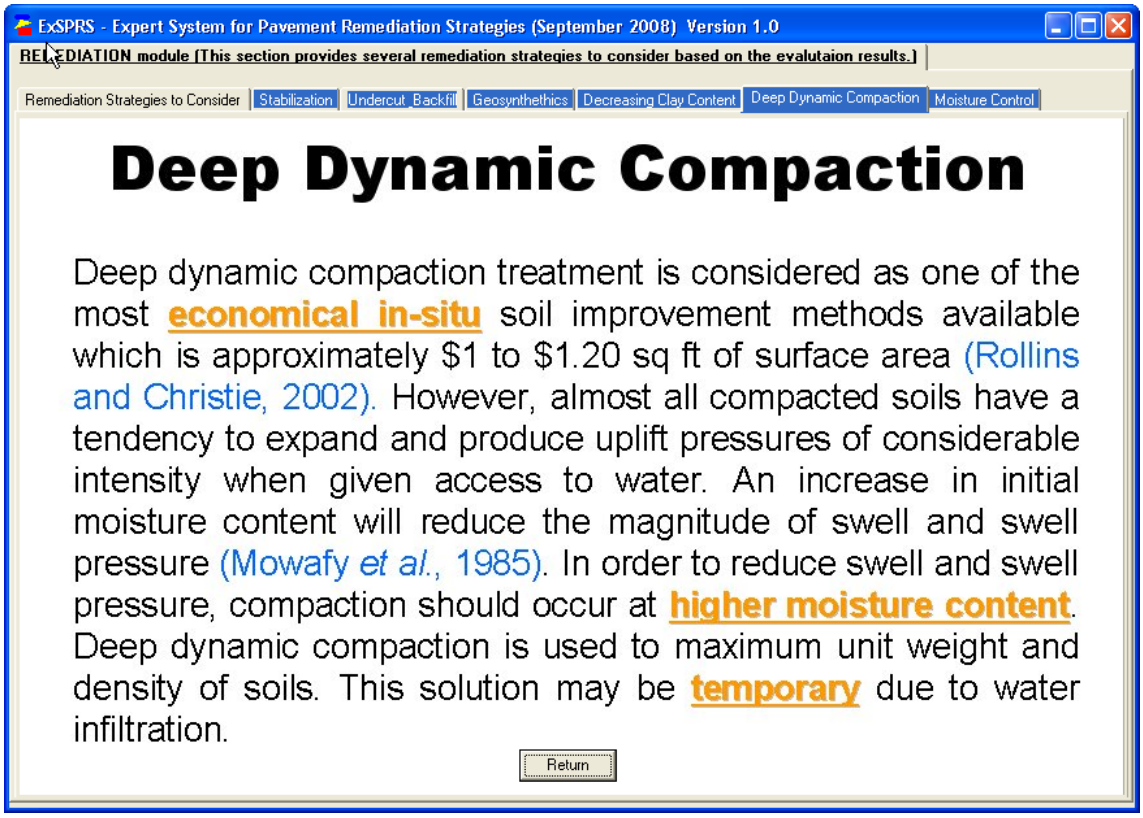


Figure 4.15—Deep Dynamic Compaction

Decreasing Clay Content

When undercut and backfill is not economically feasible, another method which is referred to as "decreasing clay content" provides an alternative. As the name implies, this process is to dilute expansive soils with non-expansive fill. It is less time consuming and cheaper compared to undercut and backfill when quantities of non-expansive fills are limited. When this method is selected, the program provides the user with the equations based on literature review to quantify required volume of mixing sand (see Figure 4.20).

The user is encouraged to explore all remediation strategies that are of interest. After studying the feasible modification methods, the user can proceed to the ***COST-BENEFIT*** module by selecting the button on the bottom right screen to determine which of the strategies are economically feasible. As mentioned at the beginning of this chapter, this module was to provide the user with the remediation option available to him/her based on the evaluation checks. For each remediation strategy selected, the user needs to provide additional information in order for that strategy to be analyzed and its benefit and cost determined. This is covered in the next chapter.

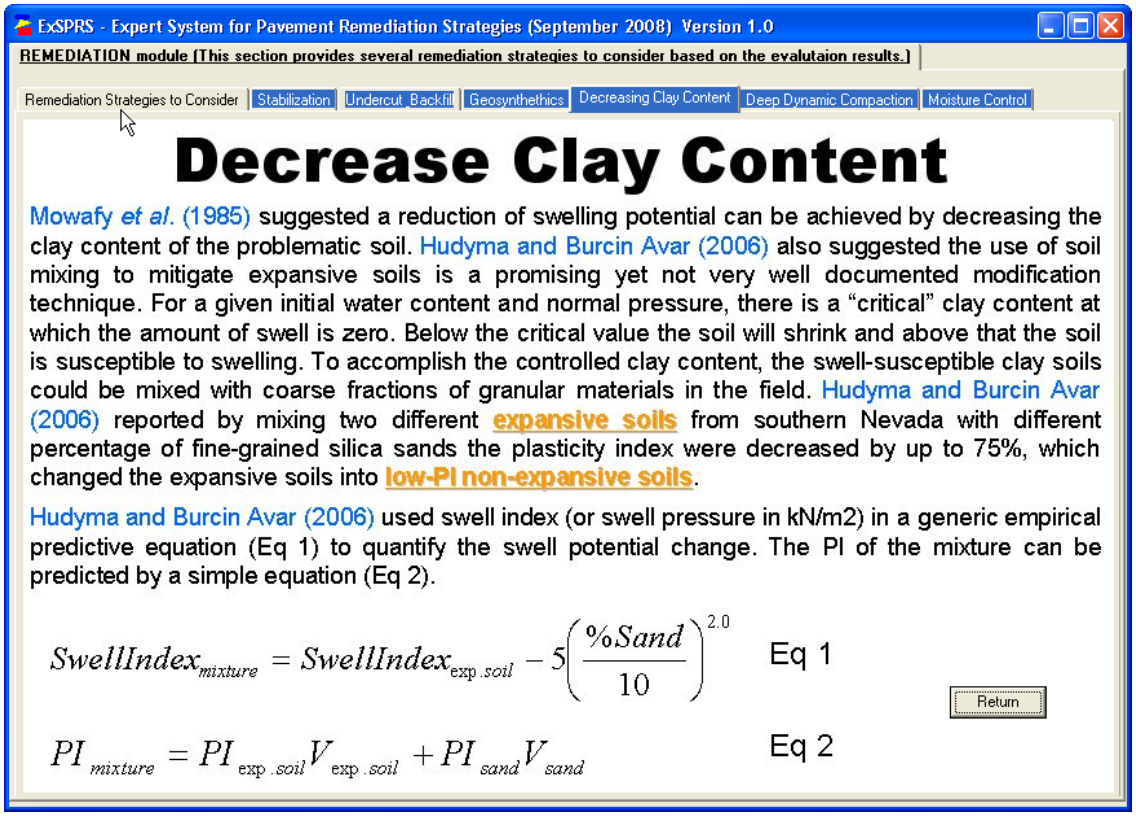


Figure 4.16—Decreasing Clay Content

CHAPTER 5 - COST-BENEFIT MODULE

In this chapter, the following items are discussed as used in the ***COST-BENEFIT*** module:

- Determination of unit costs for selected remediation strategies
- Estimation of updated pavement input parameters for selected remediation strategies
- Cost comparison of selected alternatives
- Benefit comparison of selected alternatives

The ***COST-BENEFIT*** module is the last module in the program. It provides the user with cost benefit comparison of the original design and selected remediation strategies. This module is separated into two parts:

1) Input, which acquires assumptions to estimate unit costs and updated pavement characteristic parameters to quantify benefit; and
2) Outcome, which compares cost and benefit among alternatives.

The input portion is shown first when the user first views this module. As shown in the top of Figure 5.1, all remediation strategies selected by the user are active and their corresponding treatments and unit are provided. Again if a remediation is not selected the corresponding section is grayed out. The second portion of the input is associated with the updated parameters of the pavement system that are impacted by the remediation strategies. These parameters are listed in a tabular format (see Figure 5.1).

In the second portion of the ***COST-BENEFIT*** module the outcome identifies and compares the cost and benefit of all eligible alternatives. Once all the inputs such as the detailed modification activities, unit cost and modified pavement parameters are provided, the cost-benefit analysis is computed. This outcome is presented in a similar tabular format at the bottom of the screen. In this chapter, the inputs and outcome of the cost-benefit analysis is described.

5.1 - COST ANALYSIS ASSUMPTIONS

Before describing the ***COST-BENEFIT*** module there are some basic assumptions made to simplify the procedure without compromising the results accuracy. These assumptions are presented first.

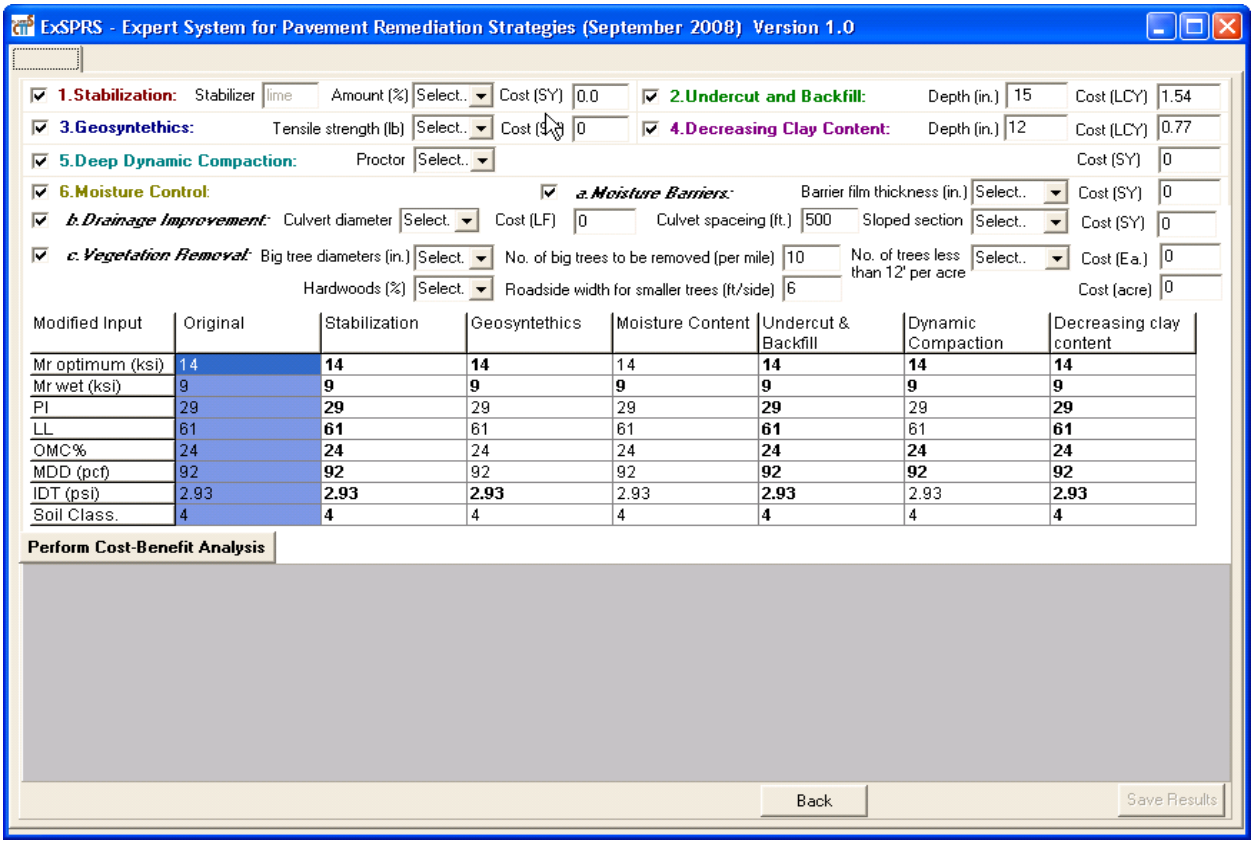


Figure 5.1—Cost and Benefit Analysis

Basic Assumptions

- For a typical lower classification pavement cost analysis, only the agency costs are considered due to the fact that the low-volume roads typically experience low daily traffic. The user costs are considered minimal and are omitted in cost estimates.
- Construction time estimation is also omitted assuming that the agency cost to be the controlling parameter.
- The agency cost is estimated using unit cost approach. Unit price information was obtained from the RS Means CostWorks Data for Heavy Construction (R.S. Means 2007). These unit cost data can be easily updated with the most current information as they become available.
- RS Means differentiates unit costs for same construction activity with different lift thickness. User defined layer thicknesses are interpolated/extrapolated based on available lift thickness information.
- Cost analysis is only considered for road lanes, and shoulders are excluded. By default, the roadway section being analyzed is a one-mile, two-lane low-volume road with 12-ft-wide lanes.
- New pavement is assumed for planning construction activities. Only main construction activities are considered, which include, but not limited to excavation, backfill, compaction,

and preparation of subbase, base, and AC layers. Minor activities such as underground utility removal, drainage and manhole installation, bridge or culvert construction, surface detailing and finishing are eliminated.

- One crew with one shift is used for all activities since expediting with more crew members or shifts results higher unit cost. For each activity, normal or ideal set of working conditions are considered. No variability is considered to account for changes in weather or other factors during the construction.
- For each remediation strategy the cost is considered separately, since they are independent of one another.

Cost Input

In Figure 5.1, the top portion of the ***COST-BENEFIT*** module shows the input needed for cost estimation of selected remediation strategies. The user needs to either select from the drop-down list or to enter numerical values for each activated remediation method. Unit cost for each strategy will be provided at the right side for quick reference.

The following sections discuss these cost input for each remediation in detail.

- Stabilization: Recall that in the ***REMEDIATION*** module the appropriate stabilizer was selected. For this example the stabilizer was lime. This information is passed and loaded in this module. ExSPRS automatically loads accordingly cost information in a drop-down list with different mix percentage. As an example, the user can select 4% mix. The unit cost for 4% lime stabilization of 12-inch lift is retrieved to be $\$11.3/yd^2$ (12-inch lift means the total treatment depth that was entered in ***INPUT*** module). As a special note, for each remediation strategy, there maybe more than one possible treatment activities available. To continue with the lime stabilization example, the user is required to identify mix percentage, but not the lift thickness. In construction however, it maybe achieved by stabilizing one single layer of 12-inch, two layers of 6-inch each, or other lift thickness combinations. The rule of thumb used in ExSPRS is always to select the cheapest one among possible pool of activities. In this case, a single layer of 12-inch treatment is cheaper than 2 runs of 6-inch layer, and that is the reason the unit cost of $11.3 is reported. If the costs need to be modified in the future, then the file installed with the program called "CostAnalysis v2.xls" needs to be updated. An example for each tab sheet in the excel file can be followed to update the proper unit cost.
- Undercut and backfill depth is automatically inputted from previous calculation. The cost associated with this method includes excavation and backfill. No extra input is needed.
- Geosynthetics: The only information needed from the user is to select the tensile strength for the geosynthetic. R.S. Means 2007 reports the tensile strength per fabric sheet in terms of pounds (lb). The available options are 120-lb, 200-lb and 600-lb. Other associated installation costs are not considered due to lack of information.
- Moisture control methods have three different categories which are identified as *a) Moisture Barriers; b) Drainage Improvement; and c) Vegetation Removal.* All encountered costs will be added up together for the final cost estimation of moisture control.

  a). *Moisture Barriers*: Regular drainage geotextile is assumed. The user will be asked for the geotextile film thickness.

b). *Drainage Improvement*: There may be several ways to improve drainage. Additional costs considered by the program include grading sloped sections and the use of culvert either to build cross-drain structures, water bars or as inlet and outlet. The user needs to provide culvert diameter, spacing and slope description (gentle or steep).

c). *Vegetation Removal*: The user needs to select from drop-down lists of the following information: diameter of big trees (meaning diameter bigger than 12-inch) to be removed per road length (entered in ***INPUT*** module); number of small trees (diameter less than 12-inch) per acre; percentage of hardwoods and roadside width for small trees (ft./side)

- Due to the lack of cost data for deep dynamic compaction, airport subgrade compaction is used as a substitute. The user needs to select the percentage of standard proctor density from R.S. Means' available pool of 80%, 85%, 90% and 95%.
- The agency cost for decreasing clay content method includes three parts: excavation, backfill and mixing. Due to lack of information, it is estimated the same way as undercut and backfill, with half the depth entered by the user (meaning a partial mix and replacement).

Table 5.1 gives an example of summarized cost analysis input that the user can follow to practice with the program.

Table 5.1—Summary of Cost Analysis Assumptions (Fort Worth Case Study)

Stabilization		Stabilizer	Lime
		Stabilization percent mix	4%
Geosynthetics		Geosynthetics tensile strength (psi)	600
Moisture Control	**Drainage Improvement**	Culvert Diameter (in)	12
		Culvert Spacing (ft)	500
		Sloped Section	Gentle
	Barriers	Barrier film thickness (in)	0.44
	Vegetation Removal	Big Tree Diameters (for trees bigger than 12")	12-24
		Number of big trees to be removed (per mile)	10
		Number of trees less then 12" per acre	Up to 400
		Percentage of hardwoods	0-25%
		Roadside Width for smaller trees (ft./side)	6
Undercut and Backfill		Undercut and backfill depth (in.)	13
Deep Dynamic Compaction		Compaction Depth (in.)	24
		Percentage of standard proctor density	95%

5.2 - BENEFIT INPUT

The benefit input portion of this module is based on comparing structural and performance evaluation results for the original design and that after using a remediation strategy. These changes in evaluation results are caused by changes in input parameters. The user will be asked to provide new input for those changed parameters by either performing laboratory tests or use their best estimation. The benefit input table will originally show the values of the original design for cases being analyzed. First column automatically loads the user's input from earlier

steps. The other columns are designated for remediation strategies as identified with corresponding remediation keyword. The values in these columns need to be modified if the corresponding remediation strategy was selected (in ***REMEDIATION***. module). Parameters that are likely to be impacted by the remediation strategy are bolded.

The following are some general discussions on changes of expansive subgrade soil properties caused by each remediation strategy. The changing trend of the parameters under each treatment is tabulated in Table 5.2 with "⇧" meaning increase, "⇩" meaning decrease, "⇳" meaning either increase or decrease is possible, and "—" meaning no change. The information can assist the user as a guide to estimate the appropriate input values. Additional information can be found in TxDOT Research Reports 0-5430-1 and 2.

Table 5.2—Summary of Parameter Changing Trend for Remediation Strategies

Parameters	**Remediation Strategies**					
	Stabilization	**Geo-synthetics**	**Moisture Control**	**Undercut & Backfill**	**Deep Dynamic Compaction**	**Decrease Clay Content**
$Mr_{optimum}$ (ksi)	⇧	⇧	—	⇳	⇳	⇳
Mr_{wet} (ksi)	⇧	⇧	⇧	⇳	⇳	⇳
PI	⇩	—	—	⇳	—	⇳
LL	⇩	—	—	⇳	—	⇳
OMC (%)	⇳	—	—	⇳	⇳	⇳
MDD (pcf)	⇳	—	—	⇳	⇳	⇳
IDT_{dry} (psi)	⇧	⇧	—	⇳	⇳	⇳
Triaxial Test	⇧	⇧	—	⇳	⇳	⇳

Expansive clays are usually chemically stabilized with cement, lime or fly ash to reduce their plasticity index, liquid limit, volume change potential, and maximum dry density and to improve optimum water content, shrinkage limit, and shear and tensile strength properties. (Croft, 1967; Little, 1999; Thompson, 1966; Bell, 1996; Basma and Tuncer, 1991) Different results are reported by researchers on how much these parameters changed.

The use of geosynthetics as reinforcement for subgrade soils in both wet and dry conditions increases tensile strength and initial stiffness of the subsoil, decreases long-term vertical and horizontal deformation, reduces desiccation cracking, fatigue cracking and rutting, and helps in holding the pavement system together better (Gurung, 2003; 1983; Abd El Halim et al., 1983; Cicoff and Sprague, 1991; Steward et al., 1977; Giroud and Noiray, 1981; Montanelli, *et al.*, 1999). However, the benefits of using geosynthetics are more noticeable for future performance rather than initial parameter values. Measured values of stresses, strains, deflections and other parameters are highly case specific. As many researchers have suggested, an average design improvement factor could be used. From literature review, this improvement factor ranges from 1.5 to 2.

Moisture control methods do not change soil properties, but rather minimize moisture migration and fluctuation. Thus prevent or minimize the subgrade from expanding during wet seasons and shrinking during dry periods. With moisture control remediation implemented, parameters such as subgrade modulus, shrinkage strain and triaxial test results will be controlled in a much smaller variation range for worst case scenarios.

Undercut and backfill method removes poor subgrade and replaces it with high quality fill. This procedure changes every aspect of subgrade soil, thus new tests are required to identify soil characteristic properties.

Deep dynamic compaction is a temporary method to densify unstable or weak subgrade. With high-energy impacts, unit weight, dry density, strength, stiffness and swell/shrinkage potential of subgrade soils are modified.

The main purpose of decreasing clay content method is to reduce problematic subgrade volumetric change potential by diluting expansive soils with non-expansive fills. Similar to undercut and backfill, every soil characteristic property will change.

For the purpose of this example, changes to the parameters required based on the remediation strategies are made based on educated guess. Again, laboratory testing would need to be carried out in order to obtain those values. The modified values are shown in the highlighted section of Figure 5.2.

5.3 - COST-BENEFIT ANALYSIS RESULTS

Figure 5.3 represents the cost analysis results for our example case. The original design costs about $347,000/mile, followed by the cost of all remediation strategies. For example, subgrade stabilization using 4% lime costs $160,000/mile and to control moisture variation by using drainage improvement, moisture barriers and vegetation removal requires an additional of $110,000/mile. However, for the remaining four remediation strategies the cost was less than $50,000/mile. To justify the benefit of each remediation method, before-after analysis results should be carefully studied. The detailed results for evaluation models are presented in this table, with a GREEN color for those that passed the criteria, and a RED color for those failed.

Cost-benefit analysis opens the door for more in-depth understanding regarding how to reach a reasonable and satisfactory design for low-volume road. A good design relies on not one single factor but many factors combined. ExSPRS program tries to identify a more critical combination of considerations in hoping for a favorable alternative. Expertise is invaluable to apply the findings to assist engineers in their decision making process. The following paragraph will discuss how to compare cost estimations and benefit results based on the example presented in this manual. As prevailing distress problems are different for each district, the concentration of the design goal changes, which in turn will yield different user preferences. In the example case, let's assume longitudinal cracking is reported to be the main issue and thus decreasing subgrade moisture susceptibility become more critical than other aspects. Computational results shown in Figure 5.3 indicates placing a geosynthetic reinforcement layer near base-subgrade interface provides the most benefits in keeping longitudinal cracking problem away. Also, by referring to the cost estimation, using geosynthetics seems to be a very cost-effective choice. Thus, original

design with geosynthetic reinforcement is very favorable compared to other possibilities. Please keep in mind that the values used in this example as benefit input were hypothetical and are for demonstration purpose only.

After the analysis is complete, the program provides a "Save Results" button at the bottom of the Cost-Benefit Analysis module, which allows the user to save the results in an Excel format.

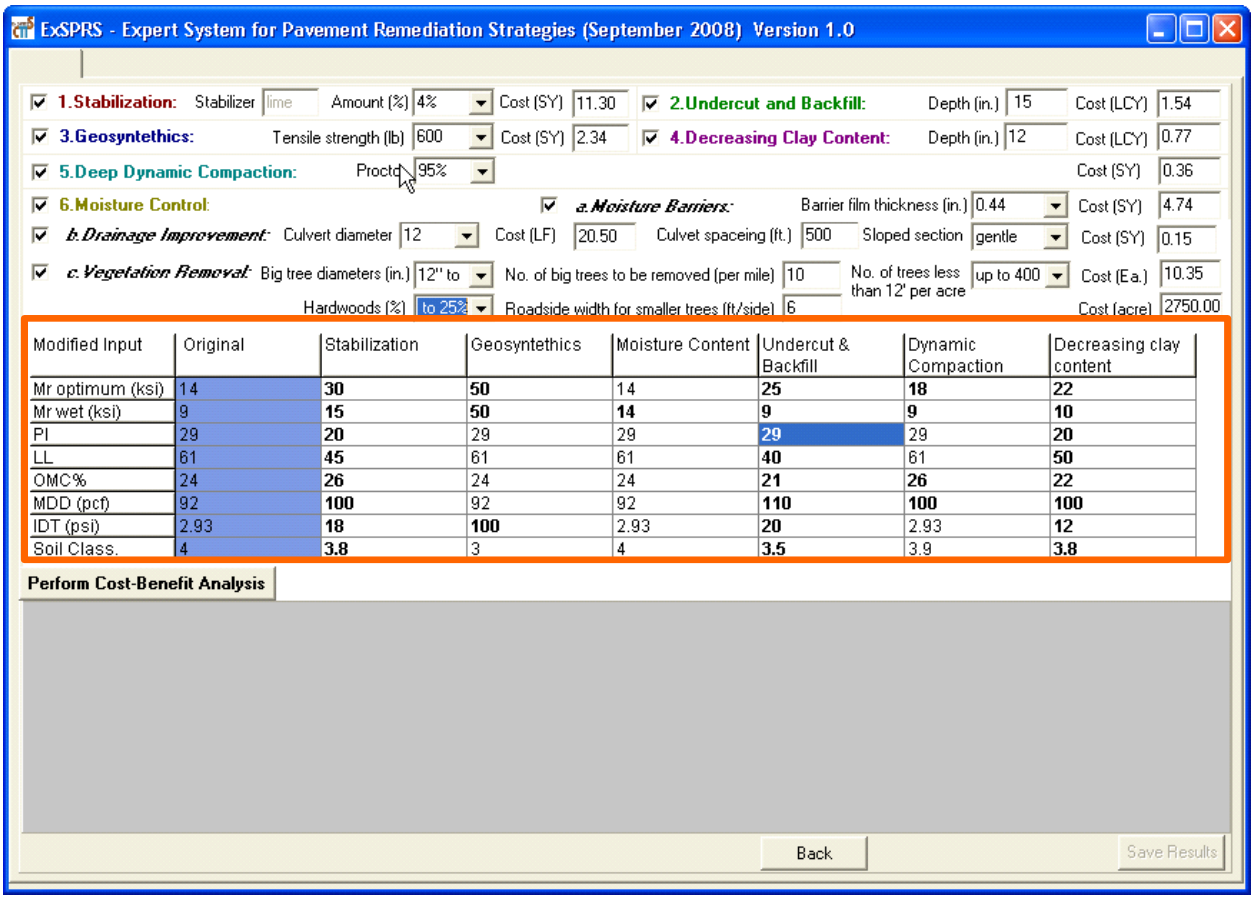
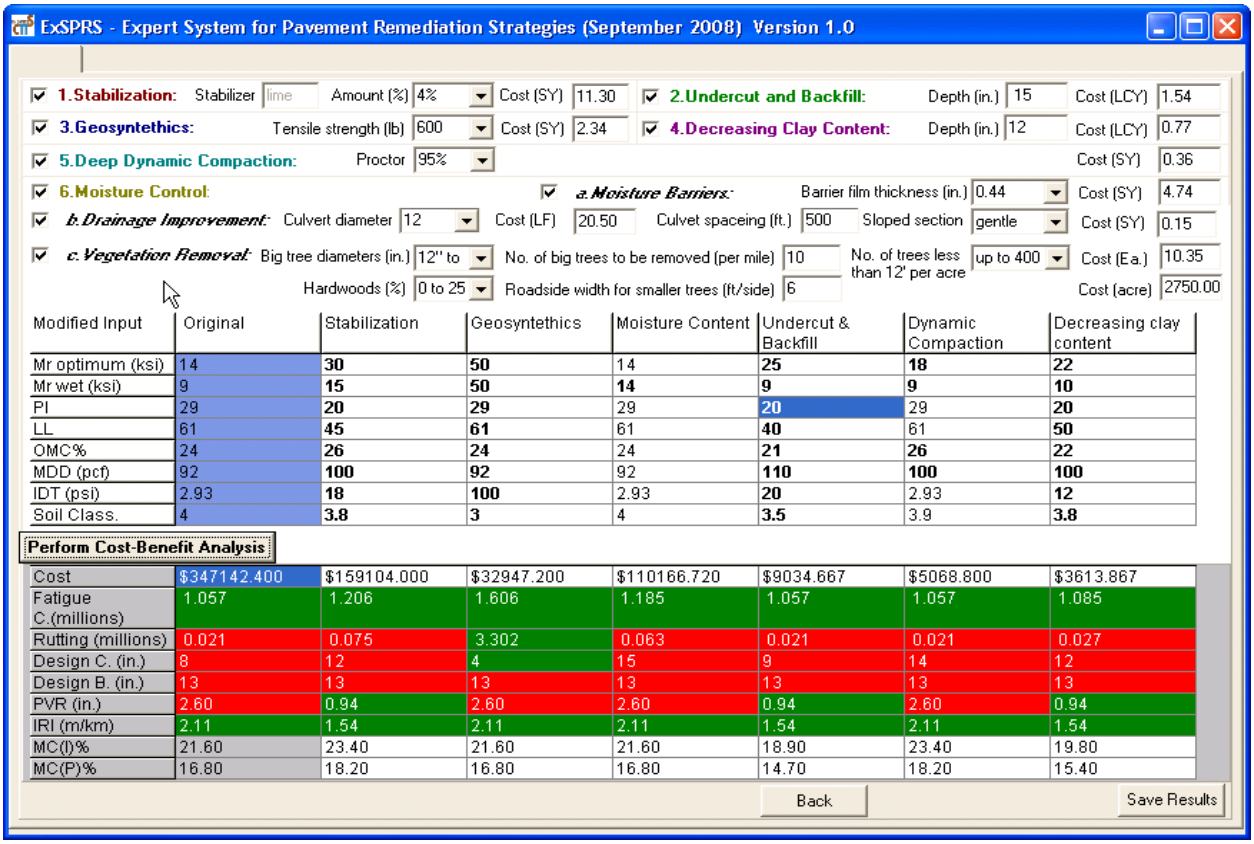


Figure 5.2—Pavement Parameters Modified for Each Remediation Strategy



Modified Input	Original	Stabilization	Geosynthetics	Moisture Content	Undercut & Backfill	Dynamic Compaction	Decreasing clay content
Mr optimum (ksi)	14	**30**	**50**	14	**25**	**18**	**22**
Mr wet (ksi)	9	**15**	**50**	**14**	**9**	**9**	**10**
PI	29	**20**	**29**	29	**20**	29	**20**
LL	61	**45**	**61**	61	**40**	61	**50**
OMC%	24	**26**	**24**	24	**21**	**26**	**22**
MDD (pcf)	92	**100**	**92**	92	**110**	**100**	**100**
IDT (psi)	2.93	**18**	**100**	2.93	**20**	2.93	**12**
Soil Class.	4	**3.8**	**3**	4	**3.5**	3.9	**3.8**
Cost	$347142.400	$159104.000	$32947.200	$110166.720	$9034.667	$5068.800	$3613.867
Fatigue C.(millions)	1.057	1.206	1.606	1.185	1.057	1.057	1.085
Rutting (millions)	0.021	0.075	3.302	0.063	0.021	0.021	0.027
Design C. (in.)	8	12	4	15	9	14	12
Design B. (in.)	13	13	13	13	13	13	13
PVR (in.)	2.60	0.94	2.60	2.60	0.94	2.60	0.94
IRI (m/km)	2.11	1.54	2.11	2.11	1.54	2.11	1.54
MC(I)%	21.60	23.40	21.60	21.60	18.90	23.40	19.80
MC(P)%	16.80	18.20	16.80	16.80	14.70	18.20	15.40

Figure 5.3- Cost-Benefit Results for the Remediation Strategies

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