



Design Modulus Values Using Seismic Moduli (SMART Users Manual)

Research Report 0-1780-4

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**Conducted for:
Texas Department of Transportation &
Federal Highway Administration**

December 2005

Center for Transportation Infrastructure Systems
The University of Texas at El Paso
El Paso, TX 79968
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Seismic Moduli
(SMART Users Manual)**

by

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Executive Summary

Nondestructive testing (NDT) methods are typically used to measure the variations in the modulus of different pavement layers. The critical strains necessary to estimate the remaining lives of a pavement system are then determined from the estimated moduli. The Falling Weight Deflectometer (FWD) and the Seismic Pavement Analyzer (SPA) are two of the NDT devices used for this purpose.

The Falling Weight Deflectometer applies an impulse load to the pavement and measures the surface deflection with seven sensors. Moduli of different pavement layers can then be backcalculated from these deflections. The shortcomings of this method are the uncertainties associated with the backcalculation procedure.

The Seismic Pavement Analyzer is based on generating and detecting stress waves in a layered system. The elastic moduli of different layers are obtained from an inversion process. The SPA imparts small external loads to the pavement; therefore, seismic moduli are linear elastic moduli. To incorporate in pavement design and analysis, seismic moduli of different layers have to be adjusted to represent moduli at strain and stress levels that are close to those applied by truck traffic. To do so, the nonlinear and viscoelastic behaviors of different layers should be accurately determined. These nonlinear parameters vary widely for different types of granular base and subgrade materials. The nonlinear parameters of each pavement layer can be preferably obtained from laboratory testing. However, adequate published information is available to be used as a first approximation.

The major objective of Project 0-1780 is to develop an algorithm for predicting the design modulus of each layer given the seismic modulus and the nonlinear parameters of each pavement layer. This is the fourth document produced as a part of this project. In the first three documents, the feasibility of the concept was demonstrated, a methodology considering the day-to-day operation of the Texas Department of Transportation (TxDOT) was studied, and an algorithm that utilizes the material model, which relates the design modulus with seismic modulus, was developed. This led to adoption of the so-called equivalent-linear structural model. An equivalent-linear model is based on an elasto-static layered system modified to incorporate the material model through an iterative process. Also investigated was an optimization algorithm to derive the nonlinear parameters of pavement materials from the FWD deflections and the seismic moduli.

The efforts towards combining all algorithms in a software package called SMART (Seismic Modulus Analysis and Reduction Tool) are described in this report. Also included is a user's manual for SMART.

Implementation Statement

With the initiation of the NCHRP Project 1-37A, which aims towards a mechanistic pavement design implemental by all highway agencies, this project may have significant impact. To develop a mechanistic pavement design that can contain performance-based specifications, the same engineering properties that are used to design a pavement should be used to determine the suitability of a material for construction and should be specified as criteria for accepting the material placed at the site. The only practical and available method at this time is based on seismic testing. Furthermore, it seems that with proper laboratory testing technique and proper simulation one can develop remaining life models that are more realistic.

Some of the software and protocols being developed can also be applied in pavement design with the FWD.

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Chapter 1

Introduction

OVERVIEW

The main purpose of the Seismic Modulus Analysis and Reduction Tool (SMART) program is to use seismic moduli and well-substantiated nonlinear relationships to provide representative moduli for pavement design and analysis. The SMART program incorporates seismic moduli in a constitutive model recommended by a National Cooperative Highway Research Program (NCHRP) research project to determine the pavement responses in terms of the stress and strain developed within the pavement structures.

The successful use of pavement design or evaluation algorithms requires a balance between the input parameters, the structural models, and the transfer functions. Striking such balance depends on the different levels of sophistication associated with different types of roads. For example, using simplified empirical models may be adequate for many tertiary roads in the network. Secondary roads can be simply designed using criteria developed based on FWD results and linear-elastic models. However, major highways should take advantage of thorough laboratory and field tests, with a reasonably sophisticated nonlinear-elastic algorithm.

The development of algorithms and models used in SMART has been well-documented TxDOT report 1780-1 (Nazarian et al., 1998), 1780-2 (Ke et al., 2000) and 1780-3 (Meshkani et al., 2001). This report will focus on the use of the SMART program. The report will contain the following:

- 1) Installation requirements
 - a. System requirements
 - b. Installation process
- 2) Users guide
 - a. Step by Step on how to use SMART
 - b. Description of options available in the program

ORGANIZATION

Chapter 2 provides an overview of the theory and algorithms used in SMART. Chapter 3 contains the system requirements and installation process involved in preparing SMART to be utilized on a PC. Chapter 4 contains a detailed guide of how to use SMART.

Chapter 2

Overview of SMART Algorithms

INTRODUCTION

This program was designed based on the classical layered elastic theory. The difference between this program and typical linear-elastic programs is in the analysis of the structural response of the pavement system. Although the algorithm is not strictly a nonlinear algorithm, it accounts for the nonlinear behavior of the pavement materials under actual truck traffic. The algorithm integrated in this program is a compromise between the simple linear model and comprehensive nonlinear model. This algorithm takes advantage of the speed of the linear analysis while incorporating the nonlinear behavior of the pavement. The algorithm is referred to as an equivalent-linear analysis method.

Each of the algorithms and models used in SMART are briefly discussed in this chapter. For more detail explanation to the development process, refer to TXDOT Reports 1780-1, 1780-2 and 1780-3. To facilitate understanding and use of the algorithm package used in SMART, First a description of the models is presented. Second, a description of each algorithm based on the pavement layers system is presented. Finally, a flowchart that demonstrates the big picture is provided.

LINEAR-ELASTIC MODEL

The simplest models for evaluating the behavior of pavements under load are linear-elastic models. The constitutive model for a linear-elastic material is rather simple since the modulus is considered as a constant value independent of the state of stress applied to the pavement. Therefore, the modulus of each layer does not change with the variation in other properties. Most algorithms used in pavement analysis and design takes advantage of this type of solution. KENLAYER (Huang, 1994), WESLEA (Van Cauwelaert et al., 1989), and BISAR (De Jong et al., 1973) are three of the popular programs in this category. The advantage of these models is that they can rapidly yield results. Their main limitation is that the results are rather approximate if the loads are large enough for the material to exhibit a nonlinear behavior.

VISCOELASTIC MODEL

The AC modulus is strongly dependent on temperature. Aouad et al. (1993), Li and Nazarian (1994) and several other investigators have studied the variation in modulus with temperature. The relationship suggested by Li and Nazarian (1994) for adjusting the modulus of AC to a reference temperature of 77° F (25° C) was used here. That relationship is in the form of

$$E_{77^{\circ}\text{F}} = \frac{E_t}{1.35 - 0.0078(t - 32)} \quad (2.1)$$

where $E_{77^{\circ}\text{F}}$ and E_t are the moduli at 77° F and temperature t (in Fahrenheit).

Using the principals of viscoelastic and time-temperature superposition, Witczak and his colleagues have provided a relationship that can be used to adjust the moduli for frequency and temperature through the so-called master curve. The Mechanistic Design Guide encourages the use of the master curve. Witczak et al. (1999) describe the newer methodology proposed in the development of the master curve. A typical distribution of complex modulus with time and temperature of an asphalt concrete mixture is shown in Figure 2.1. The general practice has been that the testing is performed at various temperatures at similar loading times (see Figure 2.1a, then a data is shifted based on a reference temperature using a time-temperature shift factor (see Figure 2.1b) and finally a master curve is generated at the reference temperature using a curve fitting technique (see Figure 2.1c). The master curve is then developed based on the assumption that asphalt concrete is a thermo-rheologically simple material. The results presented in Figure 2.1 are shifted horizontally to develop a master curve.

A sigmoidal function proposed by Ferry (1970) can be used to generate a master curve. The sigmoidal function is in the form of:

$$\log(E^*) = \delta + \frac{\alpha}{1 + e^{\beta + \gamma \log t_r}} \quad (2.2)$$

where E^* = dynamic modulus, t_r = loading period, δ = minimum value of dynamic modulus, $\delta + \alpha$ = change in dynamic modulus and β, γ = sigmoidal function shape parameter.

Mirza and Witczak (1995) have proposed the following relationships for obtaining values of the sigmoid parameters in the absence of lab tests:

$$\begin{aligned} \delta = & -1.249937 + 0.02932\rho_{200} - 0.001767\rho_{200}^2 - 0.002841\rho_4 \\ & - 0.058097V_a - \frac{0.802208V_{beff}}{V_{beff} + V_a} \end{aligned} \quad (2.3)$$

$$\begin{aligned} \alpha = & 3.871977 - 0.0021\rho_4 + 0.003958\rho_{38} \\ & - 0.000017\rho_{38}^2 + 0.005470\rho_{34} \end{aligned} \quad (2.4)$$

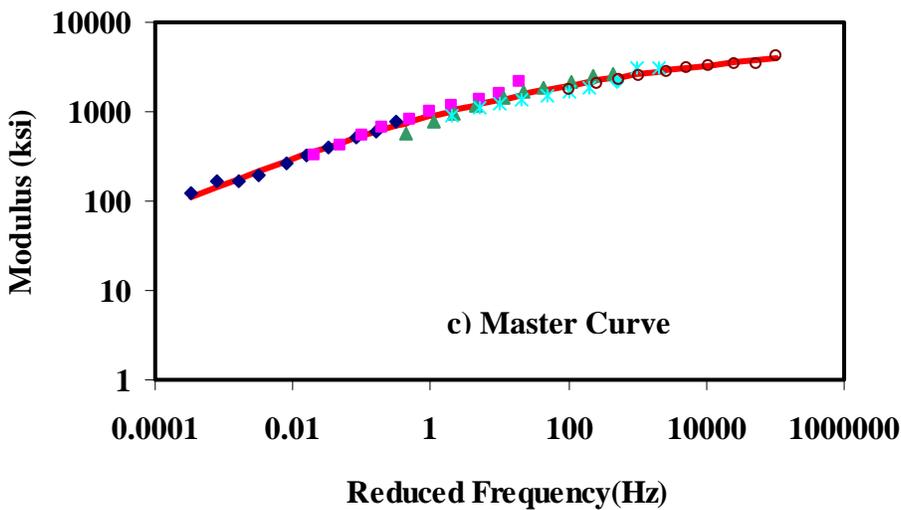
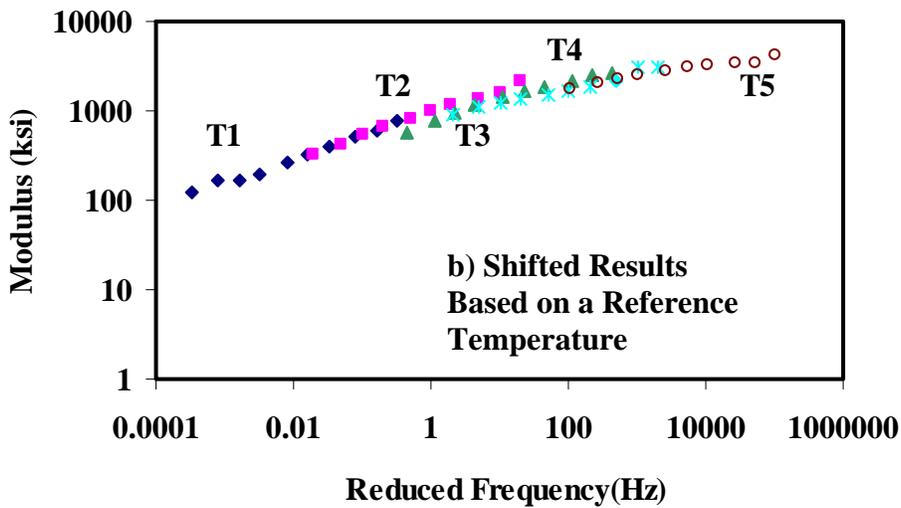
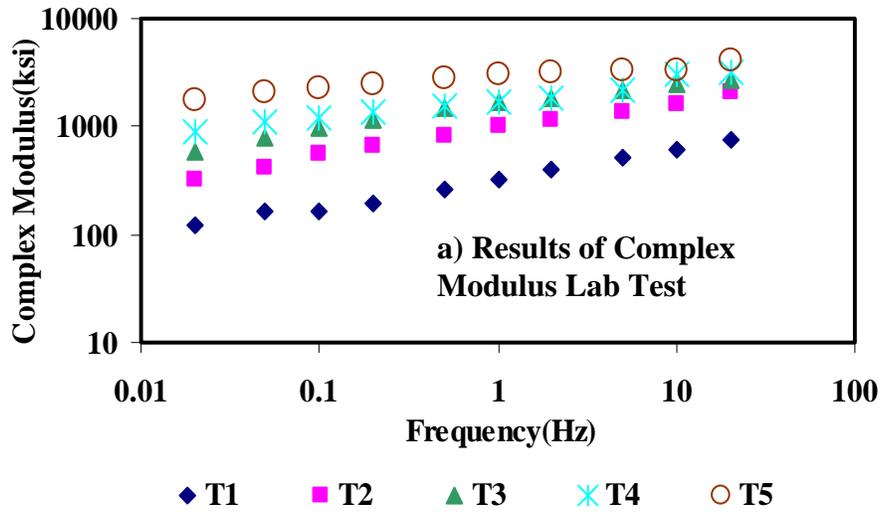


Figure 2.1 - Master Curve Concept

$$\beta = -0.603313 - 0.393532 \log(\eta_t) \quad (2.5)$$

$$\gamma = 0.313351 \quad (2.6)$$

where ρ_{200} is percent passing on the 0.075mm sieve, ρ_4 is cumulative percent retained on the 4.76 mm sieve, V_a is percent air voids in the mix by volume, V_{beff} is percent effective bituminous content by volume, ρ_{38} is cumulative percent retained on the 9.5 mm sieve, ρ_{34} is cumulative percent retained on the 19 mm sieve, η_t is viscosity of the binder at a reference temperature.

Once the master curve is established, either from lab testing or from the regression relationships presented in Equations 2.3 through 2.6, the design modulus can be readily determined from the design vehicular speed and the design temperature as recommended in the Mechanistic Design Guide

Saeed and Hall (2001), based on tests on a half a dozen specimens have shown that the seismic modulus and the master curve from complex modulus correlate well. An example from one site is shown in Figure 2.2. Typical results from one material when the seismic (defined by the gray region) and complex moduli are combined are shown in Figure 2.3. The process of defining the design modulus is marked on the figure as well. First a reference temperature is defined for the regional. A design frequency is then determined based upon the vehicular speed. The desired modulus based on these two input parameters can be readily defined.

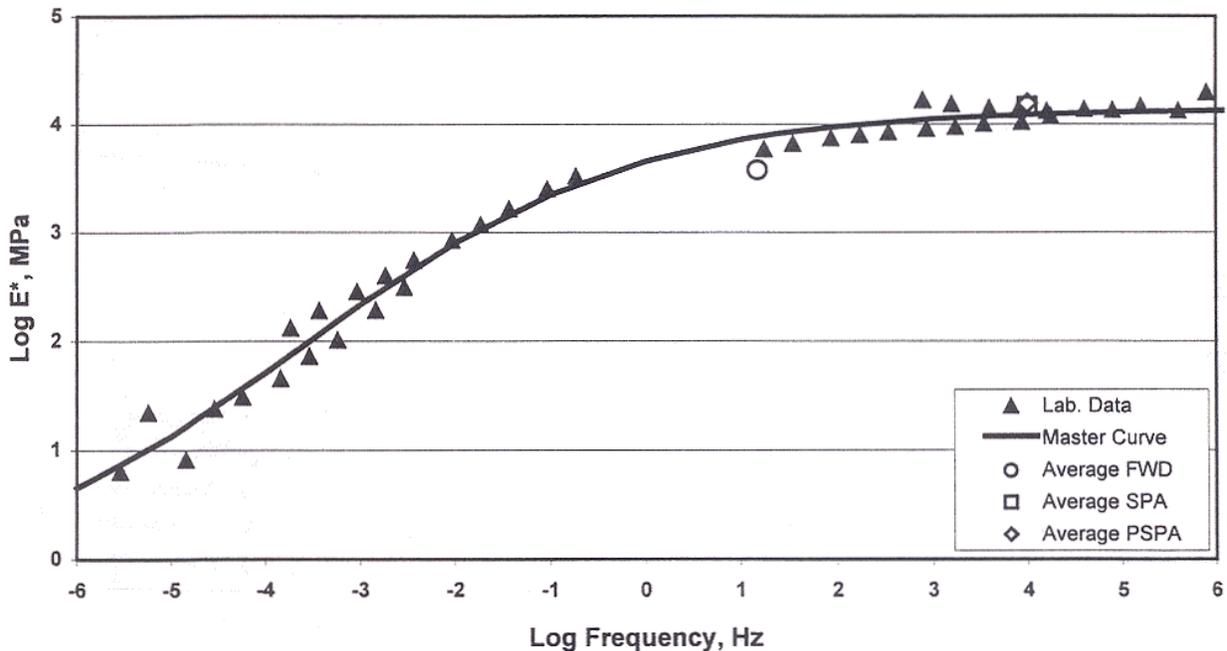


Figure 2.2 - Master Curve from Complex Modulus Compared with Moduli measured from Different NDT Tests (from Saeed and Hall, 2001)

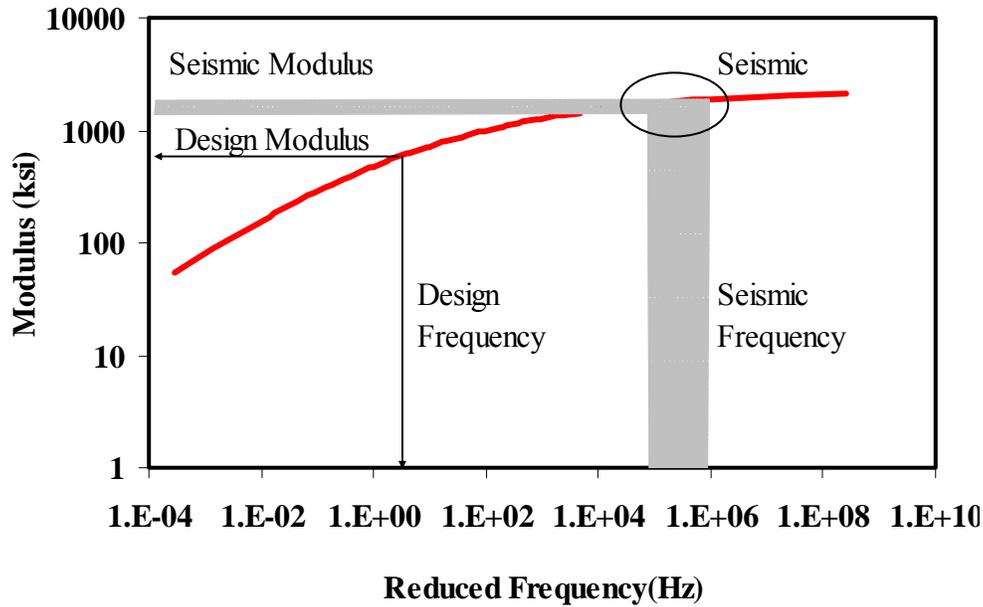


Figure 2.3 - Master Curve Concept for defining Seismic Modulus

EQUIVALENT-LINEAR MODEL

An equivalent-linear model is a model that in an approximate fashion can consider the load-induced nonlinear behavior based on the static linear-elastic-layered theory. An iterative process is employed to consider the nonlinearity of the pavement materials. The constitutive model adopted in the equivalent-linear model is:

$$E = k_1 \sigma_c^{k_2} \sigma_d^{k_3} \quad (2.7)$$

In this equation, k_1 , k_2 and k_3 are statistically determined coefficients. In Equation 2.7, the modulus at a given point within the pavement structure is related to the state of stress. Since the state of stress can be known only if the material properties, including modulus, are known, an iterative process has to be used to implement this stress-modulus relationship. The advantage of the model presented in Equation 2.7 is that it is universally applicable to fine-grained and coarse-grained base and subgrade materials.

In Equation 2.7, the term $k_1 \sigma_c^{k_2}$ corresponds to the initial tangent modulus, E_{max} , which is related to the confining pressure. Normally parameter k_2 is positive. Therefore, the initial tangent modulus increases as the confining pressure increases. Parameter k_3 suggests that the modulus changes as the deviatoric stress changes. Because k_3 is usually negative, the modulus decreases with an increase in the deviatoric stress.

One of the major purposes of this study is to relate the seismic modulus with the load-induced nonlinear modulus. For this reason, parameter k_1 in Equation 2.7 will be replaced by a term that is a function of the seismic modulus and the stresses under seismic test.

Therefore, after arithmetic manipulation and substitution the nonlinear modulus can be related to the seismic modulus through (see Report 1780-2 and 1780-3)

$$E = E_{seis} \left(\frac{\sigma_{c_ult}}{\sigma_{c_init}} \right)^{k_2} \left(\frac{\sigma_{d_ult}}{\sigma_{d_init}} \right)^{k_3} \quad (2.8)$$

Compared to Equation 2.7, parameter k_1 is eliminated when the seismic modulus is considered as input. Equation 2.8 can be used in an equivalent-linear model to obtain the modulus of a nonlinear material in this study.

Another variation to Equation 2.7 is model developed by the Georgia Department of Transportation (GADOT). In that study, Santha (1994) collected and tested a number of soil samples to determine parameters k from resilient modulus tests. He also obtained various construction parameters such as the moisture content, compaction, and percent saturation. He then developed regression equations for cohesive and granular materials that estimate parameters k from the construction parameters using the octahedral shear stress model:

$$M_R = k_1 P_a \left[\frac{\theta}{P_a} \right]^{k_2} \left[\frac{\tau_{oct}}{P_a} \right]^{k_3} \quad (2.9)$$

where $\theta = \sigma_1 + \sigma_2 + \sigma_3$ is the bulk stress, τ_{oct} is the octahedral shear stresses, P_a is the atmospheric pressure, and k_1 , k_2 and k_3 are multiple regression constants evaluated from resilient modulus test data. According to Santha, for granular material the three k parameters are in the form of

$$\begin{aligned} \log(k_1) = & 3.479 - 0.07 * MC + 0.24 * MCR \\ & + 3.681 * COMP + 0.011 * SLT + 0.006 * CLY \\ & - 0.025 * SW - 0.039 * DEN + 0.004 * (SW^2 / CLY) \\ & + 0.003 * (DEN^2 / S40) \end{aligned} \quad (2.10a)$$

$$\begin{aligned} \log(k_2) = & 6.044 - 0.053 * MOIST - 2.076 * COMP \\ & + 0.0053 * SATU - 0.0056 * CLY + 0.0088 * SW \\ & - 0.0069 * SH - 0.027 * DEN + 0.012 * CBR \\ & + 0.003 * (SW^2 / CLY) - 0.31 * (SW + SH) / CLY \end{aligned} \quad (2.10b)$$

$$\begin{aligned} \log(k_3) = & 3.752 - 0.068 * MC + 0.309 * MCR \\ & - 0.006 * SLT + 0.0053 * CLY - 0.026 * SH \\ & - 0.033 * DEN - 0.0009 * (SW^2 / CLY) \\ & + 0.00004 * (SATU^2 / SH) - 0.0026 * (CBR * SH) \end{aligned} \quad (2.10c)$$

and for cohesive materials,

$$\begin{aligned}\log(k_1) = & 19.813 - 0.045 * MOIST - 0.131 * MC \\ & - 9.171 * COMP + 0.0037 * SLT + 0.015 * LL \\ & - 0.016 * PI - 0.021 * SW - 0.052 * DEN \\ & + 0.00001 * (S40 * SATU)\end{aligned}\quad (2.11a)$$

$$\begin{aligned}\log(k_3) = & 10.274 - 0.097 * MOIST - 1.06 * MCR \\ & - 3.471 * COMP + 0.0088 * S40 - 0.0087 * PI \\ & + 0.014 * SH - 0.0246 * DEN\end{aligned}\quad (2.11b)$$

where MC is moisture content, MOIST is optimum moisture content, MCR is the ratio of MC and MOIST, COMP is compaction, SATU is percent saturation, S40 is percent passing sieve No. 40, CLY is percent of clay, SLT is percent of silt, SW is percent swell, SH is percent shrinkage, DEN is maximum dry unit weight, CBR is California Bearing Ratio, LL is liquid limit, and PI is plastic limit index.

Although these equations were generated based on test sites in Georgia they can be used in the absence of resilient modulus test for determining k_2 and k_3 values.

PLASTICITY INDEX MODEL

Ishibashi and Zhang (1993) combined the effects of the confining pressure and plasticity index on modulus behavior in the form

$$\frac{E}{E_{seis}} = K(\gamma, PI)(\sigma'_m)^{m(\gamma, PI) - m_0} \quad (2.12)$$

where PI is the plasticity index of the base or subgrade material and γ is the shear strain and

$$K(\gamma, PI) = 0.5 \left\{ 1 + \tanh \left[\ln \left(\frac{0.000102 + n(PI)^{0.492}}{\gamma} \right) \right] \right\} \quad (2.13)$$

$$m(\gamma, PI) - m_0 = 0.272 \left\{ 1 - \tanh \left[\ln \left(\frac{0.000556}{\gamma} \right)^{0.4} \right] \right\} \exp(-0.0145PI^{1.3}) \quad (2.14)$$

$$n(PI) = \begin{cases} 0.0 & \text{for } PI = 0 \\ 3.37 \times 10^{-6} PI^{1.404} & \text{for } 0 < PI \leq 15 \\ 7.0 \times 10^{-7} PI^{1.976} & \text{for } 15 < PI \leq 70 \\ 2.7 \times 10^{-5} PI^{1.115} & \text{for } PI > 70 \end{cases} \quad (2.15)$$

Influence of the confining pressure on modulus reduction, E/E_{seis} , is also illustrated in Figure 2.4. At higher confining pressures, the modulus reduction, E/E_{seis} , becomes closer to one, meaning that modulus is closer to seismic modulus.

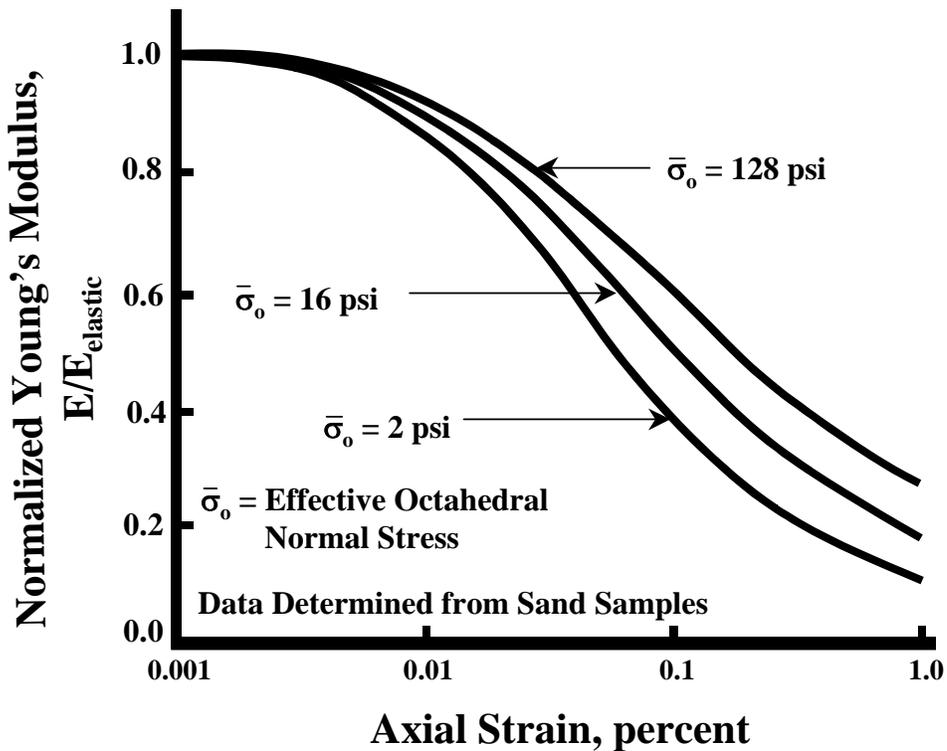


Figure 2.4 - Influence of Effective Confining Pressure on Modulus Reduction Curve

DESCRIPTION OF ALGORITHMS

The following three algorithms are incorporated into SMART:

- a multi-layer linear system, and
- a multi-layer equivalent-linear system, and
- a multi-layer nonlinear system based on the Plasticity Index.

Each of the algorithms above uses can utilize either the elastic or viscoelastic models for the Asphalt layer.

Multi-Layer Linear System

Flexible pavements are layered systems with stiffer materials on top. With the advent of computers, the theory can be applied to a multi-layer system with any number of layers (Uzan, 1994). A typical n-layer system subjected to a circular load is shown in Figure 2.3.

The basic assumptions to be satisfied are:

- Each layer is homogeneous, isotropic, and linear-elastic*.(*-Asphalt layer could be modeled as viscoelastic)
- The material is weightless and extended to infinity in horizontal directions.
- Each layer has a finite thickness, except the bottom layer, which is extended to infinity.
- A uniform pressure is applied to the pavement surface over a circular area.

SMART provides up to a total of six physical layers to be modeled (not including the rigid layer). Although the properties of the rigid layer are fixed into the program the user can select the depth to rigid layer. The depth to rigid layer could either be provided by the user or specified by the user as an infinite subgrade. The rigid layer options are same for all algorithms in SMART.

Many computer programs, such as BISAR, WESLEA and KENLAYER, are available to obtain stresses and strains for linear-elastic problems utilizing the solution of the multi-layered system. Throughout this study, algorithm from the well-established computer program BISAR was used.

Multi-Layer Equivalent-Linear System

As indicated before, the equivalent-linear model is based on the static linear-elastic layered theory. The constitutive model described in Equation 2.8 is adopted. An iterative process is employed to consider the nonlinear behavior of the pavement materials in an approximate fashion.

Chapter 5 of 1780-2 (Ke et al., 2000) describes the equivalent-linear system in detail. Basically the top layer (asphalt layer) can be modeled as elastic or viscoelastic. The nonlinear layers (base and subgrade) are modeled as any combination of linear or nonlinear. If a layer is modeled as nonlinear, the nonlinear parameters k_2 and k_3 are required as input. These values can either be obtained from lab testing, construction parameters as presented earlier in this chapter or based on the quality of the material. The nonlinear layers are divided into several sub-layers. The number of sub-layers depends on the accuracy required and the number of layers allowed by the program. This version of the program is optimized for a total of 30 layers. This allows the user to select up to three nonlinear layer with each layer divided into eight sub-layers. After the iterative process described in 1780-2 is completed a final set of design modulus values for each nonlinear layer are produced.

Multi-Layer Nonlinear System Based on Plasticity Index

The algorithm in this system adopts the model described in Equation 2.12. Similar to the Equivalent-Linear model, an iterative process is employed to consider the nonlinear behavior of the pavement materials.

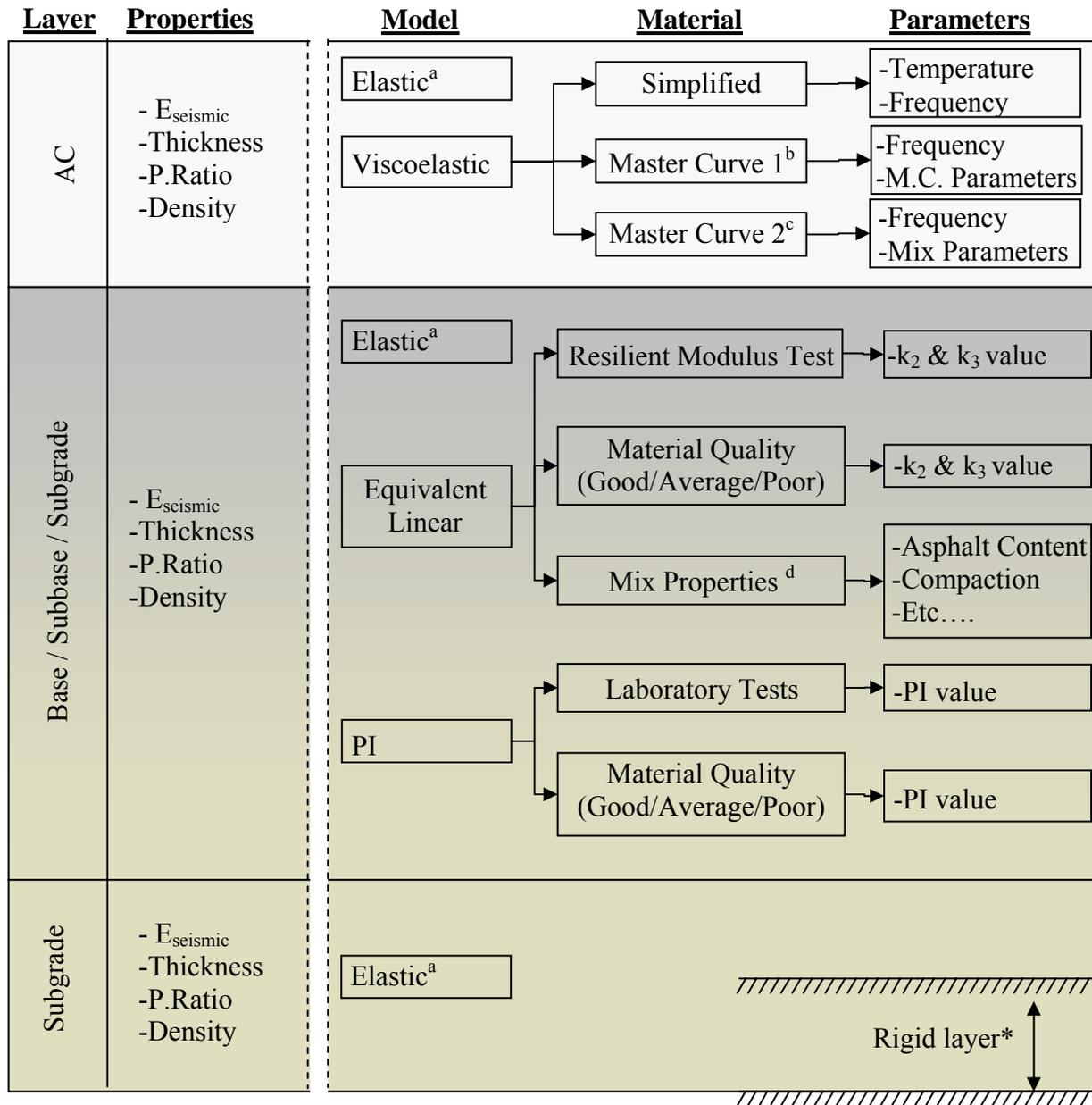
As in the equivalent-linear algorithm, the nonlinear layers are divided into several sub-layers. The number of sub-layers for this system is also eight for a maximum of three nonlinear layers. A PI value is required for each nonlinear layer. PI values for each nonlinear layer can either be obtained from the Lab or based on the quality of the material. Based on Equation 2.12, a new modulus can be obtained once an iterative process is complete (Ke et al., 2001).

Overall Algorithm

The integration of the different algorithms and models described in this chapter is best illustrated using Figure 2.5. The figure not only summarizes the overall algorithm, but illustrates the flow process used in SMART. As depicted in Figure 2.5, the models and algorithms options are dependent on each layer type. The AC layer permits users to select from two models: a) Linear-elastic and b) Viscoelastic where three material models are available for users to choose from. The base and subbase layers in SMART allow for three models: a) Linear-elastic, b) Equivalent-linear, and c) Nonlinear based on the Plasticity Index. The equivalent-linear model allows for three options that users can select from to provide material information: a) resilient modulus test, b) material quality, and c) mix properties. Likewise the nonlinear model permits users to provide material properties based on laboratory tests or material quality. The subgrade layer as presented in the figure, is separated into two parts. The first part can be modeled similar to base and subbase. The second part of the subgrade is the linear-elastic portion, which is set automatically by the program depending on the depth to rigid layer. Based on studies conducted at the early stages of this project, it was realized that after depths of 100 in. the subgrade layer behave linearly. Therefore a constraint of 100 in. was set into the program to divide the subgrade layer into the nonlinear portion up to a depth of 100 in. Another feature in the program is the rigid layer. The program allows the user to perform the analysis based on a semi-infinite layer or set a rigid layer at a specified depth. This feature is useful for pavement with shallow bedrocks.

The algorithms that are used in the program are dependent on the features that are selected for each of the project layers that are presented in the figure. SMART is flexible in allowing users to combine different models for different layers. The program has few constraints. First, the model for the first nonlinear layer will be the only selection allowed for other nonlinear layers. As an example, in a typical three-pavement system, if equivalent-linear model is selected for base layer, then the subgrade layer has to utilize the equivalent-linear model. A maximum of three nonlinear layers is allowed. Finally the nonlinear layers have to be in sequence. SMART will not allow users to set up a pavement layer system for analysis with a nonlinear base, linear subbase, and followed by a nonlinear subgrade. All three layers have to be nonlinear if the subgrade is to be nonlinear. These constraints are built into SMART to make the program very practical. These constraints are design into the program in such a way that it is easy to interact with the user interface. Once the layer system, the models, and the material properties are provided the analysis can be performed.

In the next chapters, the installation and use of the program is presented.



a- linear elastic model, b- master curve based on mix properties, c- master curve based on laboratory testing, d- mix properties using regression equations are used to estimate the nonlinear parameters k_2 and k_3 (this option is currently disabled in the program), and *- the depth to rigid layer can be adjusted by the user.

Figure 2.5 - Flowchart Summary of the Models and Properties in SMART

Chapter 3

Installation Guide

The SMART software, version 1.0, is window-based, developed with a user-friendly interface. This chapter will introduce the software guide, which is divided into two sections:

1. System Requirements
2. Installing SMART software.

This guide assumes that the user has basic knowledge about computers. This knowledge includes use of WINDOWS 98/ NT 4.0/2000/XP operating systems.

NOTE: It is strongly recommended that the user become familiarized with all the steps listed in each section of this guide, before actually carrying them out.

SYSTEM REQUIREMENTS

The minimum recommended hardware requirements are:

- IBM or compatible LAPTOP or DESKTOP with:
- Pentium processor (200 MHz or higher)
- 64 MB of RAM (128 MB recommended)
- 5 GB Hard Disk (20MB of free space recommended)
- VGA monitor or higher resolution
- CD-ROM drive
- Keyboard
- Mouse or compatible pointing device
- WINDOWS 98/NT4.0/2000/XP or higher operating system

It is recommended that a Pentium III or higher be used in order to speed up analysis and minimize program execution time.

INSTALLATION PROCESS

NOTE: When installing under the WINDOWS NT 4.0 or WINDOWS 2000 environment, all software programs must be installed from an account with Administrator privileges; otherwise, SMART may not be able to run properly after installation.

Place the SMART installation CD into the computer's CD-ROM. Follow the instructions on the screen. If the CD drive's auto-run is off, browse the CD, go to the installation directory and double click on SETUP.EXE.

The software can be installed in any hard drive under any directory. The suggested destination directory provided by the installation CD is:

C:\CHMR Programs\Seismic\SMART

The setup will automatically detect the operating system and will install the required files into their corresponding directory location. The default options in the setup process are recommended guarantying an easy and secure installation of the software. It is recommended that virus protection programs should be closed during the installation. The user can stop the setup program at any time. Once the software installation is complete, SMART can then be accessed from the program menu under the CHMR folder and should be ready for use.

To uninstall the software, follow the typical steps to Add/Remove programs under the Control Panel. When prompted to remove additional system files, select the "No to All" option. This ensures that other programs installed on the computer, which might share common system files under the operating system folder, run properly. After uninstalling the software, the SMART folder can and should be manually deleted from the computer's hard drive.

There are three sets of files that comprise the SMART software and are necessary for proper execution. The system and program files are provided during the installation process. These files are required to start the program. The third set of files is the project files. These files are not created during installation. However, they are created when using SMART. These file are used to store results of after analysis is completed.

System files

The system files are installed in the operating system directory. These files are Windows based files that are crucial to proper execute the program in windows environment. The number of files installed depends on the type of programs that currently exist on the computer. These files are usually shared by a number of programs on the system and should not be manipulated.

Program files

The program folder will contain the following files and folders.

- Countys (folder) Text files identifying all counties and districts in Texas,
- Highlitdis (folder) JPG files identifying high lights of the districts,

- Acbasesubg (folder) JPG files identifying the different layers,
- Mainmoddll.dll Processing modules,
- Calst2.dll Processing modules,
- Dforrt.dll Processing modules,
- Disperdll.dll Processing modules,
- Spinv1dll.dll Processing modules,
- Smart1.exe Application module,
- Sasw.exe Application module,
- Dbase files Database files required by SMART to run properly
consisting of data.dbf, disp.dbf, modulus.dbf, and
remlife.dbf,
- JPG files Used in graphical interface of program including front.jpg,
pav.jpg,
- Users guide.exe Contains information about installing the program and
running it,
- Palettesnew.reg Registry file used for charting
- Districts.txt Text file that contains nonlinear parameters for districts,
k2k3pib, k2k3pisb, k2k3pisg defining default K2, K3, PI
values, and
- Text files k2k3pib, k2k3pisb, k2k3pisg defining default K2, K3, PI
values, and
- AVI files progress.avi, waiting.avi used during program execution

These files will be created automatically in the program folder during the installation process.

Project Files

The project files are generated upon execution of the program. These files are stored in the user specified project folder. There are several files summarizing all the data used by the program. These files are used by SMART to retrieve and display the results of the project. The main files that are of interest to users are:

- Data.dbf: contains the pavement properties and model parameters,
- Modulus.dbf: contains modulus results,
- Application.dsc: contains project identification information,
- Appcomments.txt: contains the type of project selected,
- Infocomments.txt: contains comments about the project, and
- Layerinfo.txt: contains the layer system developed in the project

These files can be accessed independently in WordPad (ex. *.txt files) and or Excel (ex. *.dbf). Other files that are generated upon analysis are intermediate files. These files are used in different phases of the analysis process and should not be accessed by users. Appendix A contains a copy of the help file that can be accessed from the SMART program.

Chapter 4

Description of SMART

INTRODUCTION

The main purpose of the software package SMART (**S**eismic **M**odulus **A**nalysis and **R**eduction **T**ool) is to use seismic moduli and well-substantiated nonlinear relationships to provide representative moduli for pavement design and analysis. SMART incorporates seismic moduli in a constitutive model recommended by a National Cooperative Highway Research Program (NCHRP) research project to determine the pavement responses in terms of the stress and strain developed within the pavement structures. The main features of the program are described in this chapter.

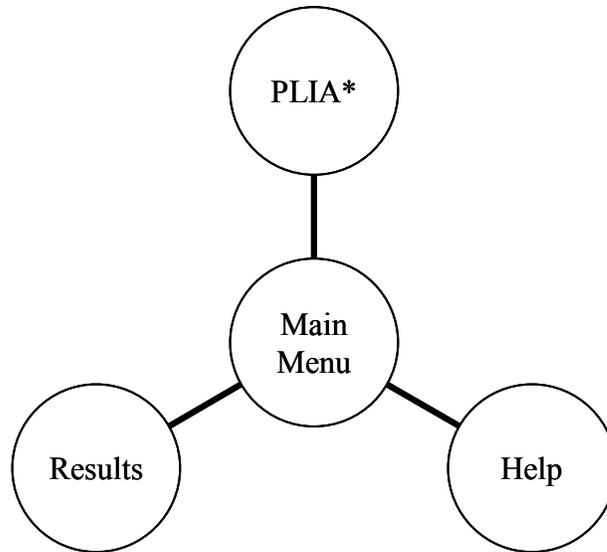
The main modules of the program presented in Figure 4.1 are: a) main menu, b) pavement property information and analysis, c) results, and d) online help. The flow of execution starts from the main menu, proceeds to pavement property information and analysis menu, and ends with the results menu. The online help menu offers detailed explanation of all features in each of the SMART menus.

USERS GUIDE

Main Menu

The main menu is shown in Figure 4.2. This menu controls access to different aspects of the program. The options available in the main menu are:

1. Analysis
2. Results
3. Help
4. Optional features



* Pavement Layer Information/Analysis

Figure 4.1 - Modules of SMART

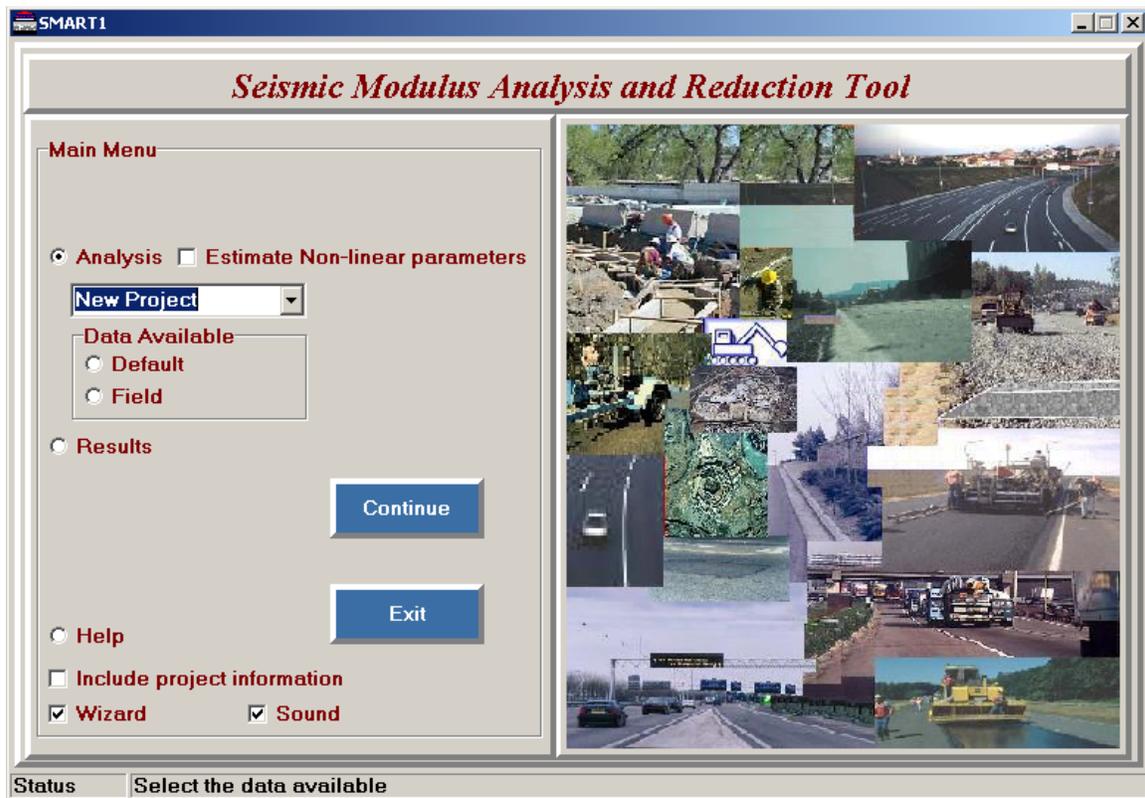


Figure 4.2 - Main Menu of SMART

Analysis: Analysis is the first option that the users select in the main menu. It allows the user to be prompted for the required data necessary to conduct a given analysis.

Results: This menu option provides users with the flexibility to directly access previously-analyzed data without performing the analysis again.

Help: This option brings up the online help menu providing users access to detailed explanations and information on all features of the program.

Optional features: Three additional (optional) features are provided in the main menu. The first feature is the project information option. Project information is a menu that allows a user to provide header information for each project. The second feature is the wizard option which provides instructions for novice users. The last optional feature is the sound option. Sounds are incorporated into SMART to help users transition with the flow of execution.

USING SMART

To start using SMART, a user first selects the analysis option. The user is then prompted to make a selection of either working with a new project or opening an existing one. The existing project option enables the user to select and rerun a previously-defined project. By selecting a new project, the user is prompted for the necessary data. At this point, the user can choose to use either a) default data or b) actual field data. The default data consists of a set of typical values which can be used during the design stages. These values are only recommendations and can be modified by users. Alternatively, the seismic data collected in the field can be retrieved. SMART provides the user with an option to link with a seismic reduction program.

Analysis with Default Data

The analysis with default data option provides a preliminary analysis without the need for complete field data. Users might have partial seismic data (e.g. modulus of AC from PSPA), in which case these values can be substituted in for the default values. When laboratory values are available, the user can substitute laboratory values as well. In the planning stages, the built-in typical seismic values can be used to run the analysis.

Figure 4.3 shows an example of the menu where the pavement structure is developed. For each layer, the user selects a) layer type, material type and constitutive model. Five layer types are available: a) overlay, AC, base, subbase and subgrade. After the layer is selected SMART will prompt the user to select a material type from a list of suitable options. Once the material type is selected, the user then selects a suitable constitutive model applicable to a given material. SMART has six models to select from: a) linear, b) viscoelastic, c) nonlinear (using resilient modulus test results), d) nonlinear (using the plasticity index test results), e) nonlinear (using estimated nonlinear parameters based on material quality) and f) nonlinear (using estimated nonlinear parameters based on index tests).

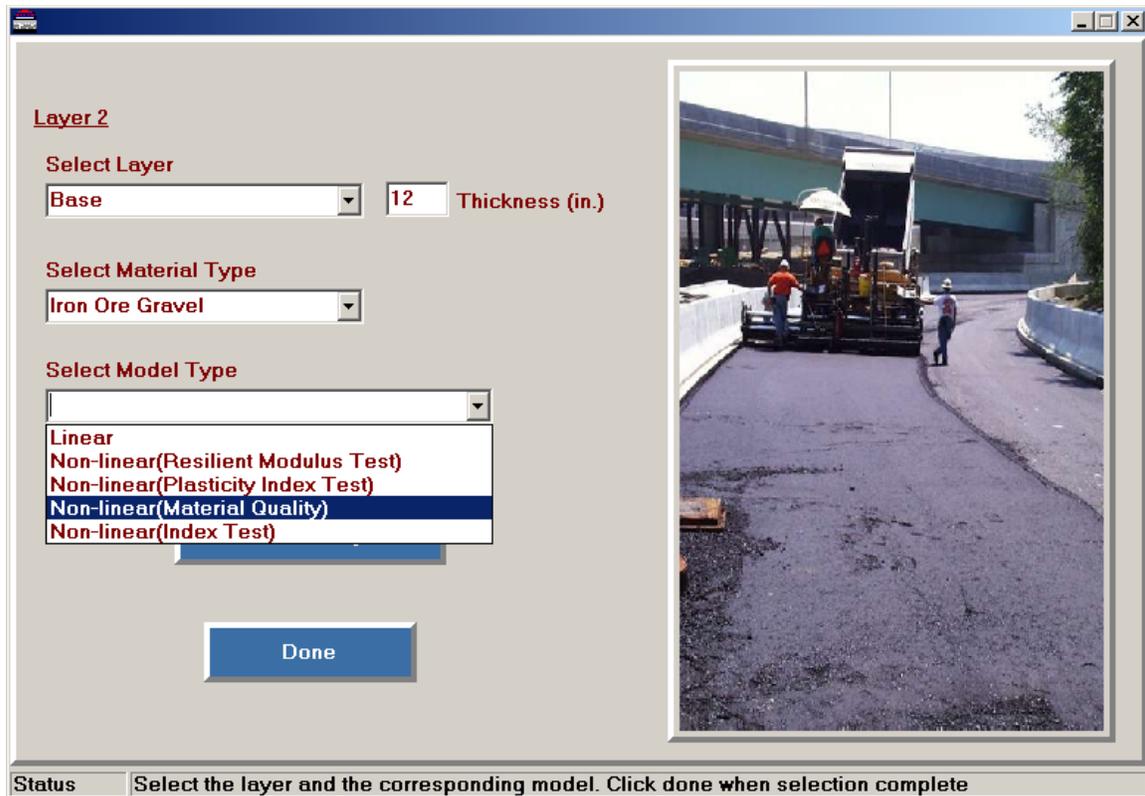


Figure 4.3 - Assembling Layer Property Information

The next menu provides a layer-by-layer summary of the information input (see Figure 4.4). The user can make any final changes to any parameter before performing the analysis. As depicted in Figure 4.4, the user can either enter the depth to rigid layer or select a semi-infinite layer. The first option allows users to consider shallow depth to rigid layer.

Analysis with Field Data

Analysis with field data allows the user to process seismic modulus and thickness values reduced with seismic inversion programs such as SASW for SPA. The goal would be to use reduced data from seismic test of an entire pavement section in SMART to obtain design modulus values.

SMART provides two options to incorporating reduced seismic data: a) reduce the data using SASW program and b) retrieve reduced data. If the field data has not been reduced the first option is used, where SMART links up to SASW for SPA. Once the data has been reduced and saved using SASW, it can be retrieved and analyzed using SMART. The second option retrieves reduced data by any seismic reduction software as long as the format of the output file is compatible. The format of the output file is available in the online help menu.

Layer	Layer Type	Material Type	Modulus (ksi)	Thickness (in.)	Density (pcf)	PR
<input checked="" type="checkbox"/> Layer1	AC		1500	4	138	0.3
<input checked="" type="checkbox"/> Layer2	Base	Iron Ore Gravel	50	12	134	0.35
<input checked="" type="checkbox"/> Layer3	Subgrade	Clay, LL<50	80		120	0.4
<input type="checkbox"/> Layer4	Select Layer					
<input type="checkbox"/> Layer5	Select Layer					
<input type="checkbox"/> Layer6	Select Layer					

Bedrock 300 Depth to bedrock (in.)
 Infinite Subgrade

Back Save Configuration

Status Select bedrock/infinite-subgrade and click on Save Configuration

Figure 4.4 - Summary of Layer Properties

Upon selection of the data file, SMART reads and interprets the file containing seismic data and prompts the user to select the analysis model and the constitutive material types for each layer. Figure 4.5 shows a snapshot of the menu where the model types are selected. Once the model types for each layer are selected, the data from the reduced seismic file is read and summarized as shown in Figure 4.6. After reviewing all input data, the user initiates the analysis by selecting the run analysis button.

Viscoelastic Feature for Overlays and AC Layers

SMART program features three options for temperature and frequency adjustments for the AC layer modulus values. These options are listed as: a) simplified, b) master curve based on mix properties, c) master curve based on lab testing. The details of adjusting modulus values based on temperature for all three methods were described in Chapter 2. Figure 4.7 contains the menus used for temperature adjustment. Figure 4.7a is a snapshot of the simplified method where the user only inputs the field or testing temperature. After selecting the update button from the menu, the program calculates the modulus value for the AC layer at a temperature of 77°F (25°C).

If the second or third options are selected, the temperature adjustment is based on the master curve. The main premise of temperature adjustment, using the master curve, is to calculate a modulus value at any given temperature. A sigmoid curve is a four-parameter curve (α , β , γ , σ).

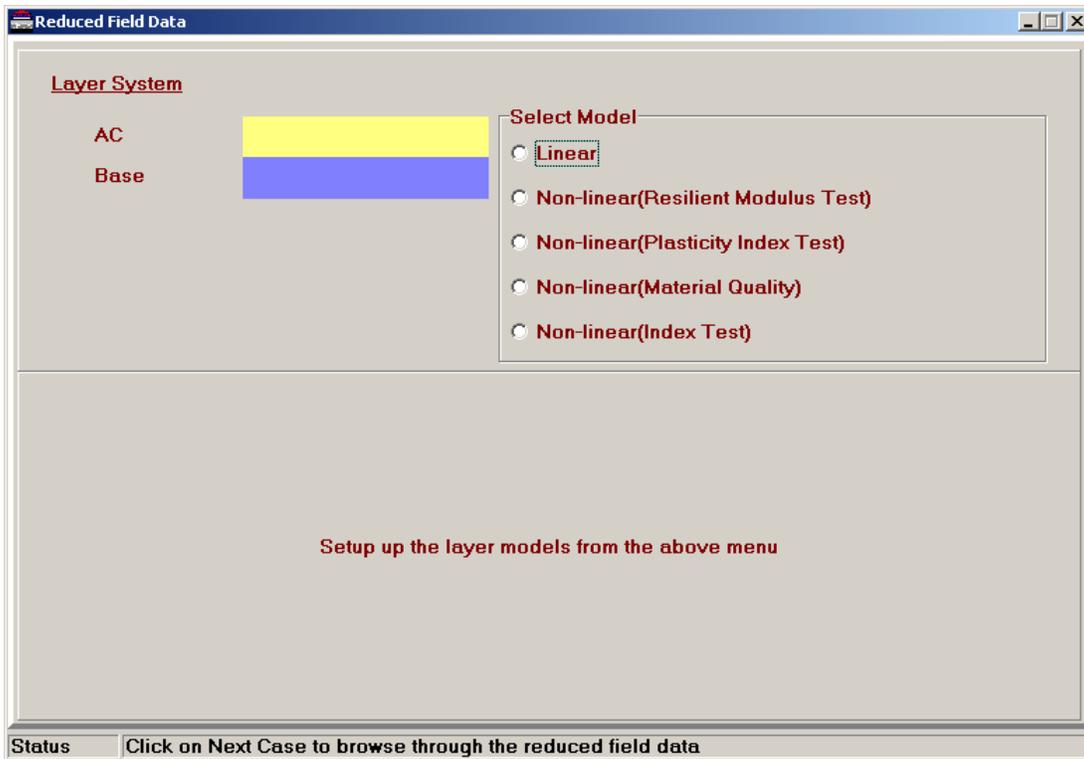


Figure 4.5 - Selecting Layer Models for Reduced Data File

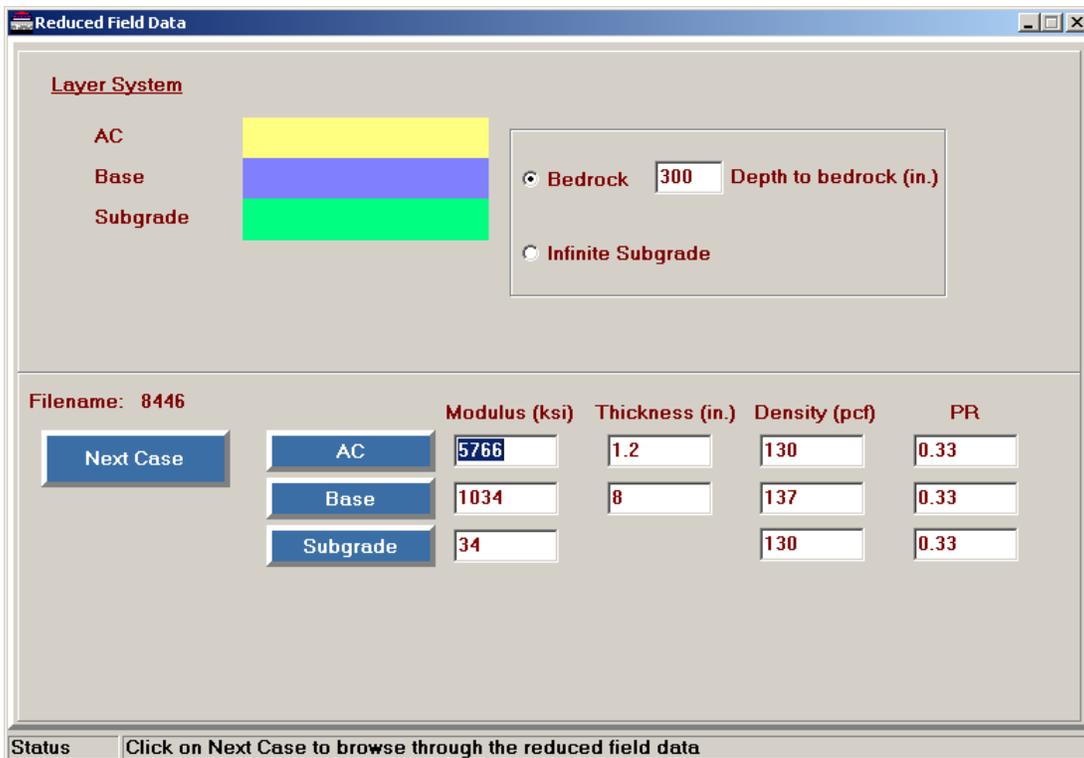


Figure 4.6 - Browsing through Reduced Data file

a) Simplified Method

Options

- Simplified
- Master-Curve based on mix properties
- Master-Curve based on lab testing

$$E_{77^\circ\text{F}} = \frac{E_{\text{Measured}}}{(1.35 - 0.014 \times t) \times 3.2}$$

Seismic Modulus: 1500 ksi

Field Temperature: 77 °F

PICTURE

Update Cancel

b) Master-Curve Based on Mix Properties

Options

- Simplified
- Master-Curve based on mix properties
- Master-Curve based on lab testing

$$\log(E^*) = \delta + \frac{\alpha}{1 + e^{\beta + \gamma \log t_r}}$$

Place cursor over the parameters for more information

V_a: 5 R₄: 60

V_{b eff}: 5 R_{3/4}: 3

P₂₀₀: 5 R_{3/8}: 30

VTS: -3.6 η_{Tr} : 1

A: 10.7 T_R: 77

E_{Seis.}: 1500 ksi

F_{Seis.}: 2041 Hz

F_{Des.}: 25 Hz

Set Default

PICTURE

Update Cancel

c) Master-Curve Based on Lab Testing

Options

- Simplified
- Master-Curve based on mix properties
- Master-Curve based on lab testing

$$\log(E^*) = \delta + \frac{\alpha}{1 + e^{\beta + \gamma \log t_r}}$$

Place cursor over the parameters for more information

Master-Curve Parameters

α : 3.6626

β : -0.9226

γ : 0.58189

δ : 3.02998

E_{Sies.}: 1500 ksi

F_{Sies.}: 2041 Hz

F_{Des.}: 25 Hz

Set Default

PICTURE

Update Cancel

Figure 4.7 - Snapshots from SMART Viscoelastic Menus

As indicated in Chapter 2, by knowing the four parameters of the master curve, the adjusted modulus values can be calculated. The difference between the two master curve options is in the method of determining the four parameters.

The first method uses regression equations that are functions of material mix properties to calculate the curve parameters. Figure 4.7b shows the section where mix property values are provided to calculate the master curve parameters. Along with the mix properties, the design and testing frequencies are needed. These values are used to shift the curve and determine the design modulus value.

The second method for extracting master curve parameters as indicated in Chapter 2 is by laboratory testing using the complex modulus test. This option assumes that the laboratory test is performed and the master curve parameters are known. Figure 4.7c shows where the master curve parameters need to be entered. Along with parameters values, design and testing frequency values are also needed.

Nonlinear Feature for Base, Subbase and Subgrade

As discussed in Chapter 2, SMART uses two nonlinear material models: a) nonlinear constitutive model (refer to Equations 2.8), and b) plasticity index model (refer to Equations 2.12 through 2.15). The nonlinear constitutive model requires parameters k_2 and k_3 since parameter k_1 is calculated from seismic modulus. SMART provides three options from which parameters k_2 and k_3 can be obtained.

The first and the most desirable option is to obtain the parameters k_2 and k_3 from the resilient modulus tests. Figure 3.8a shows a snapshot of where the parameters k_2 and k_3 from lab test can be incorporated. The second alternative is by selecting the quality of the materials (see Figure 4.8b). The material quality is classified from basically good to average to poor. Based on literature and previous studies, preset k_2 and k_3 values are selected for each quality. This option is not recommended, and should only be used for preliminary analysis when values from the resilient modulus tests are not available. A third option is to obtain the parameters k_2 and k_3 from index tests such as compaction, moisture, density, saturation, etc. (see Equations 2.10 and 2.11). This option is disabled at this time until an extensive study for Texas condition is carried out.

The plasticity index nonlinear option only requires the PI of the material. Figure 4.8c shows a snapshot from SMART, where a user inputs a PI value of a material if the nonlinear plasticity option is selected. This option is borrowed from the geotechnical earthquake engineering field and should provide reasonable results.

Results

The results menu in SMART is either accessed from the main menu directly or automatically after an analysis is complete. As a reminder the main use of SMART is to determine design

a) Resilient Modulus Test

b) Material Quality

c) Plasticity Index Test

Figure 4.8 - Snapshot of Nonlinear Parameters Options

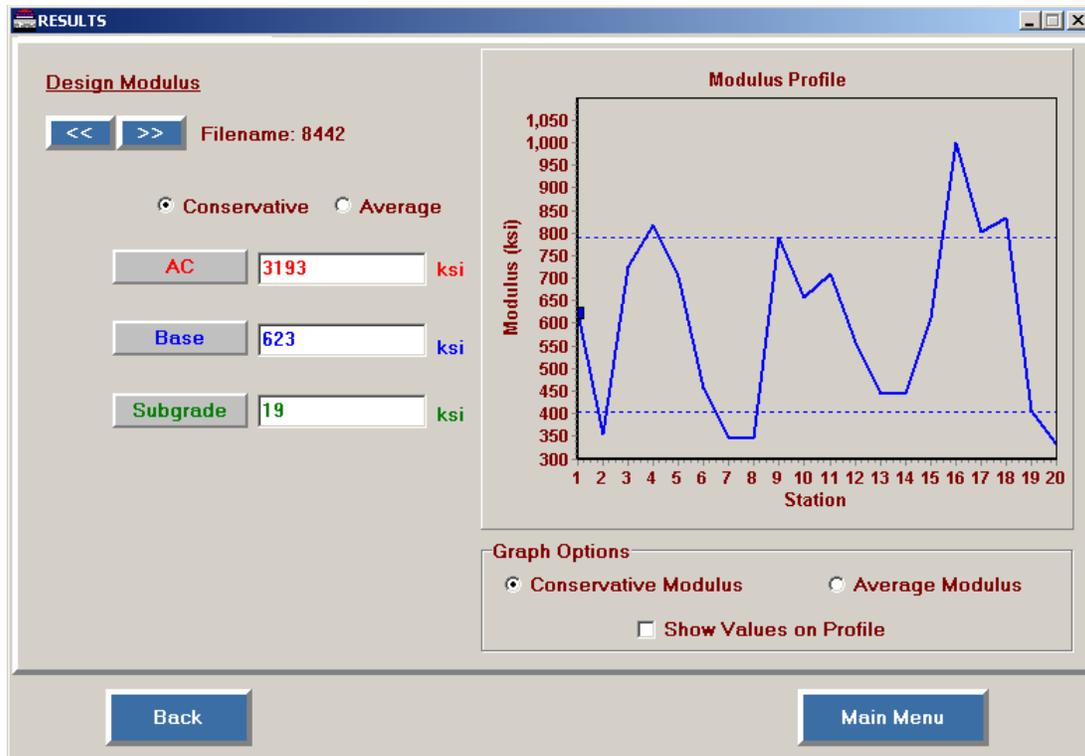


Figure 4.9 - Results Menu

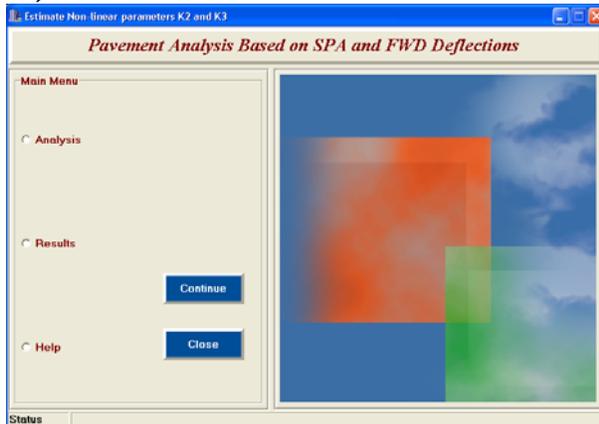
modulus values from seismic data and as such the design modulus values are presented by SMART's results menu. An example of the results menu is shown in Figure 4.9. Design modulus of each layer is presented in two fashions: a) conservative values and b) average values. The conservative design value is the minimum nonlinear value calculated for each layer and the average design value is the mean value calculated for each layer. A graph of the variation in the design modulus of each layer as a function of test point is also depicted in Figure 4.9.

Estimation of Nonlinear Parameters

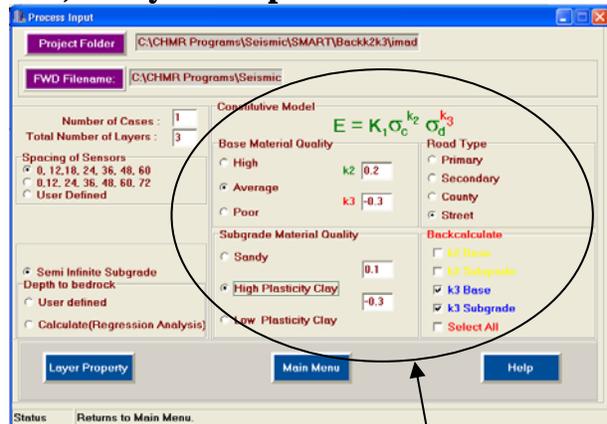
The estimation of the nonlinear parameters is a separate module that is linked with SMART. This program was developed to determine the feasibility of backcalculating the nonlinear parameters k_2 and k_3 from the SPA and FWD data. Meshkani et al. (2001) contains the algorithm used in this program. An overview of the features of this module is included here.

A menu similar to the main menu in SMART is used and allows the user to retrieve FWD data. (see Figure 4.10a). Once the FWD information is retrieved, all the required information for the analysis is provided through a menu shown in Figure 4.10b. The user selects the number of cases to analyze and the number of layers in the pavement section. The user also either specifies the depth to rigid layer or the program automatically uses a regression analysis advocated by Michalak and Scullion (1995) to calculate the depth to the rigid layer. The next step consists of determining the seed values for the two nonlinear parameters for each layer based on the type and quality of the material.

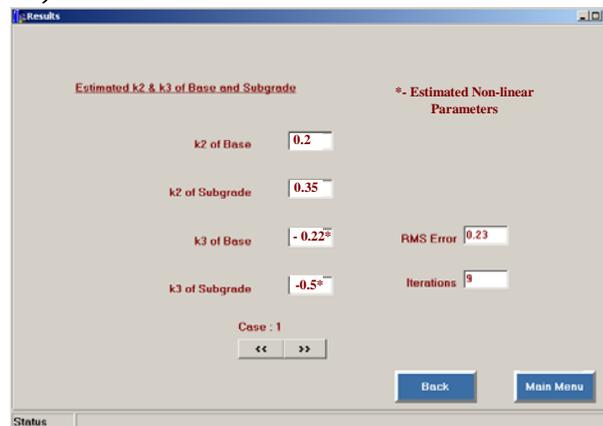
a) Main menu



b) Analysis Setup Menu



c) Results Menu



“expert system”
menu

Figure 4.10 - Select Menus from Nonlinear Parameter Estimation Program

A simple “expert system” is built into the program based on studies by Meshkani et al. (2001) to provide recommendations to the user in terms of whether obtaining a reasonable backcalculated parameter is feasible or not. Meshkani et al. (2001) extensively demonstrated the limitations of backcalculating nonlinear parameters for thick and strong pavement structures.

Once the SPA data are retrieved, the results of the analysis are shown in the results menu (see Figure 4.10c). The figure displays k_2 and k_3 values highlighting values that were backcalculated. Also presented in the result menu are the RMS error related to the mismatch between the measured and calculated deflection basins to assess the fit of the two deflection basins. The values from this program can then be used to calculate the design modulus values of the pavement section being analyzed.

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APPENDIX A
ONLINE HELP FILE

The “*Online Help*” form is used to access information that assist in knowing how this program works. This form contains six features:

- a. Overview
- b. Quick Start
- c. Input
- d. Process
- e. Results
- f. About

Each of these options provides help on how this program works. The Online Help feature works simply by clicking on any of the topics. Once clicked, a detailed explanation pops up on the right hand side of the form.

This help file can be accessed from any window in the program by clicking on the [*HELP*] button.

Overview

SMART is a user-friendly program based on the equivalent linear analysis that considers the nonlinear behavior of flexible pavements. The program calculates the critical strains within the pavement due to a standard dual tandem load. This information is used to estimate design parameters such as fatigue life and rut depth through empirical equations.

This program is based on the following constitutive model for both Granular and Cohesive materials:

$$M_R = K_1 \sigma_c^{k_2} \sigma_d^{k_3}$$

where k_1 parameter is based on the Seismic Pavement Analyzer (SPA) and initial stress conditions. Parameters k_2 and k_3 are determined from laboratory tests and or published values. σ_c is the stress due to the confining pressure and σ_d is the stress due to the deviatoric stress.

Detail explanation about the modeling and analysis are given in **TxDOT** Reports 1780-1, 1780-2 and 1780-3.

Quickstart

This program runs on any version of windows operating systems later than windows 98. The program can be installed in any drive. However, the recommended drive is “C Drive” in the directory C:**CHMR Programs\SMART**\. To execute the program either type C:**CHMR Programs\SMART\SMART1.EXE** under the run command or click SMART under CHMR Programs, which is located under Programs of the Start menu.

The flow of the program is setup to allow the user ease of use with minimal expertise.

There are three main selections in the main menu of this program

- Analysis: This selection is used to select and generate a Project Folder.
- Results: This selection allows the user to view the results directly of an existing project.
- Report: This selection allows the user to generate a report for an existing project that contains project description and results of analysis. This report feature is set up to print the project result in a preset report format.

Three other feature are available in the main menu:

- Help: This feature accesses the online help menu
- Include Project Information: This optional feature allows users to include input information about the project.
- Wizard: This optional feature if checked, provides users with guided help on the next step in the process.
- Sound: This optional feature if checked, plays sound alert at various stages of the program to alert users of the completion or beginning of a process.
- Exit: This feature exits the program

Project Folder

Project Folder is used by SMART to store all the files which contain information pertaining to the project that are produced by the program. After selecting either New Project or Old Project option, a set of steps follows that guides the user through the rest of the process.

New Project: This selection generates a new project folder.

Old Project: This selection allows the user to modify an existing project for re-analysis.

NOTE: The data files produced by SMART are either in text format or in DbaseIV format (.dbf). These files can be viewed in Microsoft Excel.

Input

Three types of inputs are required by SMART.

Project Description - Project description requires inputs that identifies the project identification such as:

- Problem ID,
- Highway,
- Control,
- Section,
- Job,
- District,
- County,

- Comments and
- Date.

It also requires the user to select the county and district to identify the project location.

Pavement Type - Pavement type has six predetermined pavement layouts for three to six layer flexible pavements. These options were identified as per Texas pavement needs and are currently the options used by TxDOT flexible pavement design programs.

Once the pavement section is selected, the next step is to select the material type for each of the base and subgrade. In the case of a four, five or six-layer system, the subbase material type is selected. This selection specifies predetermined layer quality that is used in the equivalent-linear analysis. This version SMART considers the Asphalt-Concrete (AC) layer as linear or visco-elastic, and as such the AC layer quality is not identified.

Seismic Data: If data was collected from a site or determined from laboratory testing, it can be provided as part of the input into the program. Seismic data can be conveniently retrieved from the program or processed directly by linking to a seismic program.

Process

The program starts with a main-form where users can make selection to create a new project or re-run an already developed project. In the main-form users could also view results of an existing project directly.

Analysis:

New Project: Upon selection to create a new project, you are given an option to create a new project or re-create a new project in an already existing folder.

Existing Project: This prompts for an existing project.

After a project folder is selected, users have the option to select to either retrieve filed data or select the default option and use the default values in the program. Next, users are prompted to input the project information, pavement type and material properties for each pavement layer. Users then proceed to the next menu to view the a priori information in the layer property menu. These values are display in a tabular format and can be modified based on the users' digression. If the values are satisfactory to users, users at this point selects to continue and run the analysis. Once the analysis is complete, the program automatically pulls up the results menu. The results menu displays the results of the analysis. The program also provides users the option to a report.

Results

The results portion of this program is either accessed from the main menu or automatically viewed after the analysis process is completed. The result menu shows a detailed version of the

results both graphically and numerically. An option in the results menu allows users to generate a report of the results in a text format that can be viewed from notepad.

About

“Seismic Moduli Analysis and Reduction Tool” **SMART Program version 1.0**

For Windows 9x, Windows 2000 and Windows NT 4.0 or Higher

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