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**A MICROCOMPUTER BASED PROCEDURE FOR  
BACKCALCULATING LAYER MODULI FROM FWD DATA**

**by**

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**Research Report 1123-1**

**Study Title: "Non Destructive Test Procedures for Analyzing  
the Structural Condition of Pavements"**

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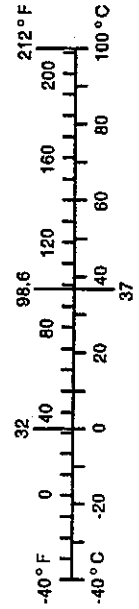
**Texas Transportation Institute  
July, 1988**

# METRIC (SI\*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS				APPROXIMATE CONVERSIONS TO SI UNITS			
Symbol	When You Know	Multiply By	To Find	Symbol	When You Know	Multiply By	To Find
<b>LENGTH</b>				<b>LENGTH</b>			
in	inches	2.54	centimeters	mm	millimeters	0.039	inches
ft	feet	0.3048	meters	m	meters	3.28	feet
yd	yards	0.914	meters	yd	meters	1.09	yards
mi	miles	1.61	kilometers	km	kilometers	0.621	miles
<b>AREA</b>				<b>AREA</b>			
in <sup>2</sup>	square inches	6.452	centimeters squared	mm <sup>2</sup>	millimeters squared	0.0016	square inches
ft <sup>2</sup>	square feet	0.0929	meters squared	m <sup>2</sup>	meters squared	10.764	square feet
yd <sup>2</sup>	square yards	0.836	meters squared	yd <sup>2</sup>	kilometers squared	0.39	square miles
mi <sup>2</sup>	square miles	2.59	kilometers squared	ha	hectares (10,000 m <sup>2</sup> )	2.53	acres
ac	acres	0.395	hectares	<b>MASS (weight)</b>			
<b>MASS (weight)</b>				<b>MASS (weight)</b>			
oz	ounces	28.35	grams	g	grams	0.0353	ounces
lb	pounds	0.454	kilograms	kg	kilograms	2.205	pounds
T	short tons (2000 lb)	0.907	megagrams	Mg	megagrams (1000 kg)	1.103	short tons
<b>VOLUME</b>				<b>VOLUME</b>			
fl oz	fluid ounces	29.57	milliliters	mL	milliliters	0.034	fluid ounces
gal	gallons	3.785	liters	L	liters	0.264	gallons
ft <sup>3</sup>	cubic feet	0.0328	meters cubed	m <sup>3</sup>	meters cubed	35.315	cubic feet
yd <sup>3</sup>	cubic yards	0.765	meters cubed	m <sup>3</sup>	meters cubed	1.308	cubic yards
Note: Volumes greater than 1000 L shall be shown in m <sup>3</sup> .				<b>TEMPERATURE (exact)</b>			
<b>TEMPERATURE (exact)</b>				<b>TEMPERATURE (exact)</b>			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature

These factors conform to the requirement of FHWA Order 5190.1A

\*SI is the symbol for the International System of Measurements



## ABSTRACT

The purpose of this report is to describe a backcalculation procedure (MODULUS) developed to interpret Falling Weight Deflectometer (FWD) data and to illustrate how this procedure was built into a pavement analysis system for the Texas State Department of Highways and Public Transportation.

MODULUS is microcomputer based and can be used on 2-, 3-, or 4-layer pavement systems. It used a linear-elastic program to generate a database of deflection bowls; in a four-layer system, a minimum of 27 runs (3 x 3 x 3 moduli values for surface, base, and subgrade) would be performed. The size of the database depends on the user-supplied range of acceptable modulus values for each layer. Once the database is generated, a pattern search routine is used to fit measured and calculated bowls; error minimization is very rapid, less than 5 seconds per bowl on a 386-type microcomputer.

The system developed for the State of Texas is designed to accept the FWD field diskette as input. The user then has several options when performing backcalculation including specifying the depth to bedrock or using existing default databases for common pavement structures. Outputs include summary listing showing mean and variances of moduli values and also a graphics output which plots moduli values along a project and automatically performs subsectioning.

The system was developed for an AT-compatible microcomputer with 640 KB RAM, a 10 MB hard disk, EGA card with 256 KB screen memory and a dot matrix printer with parallel interface. However, a version is available for machines with 512KB RAM and 64KB screen memory.

Keywords: modulus, backcalculation, Falling Weight Deflectometer, microcomputer, linear-elastic

## **DISCLAIMER**

This report is not intended to constitute a standard, specification or regulation and does not necessarily represent the views or policy of the FHWA or Texas State Department of Highways and Public Transportation.

## IMPLEMENTATION STATEMENT

The Texas SDHPT is currently implementing a new Flexible Pavement Design System developed under study 455. A crucial input to that system, is the subgrade resilient moduli value and its variance along the highway. Both of these can be readily calculated from Falling Weight Deflectometer data using the system described in this report.

The version of MODULUS described in this report uses BISAR as the linear elastic calculation program. Both TTI and the Texas SDHPT have permission to use BISAR. However, other versions of MODULUS are available using public domain software.

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## CHAPTER I

### INTRODUCTION

Non-Destructive Testing (NDT) is performed in order to characterize each layer in the pavement structure. In the commonly used linear-elastic approach the elastic modulus and its variance are the parameters of interest. Therefore, NDT consists of measuring and processing numerous deflection bowls along the length of the project. For project level testing the recording interval is frequently left at the discretion of the engineer but spacing between 100-500 feet are common.

To assist the engineer in the analysis process an efficient procedure must be developed which permits modulus backcalculation from surface deflection data and allows the engineer to review the data to determine if subsectioning is required. A microcomputer-based procedure called MODULUS is presented in this report (1). It has been designed to process data collected with the Falling Weight Deflectometer. A unique feature of MODULUS is that it uses a linear elastic program to generate a data base of computed deflection bowls, prior to fitting the measured bowls. Once the data base is generated for a particular pavement the linear elastic program is not called again, no matter how many bowls are to be analyzed. Therefore, the data base can be generated prior to testing and the measured bowls can be processed in real-time. The procedure as described in section 2 of this report make use of the properties of the linear-elastic solution by working in terms of modular ratios. It can handle a 2, 3, or 4 layer problem, in the case of a 4 layer problem the elastic layer program is automatically run at least 27 times (3 surface x 3 base x 3 subbase modular ratios) to generate the required data base. A pattern search routine is used to fit the measured and calculated bowls.

The data base concept has an advantage over existing programs such as CHEVDEF (2) which calls the linear elastic deflection program (NLAYER + 1) \* ITER + 1 times, where NLAYER is the total number of layers and ITER is the user specified number of convergence iterations. In the case of the four layer system the BISDEF program with ITER=3 would require 16 runs of the linear-elastic program per bowl whereas the MODULUS program would require

only 27 runs independent of the number of bowls to be analyzed. Therefore, in this case the MODULUS would be more efficient than CHEVDEF when more than 2 bowls are measured on the same section.

This report is subdivided as follows. In section 2 the theoretical background to the modulus backcalculation procedure is presented. This section contains a description of the error minimization objective function, a description of the steps in the analysis and the convexity test which attempts to identify if the particular solution is a local minimum. Section 3 describes the delineation scheme built into the system to permit automatic subsectioning of projects when significantly different pavement strengths are observed. Sections 4 and 5 presents a Case Study and overall conclusions. The MODULUS program as described has been custom built into a deflection analysis system for the State of Texas. A description of this system and a Users Manual is presented in Appendix A. The Texas SDHPT system has the following 3 subroutines.

1. Deflection Data Input - This is read directly from the FWD field data collection diskette. (Dynatest Version 9.0)
2. Backcalculation - The user has several options here including using existing default data bases or running the linear elastic routine to create a new data base prior to backcalculation. Summary or detailed reports of moduli values are generated.
3. Graphic Outputs - The deflection or backcalculated moduli values are plotted and the delineation routine is run to find strong and weak pavement sections. A mean value and standard deviation are generated for each.

## CHAPTER 2

### MODULUS BACKCALCULATION PROCEDURE

In this chapter the backcalculation procedure will be presented.

#### 2.1 Formulation of the Objective Function

The ultimate goal of the backcalculation process from NDT results is to estimate the pavement material properties. The procedure is to find the set of parameters which correspond to the best fit of the measured deflection bowls. The best fit is achieved by minimizing the error between the measured and calculated deflection bowls. The objective function can therefore be written as:

$$\text{minimize} \quad \epsilon^2 = \sum_{i=1}^s \left[ \frac{W_i^m - W_i^c}{W_i^m} \right]^2 W_{e_i} \quad (1)$$

where:

$\epsilon^2$  = squared error

$W_i^m$  = measured deflection at sensor i

$W_i^c$  = computed deflection at sensor i

s = number of sensors

$W_{e_i}$  = user supplied weighing factor for sensor i

Equation 1 can be written simply as:

$$\text{minimize} \quad \epsilon^2 = \sum_{i=1}^s \left[ 1 - \frac{W_i^c}{W_i^m} \right]^2 W_{e_i} \quad (2)$$

Different techniques are available for minimizing the objective function expressed in Equation (2). The program described in this report uses the Hooke-Jeeves' pattern search algorithm (4). This algorithm is known to converge always (sometimes to a local minimum), unlike other algorithms that may in some cases not converge at all. The unknown

variables are those required to compute the surface deflection  $W_i^c$ , i.e.

$$W_i^c = F_i (X_j) \quad (3)$$

where:

$X_j$  = unknown variables,  $j = 1$  to  $n$  unknowns

Any solution to Equation (2) calls for a solution of Equation (3) obtained numerically in most cases by running a separate program (such as BISAR, CHEVRON computer programs in the case of linear elasticity and ILLI-PAVE in the case of non-linear elasticity). The number of calls depends on the minimization algorithm used. For example, the CHEVDEF program (2) calls the deflection computation program  $(N_{\text{LAYER}} + 1) * \text{ITER} + 1$  times for each bowl to be analyzed, where  $N_{\text{LAYER}}$  is the total number of layers for which moduli are to be determined, the  $\text{ITER}$  is the number of iterations.

Generally, the pattern search technique requires numerous calls of the deflection computation program for each measured bowl, this can be inefficient in the case where a large number of bowls are to be analyzed for a single project, which is frequently the case. This drawback is overcome in this system by generating ahead of time a data-bank containing deflection bowls for the expected range of moduli and using the 3-point Lagrange interpolation technique to compute the deflection bowl for any set of unknown values within the expected range. It is worth mentioning that after the generation of the data-bank, the deflection computer program is no longer required.

In the case of linear-elasticity the computed deflection  $W_i^c$  at sensor  $i$  (or radial distance  $r_i$ ) can be expressed as follows:

$$W_i^c = f_i (E_k, \nu_k, h_k, r_i, 0) \quad (4)$$

$E_k, \nu_k$  = modulus of elasticity and Poisson's ratio of layer  $k$  ( $k = 1$  to  $n$  layers)

$h_k$  = thickness of layer  $k$

$0$  = other variables, such as pressure, contact area, radius, interface conditions, etc.

In the backcalculation, all variables except  $E_k$  are either assumed or known, and the moduli are the only variables to be backcalculated.

In the case of linear elasticity and a circular contact area, Equation (4) can be written as:

$$W_i^c = \frac{P}{E_{sg}} f_i \left( \frac{E_1}{E_{sg}}, \dots, \frac{E_k}{E_{sg}}, \dots, \frac{E_n}{E_{sg}} \right) \quad (5)$$

where:

$p$  = pressure (psi)

$E_{sg}$  = subgrade modulus of elasticity

Equation (5) represents a unique property of linear elasticity in that the deflection is a) linearly related to load level, b) inversely proportional to subgrade modulus and c) a function of the modular ratios.

Using Equations 2 and 5 it is possible to obtain a direct solution for the subgrade modulus  $E_{sg}$ . To minimize the squared error of Equation 2 with respect to  $E_{sg}$  requires that its derivative with respect to  $E_{sg}$  is zero, as follows:

$$2\epsilon \frac{\partial \epsilon}{\partial E_{sg}} = \sum_{i=1}^S 2 \left[ 1 - \frac{W_i^c}{W_i^m} \right] \left[ -\frac{1}{W_i^m} \frac{\partial W_i^c}{\partial E_{sg}} \right] W_{ei} = 0 \quad (6)$$

and from (5):

$$\frac{\partial W_i^c}{\partial E_{sg}} = \frac{\partial}{\partial E_{sg}} \left[ \frac{P}{E_{sg}} f_i \left( \frac{E_k}{E_{sg}} \right) \right] \quad (7)$$

for the sake of clarity the term  $f_i (E_k/E_{sg})$  is replaced by  $f_i$  in the equations below:

$$\frac{\partial W_i^c}{\partial E_{sg}} = -\frac{P}{E_{sg}^2} f_i + \frac{P}{E_{sg}} \frac{\partial}{\partial E_{sg}} (f_i) \quad (8)$$

When the ratio  $E_k/E_{sg}$  is kept constant, i.e., at a particular set of modular ratios in the data base, the second term in Equation (8) is zero. Therefore, Equation (8) can be written as:

$$\frac{\partial W_i^c}{\partial E_{sg}} = -\frac{W_i^c}{E_{sg}}$$

Substituting Equation (8) back into Equation (6) yields:

$$\sum_{i=1}^S \left( 1 - \frac{W_i^c}{W_i^m} \right) \left( \frac{W_i^c}{W_i^m} \frac{1}{E_{sg}} \right) W_{e_i} = 0 \quad (9)$$

Using Equation (5) to substitute back for  $W_i^c$  yields:

$$\sum_{i=1}^S \left( 1 - \frac{pa}{E_{sg}} \frac{f_i}{W_i^m} \right) \left( \frac{pa}{E_{sg}^2} \frac{f_i}{W_i^m} \right) W_{e_i} = 0 \quad (10)$$

simplifies to:

$$\frac{1}{E_{sg}} \left( \frac{p}{E_{sg}} \right)^2 \sum_{i=1}^S \left( \frac{E_{sg}}{pa} - \frac{f_i}{W_i^m} \right) \left( \frac{f_i}{W_i^m} \right) W_{e_i} = 0 \quad (11)$$

normalizing (11) with respect to  $f_1$  yields:

$$\sum_{i=1}^S \left( \frac{E_{sg}}{p f_1} - \frac{f_i}{f_1} \frac{1}{W_i^m} \right) \left( \frac{f_i}{f_1} \frac{1}{W_i^m} \right) W_{e_i} = 0 \quad (12)$$

leading to:

$$E_{sg} = \frac{p f_1 \sum_{i=1}^S \frac{f_i^2}{f_1^2} \frac{W_{e_i}}{(W_i^m)^2}}{\sum_{i=1}^S \frac{f_i}{f_1} \frac{W_{e_i}}{W_i^m}} \quad (13)$$

Although Equation (13) can be simplified this normalized form is preferred for data processing. Equation (13) provides a direct method for estimating subgrade modulus  $E_{sg}$  from the data base of normalized  $(f_i/f_1)$  deflection values. This data base, as will be demonstrated below, is built from multiple runs of the BISAR program. Each run corresponds to a set of modular ratios  $E_k/E_{sg}$ . Therefore an  $E_{sg}$  can be calculated for each set of  $f_i(E_k/E_{sg})$ . To decide which solution minimizes error it is necessary to calculate squared error associated with each set of modular ratios using Equation (14) which is simply an expanded version of Equation (2).

$$\epsilon^2 = \sum_{i=1}^S \left( 1 - \frac{p f_i}{E_{sg} W_i^m} \right)^2 W_{e_i} \quad (14)$$

where the  $E_{sg}$  is the particular solution of Equation (13) corresponding to



the given modular ratio and  $p$  is the actual pressure under which the  $W_1^c$  values was calculated. By locating the minimum squared error from Equation (14), a seed value of  $E_{sg}$  is selected and the corresponding seed values of  $E_{BASE}$  and  $E_{SURFACE}$  are calculated. These "seed values" are used as input to the pattern search routine.

### Case Study

To demonstrate this procedure the following case study is presented. A flexible pavement was tested with the Falling Weight Deflectometer; the measured data is shown below:

#### Input Data

Asphalt Surface Layer Thickness = 3 inches

Limestone Base Layer Thickness = 9 inches

FWD Load = 8440 lbs. Pressure = 76.9 psi

FWD Deflection (1 foot sensor spacings)

$W_1^m$  = 8.09 mils

$W_2^m$  = 4.78 mils

$W_3^m$  = 2.77 mils

$W_4^m$  = 1.80 mils

$W_5^m$  = 1.37 mils

$W_6^m$  = 1.10 mils

$W_7^m$  = 0.87 mils

### BISAR Set-Up

From the user supplied acceptable ranges of surface and base moduli the following 9 moduli ratios ( $E_k/E_{sg}$ ) were defined: (10,1), (30,1), (100,1), (10,3), (30,3), (100,3), (10,10), (30,10), (100,10). For example (10,1), the surface to subgrade modular ratio is 10 and the base to subgrade modular ratio is 1. Nine runs of BISAR were made using a nominal pressure of 10 psi and  $E_{sg} = 1$ . The results for the (10,1) run are tabulated below:

	Sensor i						
	1	2	3	4	5	6	7
$W_i^c$ (Equation 5) mils	68.66	27.26	12.40	8.19	6.15	4.93	4.11
$\frac{f_i}{f_1} = \frac{f_i(10,1)}{f_1(10,1)}$ (Equation 13)	1.0	0.396	0.181	0.119	0.089	0.072	0.60

Table 1. BISAR Output for Modular Ratio 10:1.

#### Calculation of $E_{sg}$

With reference to Equation 13 the  $W_{e_i}$  values are set to 1.0:

$$\begin{aligned}
 p \quad f_1(10,1) &= W_1^c \times E_{sg} \times 76.9/10 \text{ (adjust to FWD test pressure of 76.9 psi)} \\
 &= 68.66 \times 1 \times 7.69 \\
 &= 528
 \end{aligned}$$

Using Equation (13):

$$\begin{aligned}
 E_{sg} &= 528 \left[ \left( \frac{1.0}{8.09} \right)^2 + \left( \frac{0.396}{4.78} \right)^2 + \left( \frac{0.181}{2.77} \right)^2 + \left( \frac{0.119}{1.80} \right)^2 + \left( \frac{0.089}{1.37} \right)^2 \right. \\
 &\quad \left. + \left( \frac{0.072}{1.10} \right)^2 + \left( \frac{0.06}{0.87} \right)^2 \right] \\
 &= \frac{528 \cdot \left[ \frac{1.0}{8.09} + \frac{0.396}{4.78} + \frac{0.181}{2.77} + \frac{0.119}{1.80} + \frac{0.089}{1.37} + \frac{0.072}{1.10} + \frac{0.06}{0.87} \right]}{\left[ 0.124 + 0.0828 + 0.0653 + 0.0661 + 0.0650 + 0.0654 + 0.0689 \right]} \\
 &= \frac{528 \cdot 0.0439}{0.536}
 \end{aligned}$$

$$E_{sg} = 43.2 \text{ ksi}$$

Substituting this value of  $E_{sg}$  back into Equation 14 yields a squared error of 0.4496.

### Summary of Results

The calculation process described above was used on the remaining 8 modular ratios and the results are tabulated below:

$E_1/E_{sg}$	$E_2/E_{sg}$	$E_{sg}$ (ksi)	$\epsilon^2$
10	1	43.2	0.4496
30	1	39.7	0.1902
100	1	36.9	0.0367
10	3	36.8	0.0230
30	3	35.7	0.00213
100	3	34.7	0.0269
10	10	34.9	0.0866
30	10	34.4	0.153
100	10	33.9	0.231

Table 2. Calculated  $E_{sg}$  and  $\epsilon^2$  for Each Modular Ratio.

The program searches for the minimum error squared term and performs a convexity test (described in Section 2.3) to check for local minimum. In this example the subgrade seed modulus would be 35.7 ksi and the seed moduli for the surfacing and base would be 1,071 ksi (30 x 35.7) and 107.1 ksi (3 x 35.7), respectively (modular ratios 30 and 3). These seed moduli would be passed to the pattern search routine for further error minimization.

### 2.2 Description of Analysis

The modulus backcalculation analysis system is a user friendly micro-computer program that allows the user to select from a menu the particular options he wishes to perform. The options that the user can choose from are:

- 1) Process the FWD raw data diskette to produce the observed deflection data file needed for the analysis

- 2) Select one of the default deflection bowl data bases to use in the analysis
- 3) Generate a deflection bowl data base using default values for pavement layer and subgrade moduli
- 4) Generate a deflection bowl data base with all input data supplied by the user
- 5) Perform the analysis

In most instances the normal sequence of the analysis is to first process the FWD raw data diskette, then select or generate a deflection bowl data base, and then to run the modulus backcalculation procedure. There is the flexibility in this system such that as the user gains experience in using it, he can process the FWD raw data and/or generate a deflection bowl data base in advance and go directly to the modulus back calculation procedure.

In order to facilitate the user's understanding of the modulus back-calculation system, the following discussion will describe the generation of a deflection bowl data base with all data supplied by the user. This will be followed by a brief description of the modulus back calculation procedure.

When the user elects to generate a deflection bowl data base and supply all the input data, he is performing two separate steps: data input and deflection bowl calculation.

Step one is the execution of a data input program that requests through screen input the data necessary to produce an input data file for the deflection bowl calculation in step two. The screen inputs are:

Pavement Layer Thicknesses - Limited to four layers, including the subgrade. A rigid layer may be specified at any depth in the subgrade but it is not counted as one of the layers.

Estimated Subgrade Modulus - In ksi, best estimate of the subgrade modulus and Poisson's ratio.

Pavement Layer Moduli - Minimum and maximum values in ksi of the layer moduli and Poisson's ratio.

In Section 2.1 calculations using example data inputs are shown. These inputs are for a three layer pavement; three inch surface layer, nine inch

base layer, and subgrade. The minimum and maximum surface moduli are 200 and 800 ksi. Minimum and maximum base moduli are 30 and 150 ksi, and the estimated subgrade modulus is 20 ksi.

From the data above, two files are automatically generated by the data entry program. File one is called TMP.BIS (Figure 1) and is the data input file for the BISAR program that generates the deflection bowl data base in step two. File two is called TMP.DEF (Figure 2) and is used by the modulus calculation program. The data file TMP.BIS is in the input format for the BISAR program, but there are three exceptions in the data that should be noted. One exception is that the ratios of the minimum and maximum pavement layer moduli to the estimated subgrade modulus are used by BISAR to calculate deflections rather than using the minimum and maximum modulus values entered on the screen. Another exception is that since in linear elasticity the deflection is proportional to the pressure and inversely proportional to the subgrade modulus, only one pressure ( $p = 10$  psi) and one subgrade modulus value ( $E_{sg} = 1000$  psi) is used by the data input program to generate the BISAR input file. It should be noted that the estimated subgrade modulus entered on the screen is only used to calculate the minimum and maximum pavement layer modular ratios. The third exception is that the BISAR input file is set to calculate surface deflection only at the radial distances entered on the screen (these being the FWD sensor locations).

An example of how the data input program uses the minimum and maximum pavement layer moduli and the estimated subgrade modulus to generate the modular ratios used by BISAR to calculate the deflection bowl data base is as follows. With a minimum surface modulus value of 200 ksi, a maximum pavement modulus value of 800 ksi, and an estimated subgrade modulus of 20 ksi, the program calculates the minimum surface modular ratio of 10 ( $200/20$ ) and the maximum surface layer modular ratio of 40 ( $800/20$ ). From the set of ratios fixed in the data input program, the program will generate a minimum of three ratios covering the range between the calculated minimum and maximum modular ratios. In this example the program will generate the ratios 10, 30 and 100. This means that for this pavement layer the BISAR program will have three modular ratio values to use in calculating deflections rather than just the minimum and maximum modulus values entered on the screen. This also ensures that the modulus calculation procedure

# EXAMPLE PROBLEM TO CHECK MODULUS CALCULATIONS

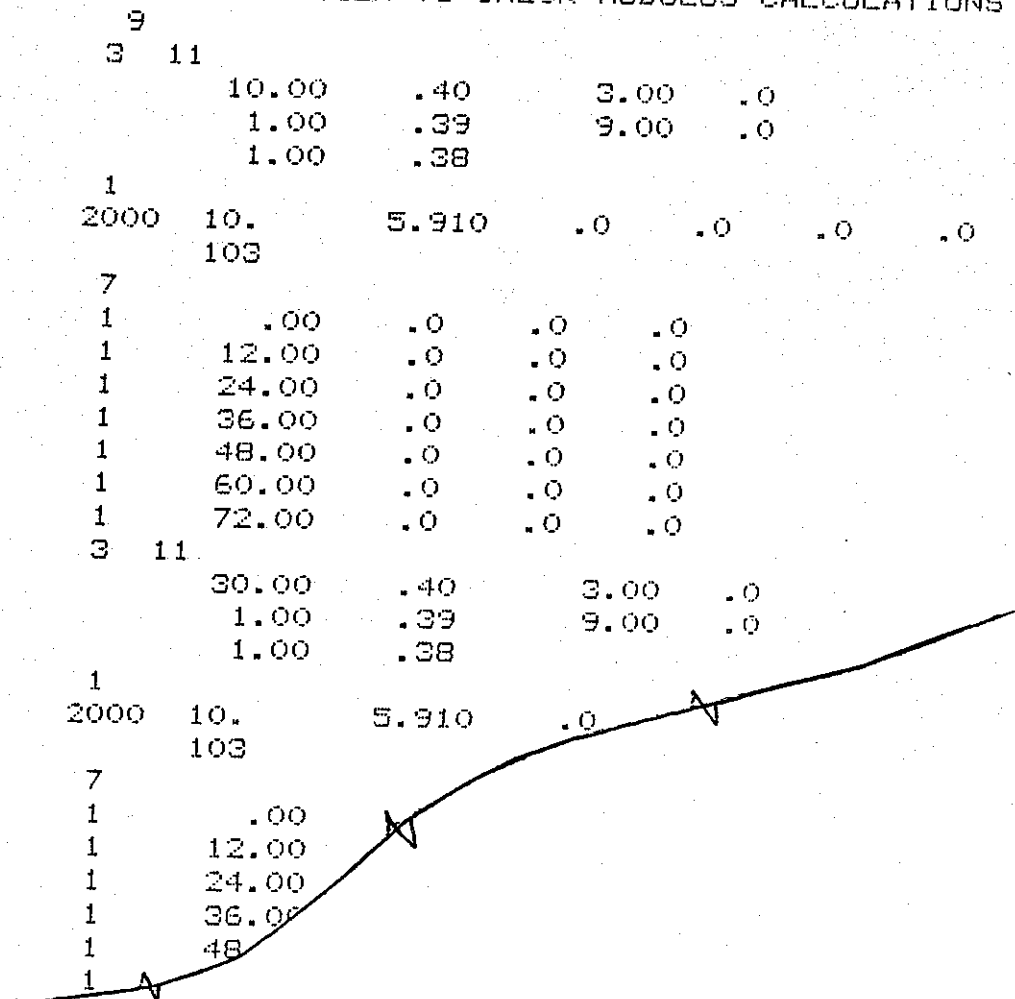


Figure 1. File TMP.BIS, data input file for BISAR, which is automatically created by the data input program.

## AMPLE PROBLEM TO CHECK MODULUS CALCULATIONS

5.910	3.00	9.00	.00	1	3	3	1	0
.200000D+03	.800000D+03							
.300000D+02	.150000D+03							
.100000D-01	.100000D+08							
7	20.0							
.00	12.00	24.00	36.00	48.00	60.00	72.00		
1.00	1.00	1.00	1.00	1.00	1.00	1.00		
111 11	8.09	4.78	2.77	1.80	1.38	1.10	.88	8440.00

Figure 2. File TMP.DEF, created by the MODULUS calculation Data Input Program used to pass initial condition to the data reporting routines.

will stay within the minimum and maximum range when calculating the modulus of this layer. However, if the estimated subgrade modulus is too high or too low from the backcalculated one, the range of modular ratios may be inadequate. In this case, the user should either correct the estimated subgrade modulus or widen the range of the pavement layer moduli. As a general "rule of thumb," when selecting the range of moduli values for a granular base course, it is recommended that the range be set from 1 to 5 times the subgrade moduli value. For example, if  $E_{sg}$  is set to 10 ksi, then the base should be given a range of 10 to 50 ksi.

A set of modular ratios for each pavement layer is generated and the total number of deflection bowls in the data base is the product of the number of modular ratios of layer one, layer two and layer three, or  $NE1*NE2*NE3$ . Note that modular ratios are used for the pavement layers only. The subgrade modulus is set at 1 ksi as mentioned previously.

For the instance where the user desires to ascertain the effects of a deep rigid layer in the subgrade, a thickness or depth to the rigid layer is entered for the subgrade layer. The rigid layer is assigned a modulus value of 1000 ksi by the program and a modular ratio using the estimated subgrade modulus is calculated. In this example that ratio would be 50 ( $1000/20$ ). It should be noted that the modulus calculation program does not compute a modulus value for this deep subgrade material. The calculated subgrade modulus is for the subgrade material between the last pavement layer down to the rigid layer.

In step two, the linear elastic program BISAR is used to generate the deflection bowl data base, using the data file TMP.BIS from step one. The number of deflection bowls in the data base is determined by the number of modular ratios computed for each pavement layer in step one. The deflection bowl data base is written to a file called BIS.RES (Figure 3). This file contains the pavement layer modular ratios and the deflection bowls calculated by BISAR. This step is the most lengthy part of the modulus backcalculation procedure. A simple three layer problem (surface, base, subgrade) with nine deflection bowls in the data base can take fifteen minutes of execution time on a Compaq 286 microcomputer. With experience, the user can learn to process the FWD raw data and generate the deflection bowl data base ahead of time and go directly to the modulus calculation

procedure. It should be noted that once the deflection bowl data base has been generated for a section of pavement, additional modulus calculations can be made with updated or additional observed deflection bowls without having to recreate the deflection data base.

$E_1/E_{sg}$	$E_2/E_{sg}$	$E_3/E_{sg}$	$W_1^c$
10.0	1.0	1.0	.686652D+02
10.0	1.0	1.0	.272577D+02
10.0	1.0	1.0	.124012D+02
10.0	1.0	1.0	.819355D+01
10.0	1.0	1.0	.615543D+01
10.0	1.0	1.0	.493227D+01
10.0	1.0	1.0	.411575D+01
30.0	1.0	1.0	.548123D+02
30.0	1.0	1.0	.277301D+02
30.0	1.0	1.0	.127850D+02
30.0	1.0	1.0	.814697D+01
30.0	1.0	1.0	.609439D+01
30.0	1.0	1.0	.488487D+01
30.0	1.0	1.0	.407785D+01
100.0	1.0	1.0	.404063D+02
100.0	1.0	1.0	.260042D+02
100.0	1.0	1.0	.137475D+02
100.0	1.0	1.0	.843398D+01
100.0	1.0	1.0	.608887D+01
100.0	1.0	1.0	.483755D+01
100.0	1.0	1.0	.403557D+01
10.0	3.0	1.0	.438191D+02
10.0	3.0	1.0	.221142D+02
10.0	3.0	1.0	.128797D+02
10.0	3.0	1.0	.864318D+01
10.0	3.0	1.0	.636608D+01
10.0	3.0	1.0	.501693D+01
10.0	3.0	1.0	.414585D+01
30.0	3.0	1.0	.381153D+02
30.0	3.0	1.0	.217610D+02
30.0	3.0	1.0	.137193D+02
30.0	3.0	1.0	.137193D+02
30.0	3.0	1.0	.137193D+02
30.0	3.0	1.0	.137193D+02
30.0	3.0	1.0	.137193D+02
30.0	3.0	1.0	.137193D+02
100.0	3.0	1.0	.137193D+02

Figure 3. File BIS.RES, the Deflection Bowl Data Base generated by BISAR,  $W_1^c$  is the calculated deflection at each FWD sensor location.



## Modulus Calculation Procedure

The modulus calculation program is a function optimization program called PATTERN SEARCH (4) that is based on the HOOKE and JEEVES optimization algorithm. This technique finds the optimum solution for an objective function  $f(X_1, X_2, \dots, X_n)$  by changing the  $X_i$  values until the minimum squared error between the observed values and the values calculated with the objective function is obtained. As mentioned in Section 2.1, this technique will always converge although not always at the true function minimum.

The objective function portion of the PATTERN SEARCH program is the linear elastic program BISAR. Because the time to run the PATTERN SEARCH program using BISAR to generate the calculated deflection bowls for each iteration would be prohibitive, the modulus calculation procedure uses a three point Lagrange interpolation technique to determine the calculated deflections from the deflection bowl data base for each set of  $X_i$  values produced by the PATTERN SEARCH program.

The main program of the PATTERN SEARCH controls the sequence of calculations (Figure 4) in the modulus calculation procedure. This sequence includes calling the appropriate subroutines to read in the data files generated previously, changing the  $X_i$  (in this case the pavement layer and subgrade moduli values), interpolating for the calculated deflections from the deflection data base, and calculating the squared error between the observed and calculated deflection bowls for each iteration.

To illustrate the sequence of calculations that are performed to determine the set of pavement layer and subgrade moduli values that give the minimum squared error between an observed and a calculated deflection bowl, one iteration of the PATTERN SEARCH will be discussed.

The main program reads the file TMP.DEF (Figure 2) to obtain the layer thicknesses, number of modular ratios for each layer, the minimum and maximum pavement layer moduli values, and the estimated subgrade modulus. The layer thicknesses are used in the data base generation and the minimum and maximum moduli values are used as check values to prevent PATTERN SEARCH from changing the  $X_i$  (modulus) values beyond the range of values set by the user. The deflection bowl data base file, BIS.RES (Figure 3) containing the

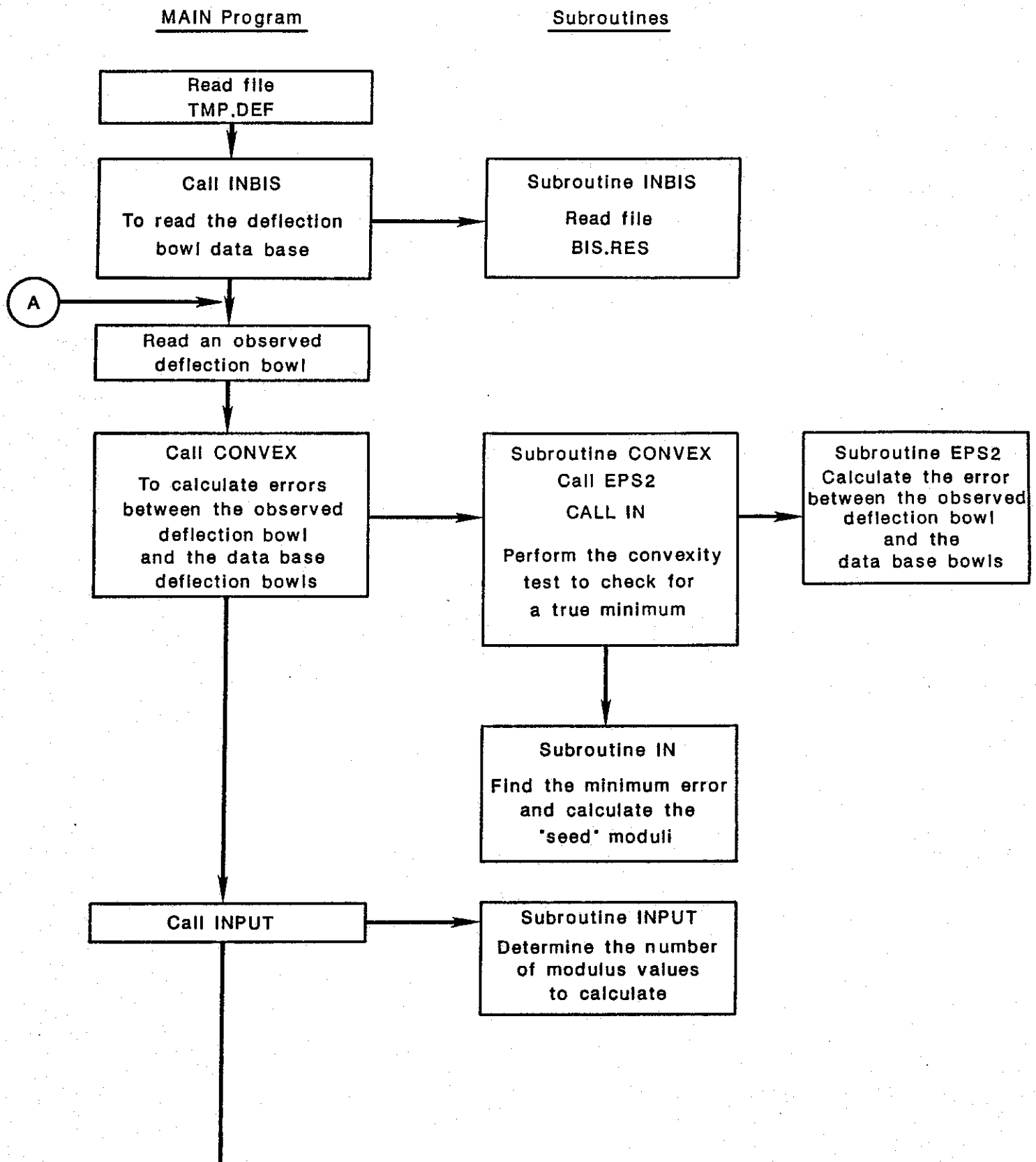


Figure 4. Program Flow Chart for MODULUS.

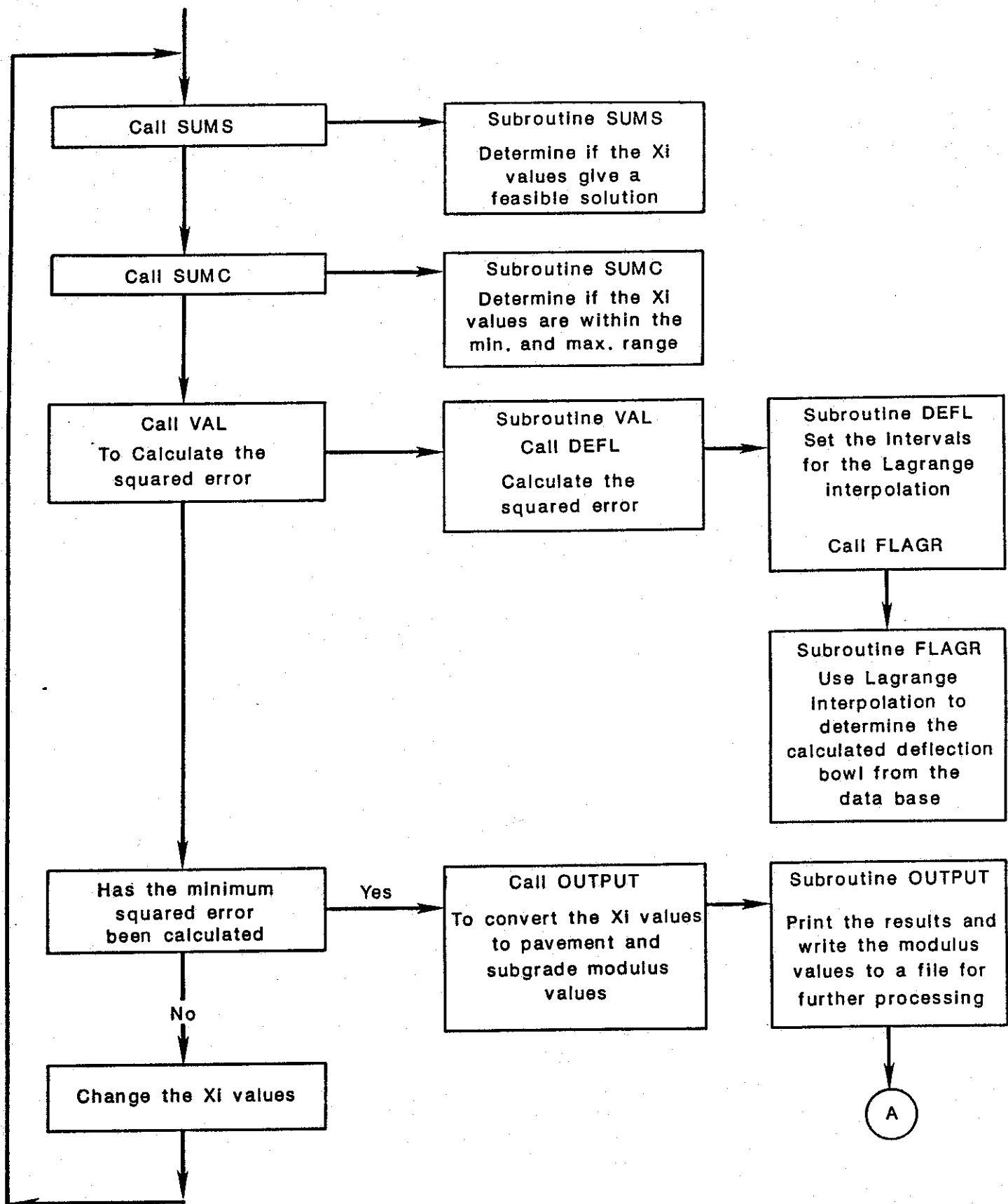


Figure 4. Program Flow Chart for MODULUS (continued)

modular ratios and the deflection bowls calculated by BISAR are read in by Subroutine INBIS.

After this initial data input, the program begins a loop that is repeated for every observed deflection bowl. This loop includes all the steps necessary to calculate the pavement layer and subgrade moduli values that produce the minimum squared error between the observed and calculated deflection bowls.

For each observed deflection bowl, PATTERN SEARCH calls Subroutine EPS2 to solve Equation (13) and to calculate the error between the observed deflection bowl and each bowl in the data base. Subroutine IN is then called to determine the minimum error and to calculate the "seed moduli" (Section 2.1) values for PATTERN SEARCH. Subroutine CONVEX (Section 2.3) performs the convexity test to determine if the  $\epsilon^2$  surface is convex. The "seed moduli" are converted to  $X_i$  values that are changed by PATTERN SEARCH for successive iterations

This next series of calculations is performed interactively until PATTERN SEARCH determines that the minimum squared error between the observed and calculated deflection bowl has been calculated. Subroutines SUMS and SUMC are called to determine if the  $X_i$  values are within the range specified. Subroutine VAL is called to determine the calculated deflections for the current set of  $X_i$  values. This is done by the Lagrange interpolation technique in Subroutine FLAGR. The intervals for the interpolation for the set of  $X_i$  values are determined in Subroutine DEFL. The squared error between the observed deflection bowl and the calculated (by Lagrange interpolation) deflection bowl is also computed in Subroutine VAL. The size of this error is used by PATTERN SEARCH to determine how much and in which direction to change the  $X_i$  values for the next iteration.

When the program determines that the minimum squared error has been calculated, Subroutine OUTPUT is called to convert the  $X_i$  values to pavement layer and subgrade moduli values that are printed and written to a file for further processing. The PATTERN SEARCH main program then reads the next observed deflection bowl, and the above procedure is repeated for all the observed deflection bowls.

### 2.3 Convexity Test

In section 2.1 the procedure used to calculate the subgrade modulus  $E_{sg}$  and the associated squared error term  $\epsilon^2$  were described. The  $\epsilon^2$  is minimized with respect to  $E_{sg}$  at given values of modular ratio. For each set of modular ratios a unique value of  $E_{sg}$  is computed. The example given in section 2.1 will be discussed further here. With reference to Table 2 the minimum  $\epsilon^2$  was obtained with modular ratios 30 and 3 and the  $E_{sg}$  value was calculated to be 35.7 ksi. The convexity test is included to indicate if the error surface is truly convex or whether this solution has the characteristics of a local minima.

The  $\epsilon^2$  terms from Table 2 are shown below plotted in a 3-D representation:

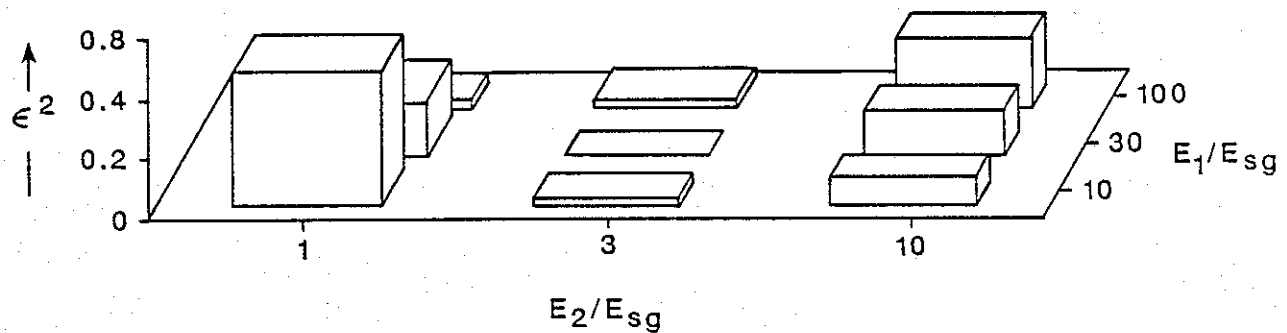


Figure 5. 3-D Representation of Error Surface.

The minimum error is located at  $\frac{E_1}{E_{sg}} = 30$  and  $\frac{E_2}{E_{sg}} = 3$  or the center column of Figure 5. The convexity test simply involves checking the x and y direction about this minimum point and determining if the error function is convex. In the above case checks would be made on:

- $\epsilon_1^2 = f_1(E_1/E_{sg})$  with  $(E_2/E_{sg})$  kept constant at 1, 3, 10, separately
- $\epsilon_2^2 = f_2(E_2/E_{sg})$  with  $(E_1/E_{sg})$  kept constant at 10, 30, 100, separately

These parameters are sketched below:

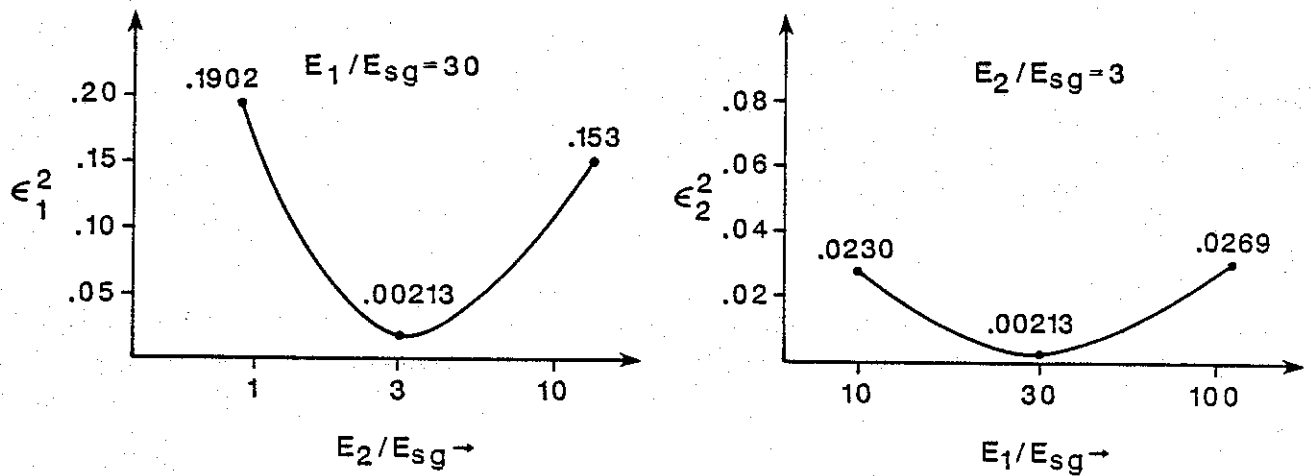


Figure 6. 2-D Error Function  $\epsilon_1^2$ ,  $\epsilon_2^2$  from Figure 5, drawn through the minimum (30,3).

The shape of the error surface in Figure 6 is convex in both the  $E_1/E_{sg}$  and the  $E_2/E_{sg}$  directions indicating that the minimum is a true minimum. The above discussion is specific to the example worked throughout this report. The discussion below is general and introduces the actual procedure to determine convexity.

For each section, the  $\epsilon^2 \min_1$  term for example, can be represented as shown in Figure 7.

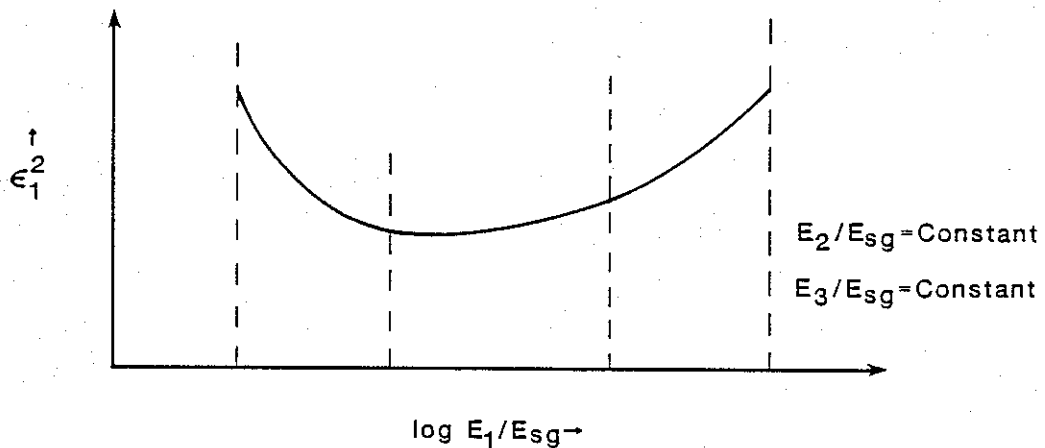


Figure 7. Generalized Plot of  $\epsilon^2$  v  $\log E_1/E_{sg}$ .

For a convex curve the function should be below any straight line connecting two points on the curve. Since the  $\epsilon_1^2$  function is known only at

specific points, the convexity test uses only those points in the data base. The convexity test includes the following two steps:

Step 1 The whole curve is below any straight line connecting two points on the curve; this is the test for strict convexity.

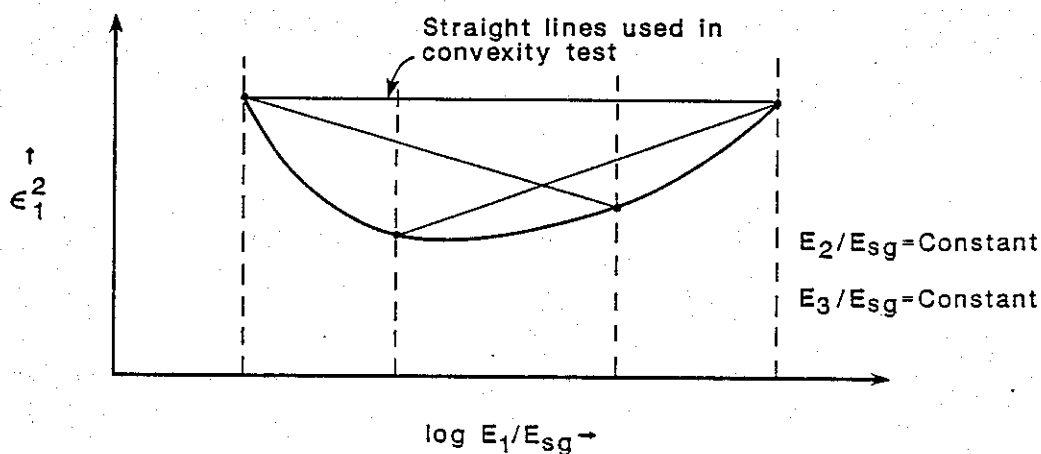


Figure 8. Convexity Test.

The equation used to check if the curve is below the straight line is given by:

$$f'(x^0) > f(x^0)$$

as shown in Figure 9 below:

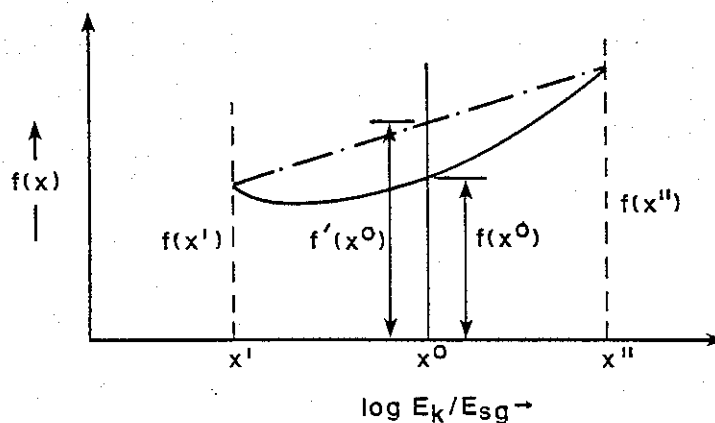


Figure 9. Definition of Terms in Convexity Test

where:  $f'(x^0) = \lambda f(x'') + (1 - \lambda) f(x')$

$$\lambda = \frac{x^0 - x'}{x'' - x'}$$

If the curve is below all possible straight lines then the function is assumed to be strictly convex.

Step 2. If the test for strict convexity is not met, the program then checks the sign of the slope of the function. If the sign does not change, the function is considered convex (not strict) and no warning message is printed as shown below:

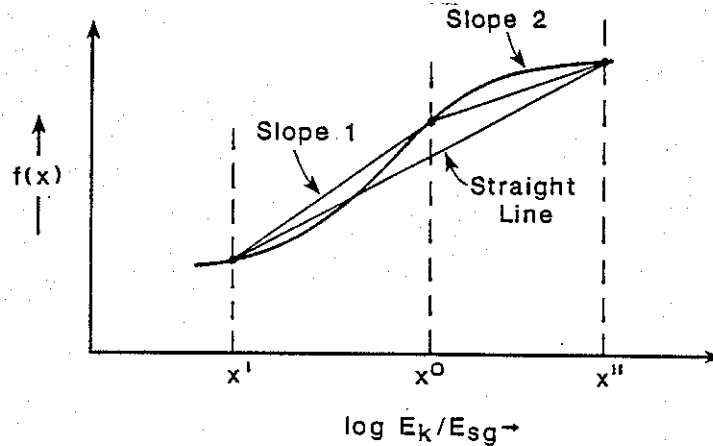


Figure 10. Second Stage Convexity Test of Slopes

If the slope changes sign, the function is not convex and a warning message "FAILED CONVEXITY TEST" is printed. For example:

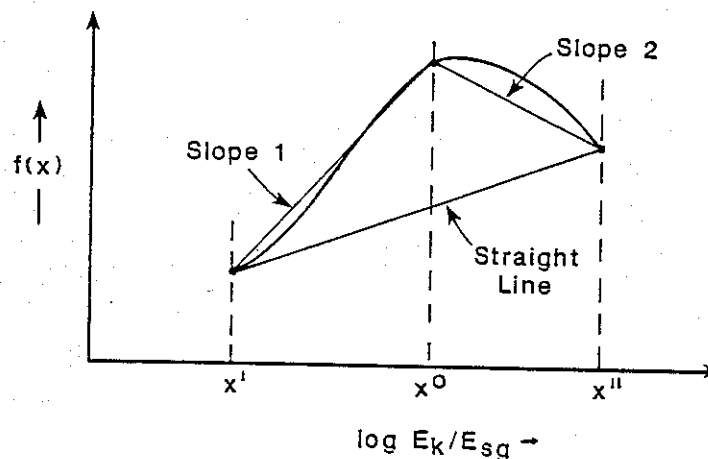


Figure 11. Error Surface Which Fails Convexity Test

The implication of failing the convexity test are that the acceptable set of moduli were too tightly defined. A widening of the range will



possibly result in a lower minimum error and a better fit between measured and calculated deflection bowls.

## CHAPTER 3

### UNIT DELINEATION PROCEDURE

#### 3.1 Overview

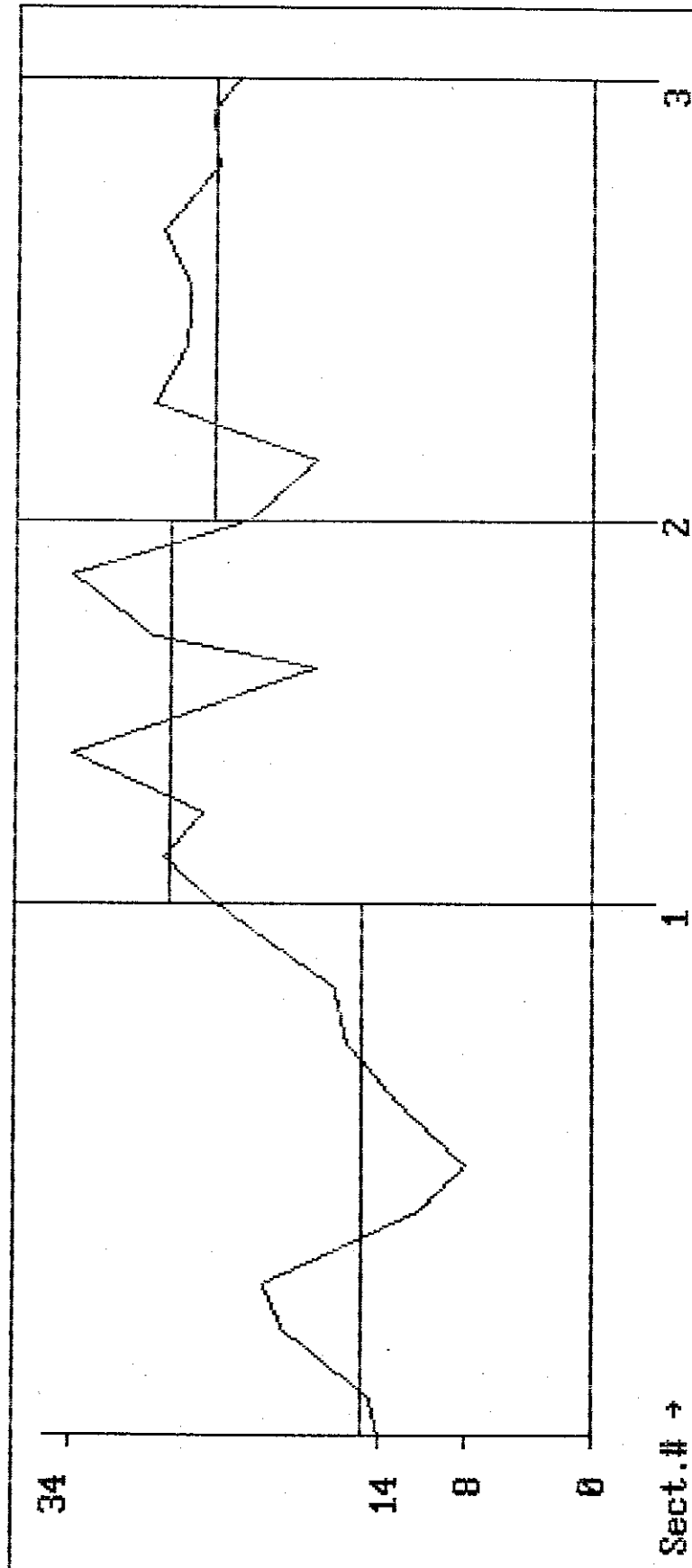
The modulus backcalculation program provides the user with a comprehensive set of output listings which display not only the original data and the results of the backcalculation algorithm, but also statistics that help in evaluating the soundness of both the data and the experimental results. Although the information presented in these output listings is adequate, the addition of a plotting routine that could map out pavement response variables (deflection and modulus of elasticity), particularly as a function of distance along the road segment, could help to visualize and better interpret the available data. It would be particularly useful in evaluating the uniformity of the section and determining if subsectioning is warranted for rehabilitation.

The third option in the Deflection Analysis System was a direct result of the above contemplation. This program plots any of the seven deflection readings or any of the pavement layer's elastic modulus as a function of total length of the road segment. It also defines boundaries for analysis units of section exhibiting relatively uniform characteristics along the road segment. The boundaries are delineated from the values of each of the specific response variables using a cumulative difference approach, and statistics are calculated for each of the delineated units.

#### 3.2 Unit Delineation Procedure

Figure 12 portrays a typical plot of a pavement response variable, the moduli value of a subgrade (E4) in this case, as a function of distance along the pavement segment being analyzed. It can be observed from the plot that the moduli values along the whole segment are subject to changes, and that the magnitude of these changes is more pronounced at some points (stations). The overall pavement response, at both sides of these points of greater magnitude change, is quite different. This observation reflects the fact that statistically homogeneous units may exist within the road segment. If so, the delineation of boundaries for these homogeneous units would be of importance, for instance, when considering pavement rehabilitation since

Road: FM2818      Pavement Response Variable: E4 (Moduli values in KSI)



Section #	From	To	Mean	S.Dev.
1	0.041	0.948	14900.56	4065.28
2	0.948	1.600	27429.71	5520.86
3	1.600	2.359	24673.33	3237.58

Press any key to continue

Figure 12. Unit delineation for subgrade layer of FM 2818

they could form the grounds for selecting project sections of road where specific analysis should be conducted. The plot in Figure 12 shows that three separate rehabilitation projects might be justified.

The method used in this program to achieve the delineation of statistically homogeneous units from deflection data and moduli values is known as the cumulative difference approach. This approach is recommended in the new AASHTO pavement design guide (6). To illustrate the principles behind this approach, assumptions of a continuous response value ( $r_i$ ), constant within the intervals along the pavement segment length, are considered (Figure 13a). There are three response values along the project,  $r_1$ ,  $r_2$ , and  $r_3$ , which could be plotted according to their cumulative areas (Figure 13b). Obviously, the cumulative area at any point  $x$  along the segment is given by the integral:

$$A_x = \int_0^{x_1} r_1 dx + \int_{x_1}^x r_2 dx \quad (15)$$

If the overall average response along the whole segment is represented by the dashed line in Figure 13b, then the cumulative area of the average response along the segment at any point  $x$  is given by:

$$\bar{A}_x = \int_0^x \bar{r} dx$$

where:

$$\bar{r} = \frac{\int_0^{x_1} r_1 dx + \int_{x_1}^{x_2} r_2 dx + \int_{x_2}^{x_3} r_3 dx}{L_s} = \frac{A_s}{L_s} \quad (16)$$

Once both  $A_x$  and  $\bar{A}_x$  are known, the cumulative difference variable  $Z_x$  can be found from:

$$Z_x = A_x - \bar{A}_x$$

Plotting  $Z_x$  as a function of segment length results in Figure 13c. By examining the plot, one should notice that location of unit boundaries

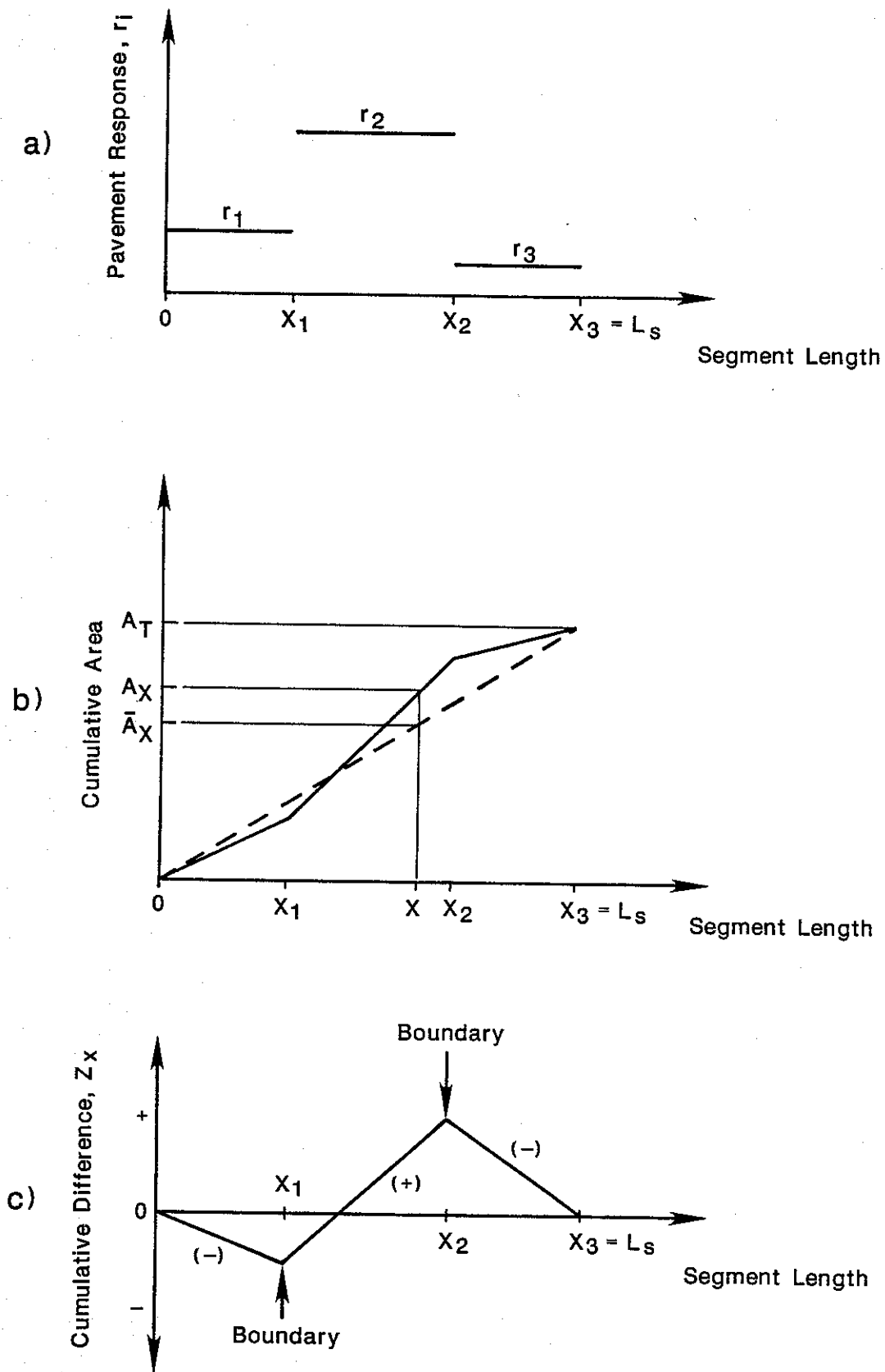


Figure 13. Cumulative Difference Approach to Unit Delineation

correspond with the points along the x-axis at which the slope of the function  $Z_x$  changes signs.

The application of this concept to discontinuous variables has been used in developing the delineation algorithm used in the graphical analysis program of this package.

The numerical difference approach used for this purpose expresses the  $Z_x$  function as:

$$Z_x = \sum_{i=1}^n a_i - \frac{\sum_{i=1}^{n_t} a_i}{L_s} \sum_{i=1}^n \Delta x_i \quad (17)$$

with:

$$a_i = \frac{(r_{i-1} + r_i) * \Delta x_i}{2} = \bar{r}_i * \Delta x_i \quad (18)$$

(Let  $r_0 = r_1$  for the first station)

where:  $n$  = the  $n^{th}$  pavement response value;  
 $n_t$  = the total number of pavement response values along the segment;  
 $r_i$  = pavement response value of the  $i^{th}$  station;  
 $\bar{r}_i$  = average of pavement response values between the  $i-1$  and the  $i^{th}$  stations; and  
 $L_s$  = the total analysis segment length.

As a demonstration of how the above procedure is implemented by the program, a partial summary of the analysis along a section of FM 2818 which resulted on the delineated plot for the subgrade layer (E4) in figure 12, is presented. Starting from the data for SUBGRADE (E4), and station in Table 3, Table 4 illustrates how equations 15 through 18 are used to determine the cumulative difference,  $Z_x$ , at each station. Table 5 exhibits the actual values resulting from the application of these calculations. Notice that

TTI DEFLECTION ANALYSIS SYSTEM													
District: 17										MODULI RANGE(psi)			
County: 21										Thickness(in)		Minimum	Maximum
Highway/Road: FM2818										Pavement:	4.00	200,000	1,200,000
										Base:	10.00	5,000	100,000
										Subbase:	0.00	0	0
										Subgrade:	INFINITY	15,000	
Station	Load (lbs)	Measured Deflection (mils):							Calculated Moduli values (psi):				Absolute % ERROR/Sensor
		R1	R2	R3	R4	R5	R6	R7	SURFACE(E1)	BASE(E2)	SUBBASE(E3)	SUBGRADE(E4)	
0.041	11,471	30.60	21.19	12.25	7.48	5.06	3.61	2.89	1,199,997	6,329	0	13,865	2.30
0.104	11,903	42.29	17.34	10.28	6.75	4.86	3.65	2.97	200,000	18,987	0	14,304	6.33
0.214	11,367	38.07	19.93	9.45	4.97	3.16	2.28	1.81	570,002	5,976	0	19,921	7.81
0.295	12,479	39.96	20.70	8.59	4.61	3.24	2.40	2.01	426,476	7,300	0	21,222	4.53
0.418	11,495	44.33	28.32	15.50	8.81	5.77	4.19	3.45	635,776	5,000	0	11,514	3.44
0.501	11,047	61.20	38.45	19.73	11.69	7.43	5.39	4.54	309,656	5,000	0	8,262	6.01
0.604	11,071	34.21	21.19	11.63	7.80	5.34	3.77	3.17	730,667	9,022	0	12,452	4.53
0.708	12,111	29.76	19.45	11.10	6.83	4.66	3.28	2.65	1,199,997	7,551	0	15,919	3.49
0.803	11,271	12.77	11.14	8.51	6.15	4.35	3.03	2.33	1,199,997	95,011	0	16,646	10.39
0.948	11,159	34.13	16.49	6.66	3.40	2.37	1.87	1.65	383,790	8,078	0	24,446	3.17
1.027	11,871	25.74	11.79	4.97	2.91	2.25	1.87	1.65	279,191	27,919	0	27,919	6.33
1.103	11,991	64.01	25.97	6.78	3.48	2.41	1.78	1.41	254,203	7,626	0	25,420	17.43
1.201	11,463	17.95	11.34	5.55	2.91	1.90	1.45	1.20	1,199,997	10,252	0	33,790	3.14
1.348	11,103	35.26	22.89	11.18	5.62	3.40	2.36	1.97	661,153	5,418	0	18,057	8.53
1.402	11,199	18.43	11.51	5.71	3.23	2.21	1.66	1.41	1,199,997	12,960	0	28,524	1.53
1.508	13,343	14.10	9.16	5.06	3.11	2.25	1.78	1.49	1,199,997	34,335	0	33,752	2.69
1.600	11,375	27.39	16.41	8.43	4.57	2.93	2.11	1.73	1,016,626	6,700	0	22,329	4.16
1.706	11,855	56.50	28.03	10.89	5.42	3.48	2.40	2.09	272,247	5,414	0	18,042	11.97
1.801	11,015	19.80	12.40	6.17	3.28	2.17	1.62	1.41	1,199,997	9,126	0	28,522	1.56
1.902	11,111	18.95	12.52	6.58	3.68	2.41	1.74	1.41	1,199,997	11,075	0	26,598	4.33
2.006	11,143	17.71	11.42	5.84	3.48	2.45	1.82	1.53	1,199,997	16,043	0	25,240	1.50
2.100	11,095	26.46	14.34	6.58	3.32	2.09	1.58	1.29	728,880	8,402	0	28,006	6.03
2.213	11,639	48.59	23.09	8.80	3.76	2.33	1.74	1.49	314,318	7,330	0	24,428	16.71
2.303	11,375	25.66	14.99	6.74	3.60	2.45	1.91	1.73	697,100	9,804	0	24,720	1.39
2.359	11,047	22.97	13.85	7.03	4.08	2.81	2.03	1.65	1,071,040	9,657	0	23,175	3.73
Mean:		32.27	18.16	8.80	5.00	3.35	2.45	2.04	774,044	14,013	0	21,927	5.72
Std. Dev:		14.35	6.99	3.49	2.20	1.43	1.00	0.82	390,505	18,294	0	6,841	4.37
Var Coeff(%):		44.47	38.48	39.69	44.06	42.68	40.68	40.07	50.45	130.55	0.00	31.20	76.43

Table 3. Deflection and Moduli values for section of FM 2818

Table 4. Iterative Solution Sequence (Reference 6).

(1) Station (Distance)	(2) Pavement Response Value ( $r_i$ )	(3) Interval Number (n)	(4) Interval Distance ( $\Delta x_i$ )	(5) Cumulative Interval Distance ( $\Sigma \Delta x_i$ )	(6) Average Interval Response ( $\bar{r}_i$ )	(7) Actual Interval Area ( $a_i$ )	(8) Cumulative Area $\Sigma a_i$	(9) Zx Value $Z_x = (8) - A * (5)$
1	$r_1$	1	$\Delta x_1$	$\Delta x_1$	$\bar{r}_1 = r_1$	$a_1 = \bar{r}_1 \Delta x_1$	$a_i$	$Z_{x1} = a_1 - A * \Delta x_1$
2	$r_2$	2	$\Delta x_2$	$(\Delta x_1 + \Delta x_2)$	$\bar{r}_2 = \frac{(r_1 + r_2)}{2}$	$a_2 = \bar{r}_2 \Delta x_2$	$a_1 + a_2$	$Z_{x2} = (a_1 + a_2) - A * (\Delta x_1 + \Delta x_2)$
3	$r_3$	3	$\Delta x_3$	$(\Delta x_1 + \Delta x_2 + \Delta x_3)$	$\bar{r}_3 = \frac{(r_1 + r_2 + r_3)}{3}$	$a_3 = \bar{r}_3 \Delta x_3$	$a_1 + a_2 + a_3$	
$L_s$	$r_n$	$N_t$	$\Delta x_{nt}$	$(\Delta x_1 + \dots + \Delta x_{nt})$	$\bar{r}_{nt} = \frac{(r_1 + \dots + r_n)}{n}$	$a_{nt} = \bar{r}_{nt} \Delta x_{nt}$	$a_1 + \dots + a_{nt}$	$Z_{xnt} = (a_1 + \dots + a_{nt}) - A * (\Delta x_1 + \dots + \Delta x_{nt})$

$$A_t = \sum_{i=1}^{n_t} a_i$$

$$A^* = \frac{A_t}{L_s}$$



Table 5. Cumulative Difference Example for Subgrade (EA) in FM 2818

Station (Distance)	Subgrade Moduli	Station	Interval Distance	Cumulative Distance	Avg. Interval Subgrade Moduli	Interval Area	Cumulative Interval Area	Cumulative Difference $\sum x$
0.041	13,865	1	0.041	0.041	13,865	568.47	568.47	-331.96
0.104	14,304	2	0.063	0.104	14,085	887.32	1,455.79	-828.21
0.214	19,921	3	0.110	0.214	19,921	1,882.37	3,338.16	-1,361.61
0.295	21,222	4	0.81	0.295	21,222	1,666.29	5,004.45	-1,474.198
0.418	11,514	5	0.123	0.418	11,514	2,013.26	7,017.79	-2,162.20
0.501	8,262	6	0.083	0.501	8,262	820.70	7,838.42	-3,164.306
0.604	12,452	7	0.103	0.604	12,452	1,066.77	8,905.19	-4,359.57
0.708	15,919	8	0.104	0.708	15,919	1,475.29	10,380.49	-5,168.28
0.803	16,646	9	0.095	0.803	16,646	1,546.84	11,927.32	-5,707.78
0.948	24,446	10	0.145	0.948	24,446	2,979.17	14,906.49	-5,913.041*
1.027	27,919	11	0.079	1.027	27,919	2,068.42	16,974.91	-5,579.59
2,100	28,006	.	.	.	.	.	.	.
2.213	24,428	23	0.113	2.213	24,428	2,962.52	48,254.55	-346.33
2.303	24,720	24	0.089	2.303	24,720	2,211.66	50,466.20	-111.21
2.359	23,175	25	0.056	2.359	23,175	1,341.06	51,807.26	0.00
								$A_j = 51,807.26$ $L_s = 2.359$ $A^* = 21,961.54$

\* 1st inflection point

the first inflection point for function  $Z_x$  occurs at a value of -5913.04, and that this value corresponds with station 10, the point at which the program makes the first delineation as shown in the plot of Figure 12.

During the program evaluation stage, it was observed that for some of the road segments being tested, the program would delineate sections that were too short in length to make them a viable rehabilitation project by themselves. In order to avoid this predicament, a feature allowing the user to specify a minimum project length, was incorporated into the program. this means that if the program finds an inflection point in the  $Z_x$  function that corresponds to a road segment that is shorter in length than the minimum length specified by the user, the delineation is overridden.

## CHAPTER 4

### CASE STUDIES

In this section the following five applications of the MODULUS backcalculation procedure are presented.

- 1) Comparison with BISDEF.
- 2) Standard run for Texas State Department of Highways and Public Transportation (SDHPT).
- 3) Analysis of multiple drops at the same location.
- 4) Effects of depth to rigid layer.
- 5) Effect of varying "seed" subgrade modulus.

#### 4.1 Comparison with BISDEF

The BISDEF program was developed at the Texas Transportation Institute by modifying the CHEVDEF program developed by the Corp of Engineers (2). The only modification was the replacement of the CHEVRON layered elastic program with the BISAR program. In this analysis FWD data were collected on two pavements at the Texas A&M Research Annex. The pavements are shown in Figure 14.

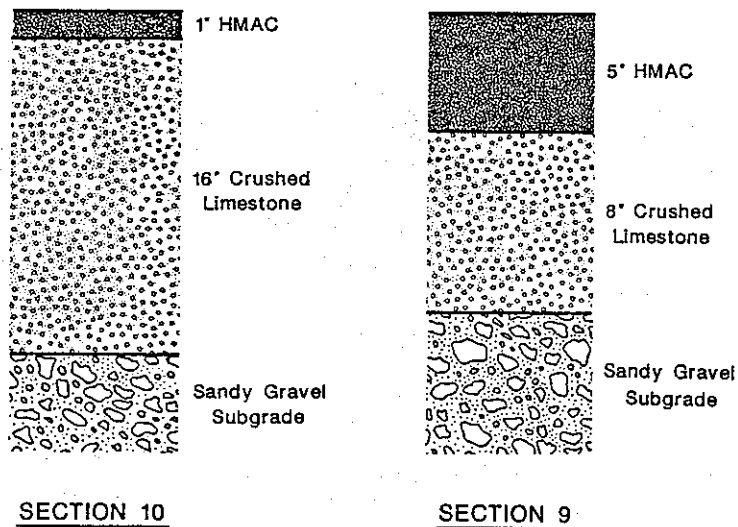


Figure 14. Monitor pavements at TTI Research Annex

The results of FWD testing are shown in Tables 6 and 7. At both sites at a single test point, three drops were taken at two load levels.

Load (lbs)	Measured Deflection (mils)						
	R1	R2	R3	R4	R5	R6	R7
8,719	12.78	6.28	3.46	2.67	2.20	1.46	1.13
8,679	12.01	6.03	3.38	2.63	2.16	1.42	1.09
8,663	11.89	5.99	3.38	2.63	2.12	1.50	1.13
16,943	22.08	11.77	6.69	5.07	3.95	3.09	2.58
16,975	21.63	11.52	6.58	4.99	3.83	3.13	2.62
17,039	21.51	11.56	6.61	5.07	3.99	3.17	2.62

Table 6. FWD results from Section 10

Load (lbs)	Measured Deflection (mils)						
	R1	R2	R3	R4	R5	R6	R7
8,711	9.66	5.66	3.08	2.08	1.59	1.26	1.01
8,527	9.46	5.57	3.04	2.00	1.55	1.22	0.93
8,551	9.62	5.66	3.12	2.08	1.63	1.30	1.05
16,743	19.53	11.14	5.96	3.87	2.97	2.32	1.89
16,711	18.92	11.02	5.88	3.95	2.97	2.42	1.97
16,751	19.00	10.98	5.85	3.91	2.97	2.40	1.97

Table 7. FWD results from Section 9

In the backcalculation procedure in both BISDEF and MODULUS the "seed" moduli were kept constant. The thin asphalt layer (1 inch) on section 10 was assigned a constant moduli value of 500 ksi.

The backcalculated moduli values are shown in Tables 8 and 9. Both procedures give similar backcalculated E values particularly in the subgrade layer. This result should be expected as both use the BISAR linear elastic program to calculate deflections, but each uses a different search routine to find the optimum set of moduli values to minimize the error between

measured and predicted bowls. As mentioned earlier the MODULUS program is considerably faster than BISDEF, and MODULUS is well suited to the case where multiple bowls on the same section are to be processed.

MODULUS				BISDEF		
Load	Base	Subgrade	Error	Base	Subgrade	Error
8.719	78.7	27.4	7.07	79.3	27.8	6.72
8.679	84.6	27.8	7.46	91.4	26.8	5.89
8.663	87.2	27.1	5.94	89.4	27.1	7.52
16.943	96.3	25.5	3.01	101.3	26.1	2.99
16.975	99.8	25.6	3.57	104.5	26.5	3.62
17.039	102.1	25.3	3.31	107.1	26.2	3.36

Table 8. Section 10 Backcalculated Moduli Values (Ksi)  
(Error = Absolute % Error/Sensor)

MODULUS					BISDEF			
Load	Asphalt	Base	Subgrade	Error	Asphalt	Base	Subgrade	Error
8,711	423.2	65.0	32.7	1.76	476.1	59.9	32.8	1.53
8,527	488.1	55.8	33.3	2.37	522.1	54.0	33.2	2.25
8,551	399.2	69.4	31.5	2.27	457.8	62.9	31.7	2.21
16,743	437.6	50.6	33.5	1.22	467.4	48.7	33.5	1.06
16,711	416.9	60.1	32.9	1.77	476.6	54.9	33.1	1.66
16,751	406.4	60.3	33.1	1.91	462.4	55.0	33.2	1.81

Table 9. Section 9 (Backcalculated Moduli Values (Ksi)  
(Error = Absolute % Error/Sensor)

#### 4.2 Standard Run for Texas SDHPT

The Texas Department of Highways and Public Transportation is currently utilizing the MODULUS program for interpretation of FWD data collected on project-level evaluation. The case study included in this section involves data collected on SH 152 in District 25, Texas. The highway consists of three to four inches of asphalt surfacing, a ten-inch granular base on top of a sandy/gravel subgrade. The six-mile section under evaluation was showing some localized load-related distresses, deep ruts and alligator cracking. The pavement was a candidate for rehabilitation and an FWD

survey was performed in order to establish inputs to the design procedure. The analysis of this data is discussed below.

FWD data were collected at two-tenth mile intervals. The output from the MODULUS backcalculation scheme is shown in Table 10 and Figure 15. Table 10 shows each deflection bowl and the backcalculated E values. The variation of granular base E values along the road is plotted in Figure 15 and the automatic section delineation routine (using the cumulative difference method discussed in Section 3) identified three subsections, from mileposts 0.0 to 4.2, 4.2 to 5.2 and 5.2 to 6.6. It is the designers responsibility to decide if this subsectioning is warranted or if the sections should be combined into a single project. In either case, the system will generate the layer modulus and its variation for input into the pavement design procedure.

#### 4.3 Multiple Drops

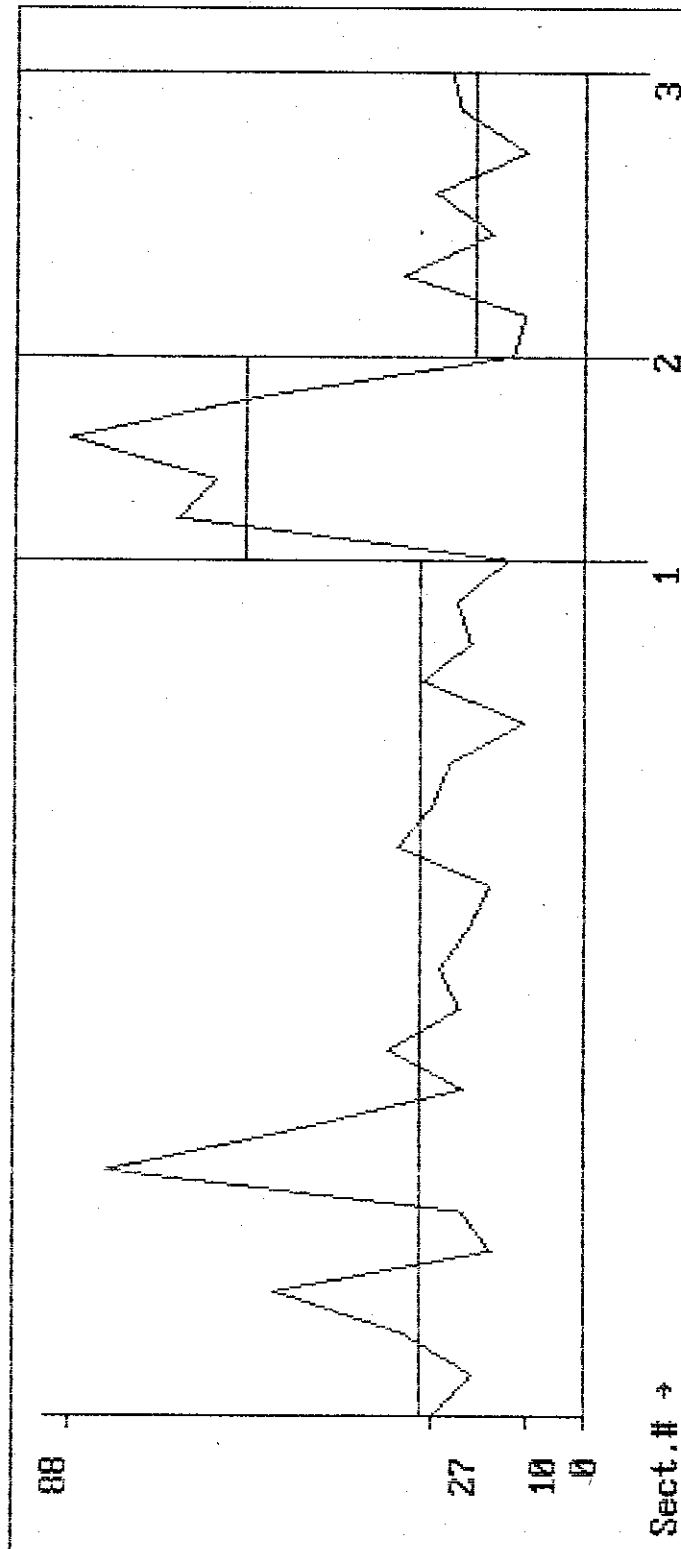
To evaluate the repeatability of the backcalculation procedure, three of the research pavements at the Texas A&M research annex were tested. At each pavement, 12 drops of the FWD were made at the same spot. Results of the backcalculation on this deflection data are shown in Tables 11, 12, and 13. Table 11 is for section 8 which has five inches of HMA over eight inches of crushed limestone base over an eight-inch cement stabilized over a clay subgrade. Table 12 is for section 11 which has a one-inch HMA surface over 16 inches of crushed limestone over a sandy gravel subgrade. Table 13 is for section 9 which has five inches of HMA over eight inches of crushed limestone over a sandy clay subgrade. The aim of this testing was to determine the number of readings to be taken at an individual site to characterize the pavement to a specified confidence level. However, on the unstabilized sections (Tables 12 and 13) it is noted that the first deflections taken are significantly higher than the following readings. In Table 12 the maximum deflection reading on the first drop is 15.16 mils compared with a mean value of 13.99 or 2.78 standard deviations above the mean. In Table 13 the first drops maximum deflection is 2.85 standard deviation above the mean. All subsequent drops on both sections are within one standard deviation of the mean. The implication here is that the FWD seating drop is inadequate. The recommendation for FWD data collection is that as a

# TTI DEFLECTION ANALYSIS SYSTEM

District: 25												MODULI RANGE(psi)	
County: 242												Minimum	Maximum
Highway/Road: SH0152													
												Thickness(in)	
												Pavement:	4.00
												Base:	12.00
												Subbase:	0.00
												Subgrade:	224.00
													15,000
Station	Load (lbs)	Measured Deflection (mils):							Calculated Moduli values (psi):				Absolute % ERROR/Sensor
		R1	R2	R3	R4	R5	R6	R7	SURFACE(E1)	BASE(E2)	SUBBASE(E3)	SUBGRADE(E4)	
0.000	11,559	19.32	10.46	3.72	2.11	1.54	1.17	1.00	380,035	26,512	0	29,611	6.93
0.200	11,447	22.30	12.44	4.05	2.22	1.50	1.13	1.41	362,721	19,332	0	27,885	10.93
0.400	11,383	22.03	14.01	6.87	4.37	3.00	2.21	1.69	452,225	31,393	0	15,860	3.51
0.600	11,503	17.79	11.04	5.60	3.77	2.70	2.05	1.61	430,078	52,976	0	18,065	4.86
0.800	10,831	27.68	14.51	5.40	2.86	2.04	1.61	1.17	277,472	15,804	0	20,632	4.04
1.000	11,463	21.71	12.11	5.73	3.42	2.12	1.41	1.29	611,312	20,723	0	21,505	4.20
1.200	12,447	10.64	5.91	2.13	1.55	1.12	0.97	0.76	499,943	81,433	0	46,697	11.96
1.400	12,119	12.80	5.62	1.80	1.43	1.21	1.01	0.84	493,908	49,390	0	49,390	18.00
1.600	11,399	18.57	10.71	3.80	2.07	1.33	1.01	0.80	549,309	20,948	0	31,926	3.51
1.800	11,287	19.91	11.49	4.95	3.06	2.21	1.65	1.41	360,814	33,735	0	20,965	6.44
2.000	11,103	25.60	14.88	6.63	4.05	2.70	1.93	1.65	367,751	21,251	0	16,464	3.80
2.200	10,855	26.03	16.33	8.06	5.08	3.50	2.58	2.05	372,190	25,114	0	12,814	3.59
2.400	11,407	24.62	14.43	6.26	3.69	2.50	1.81	1.41	439,821	19,929	0	18,427	2.30
2.600	11,143	24.31	14.10	5.56	2.98	1.96	1.49	1.21	434,626	16,526	0	21,452	3.73
2.800	10,991	20.14	11.99	4.87	3.06	2.25	1.77	1.41	339,403	32,511	0	20,127	8.13
3.000	10,895	25.68	13.44	3.93	1.99	1.50	1.25	1.05	264,394	26,439	0	26,439	14.71
3.200	11,287	23.29	12.57	4.34	2.74	2.08	1.57	1.25	265,128	23,558	0	22,888	8.91
3.400	10,687	23.56	12.73	3.44	1.51	1.08	0.93	0.84	356,107	10,683	0	35,610	8.90
3.600	10,503	21.71	10.58	3.11	1.91	1.54	1.25	1.09	277,794	27,779	0	27,779	14.57
3.800	10,743	20.03	11.45	3.56	1.95	1.37	1.01	0.88	377,978	19,508	0	30,083	6.46
4.000	10,807	25.64	12.36	4.01	2.58	2.08	1.73	1.37	221,521	22,152	0	22,152	12.64
4.200	10,543	27.88	15.87	6.09	3.10	2.08	1.61	1.25	352,954	12,977	0	19,017	3.63
4.400	11,167	17.63	9.43	4.42	2.76	1.91	1.49	1.21	230,358	69,107	0	23,035	8.83
4.600	11,607	18.53	10.71	5.03	3.18	2.21	1.77	1.37	210,324	63,097	0	21,032	7.60
4.800	10,975	9.93	5.62	2.58	1.71	1.25	0.97	0.84	559,693	87,735	0	36,647	7.99
5.000	11,095	15.39	9.14	4.79	3.22	2.21	1.61	1.29	473,877	56,165	0	21,162	2.81
5.200	10,359	24.31	14.01	5.07	2.50	1.58	1.17	1.05	436,944	12,522	0	23,594	4.44
5.400	10,231	21.40	13.10	4.91	2.30	1.41	0.97	0.80	675,556	10,831	0	27,160	2.73
5.600	10,287	22.97	15.13	7.69	5.04	3.58	2.70	2.05	400,409	31,409	0	12,173	4.17
5.800	10,687	24.74	12.94	5.11	2.78	1.75	1.37	1.05	369,109	16,175	0	22,541	2.17
6.000	10,759	20.30	10.91	3.68	2.18	1.71	1.33	1.09	287,864	25,723	0	24,050	9.99
6.200	10,119	31.18	16.54	5.36	2.42	1.66	1.45	1.21	257,966	9,955	0	21,168	7.80
6.400	10,639	23.40	14.80	6.38	3.73	2.62	1.97	1.55	421,006	21,252	0	16,272	6.04
6.600	11,207	21.71	13.02	5.32	3.18	2.21	1.65	1.25	448,497	22,856	0	20,554	4.19
Mean:		21.55	12.19	4.83	2.84	1.99	1.52	1.24	389,973	30,515	0	24,329	6.90
Std. Dev:		4.67	2.77	1.44	0.93	0.63	0.45	0.33	111,474	20,145	0	8,282	4.00
Var Coeff(%):		21.65	22.76	29.84	32.81	31.61	29.50	26.50	28.59	66.02	0.00	34.04	57.92

Table 10. Typical SDHPT Analysis. State Highway 152 in District 25.

Road: SH0152 Pavement Response Variable: E2 (Moduli values in KSI)



Section #	From	To	Mean	S.Dev.
1	0.000	4.200	28461.71	15818.58
2	4.200	5.200	57816.20	27675.73
3	5.200	6.600	18840.38	7722.03

Press any key to continue

Figure 15. Graphic Output Variation in Base Modulus for SH 152.



Table 11. E Values for Multiple Drops at Same Location (Section 8).

TTI DEFLECTION ANALYSIS SYSTEM													
District: 17										MODULI RANGE(psi)			
County: 21										Thickness(in)		Minimum	Maximum
Highway/Road: TTIANX										Pavement:	5.00	200,000	500,000
										Base:	8.00	30,000	150,000
										Subbase:	8.00	1,000,000	4,000,001
										Subgrade:	INFINITY		30,000
Station	Load (lbs)	Measured Deflection (mils):							Calculated Moduli values (psi):				Absolute %
		R1	R2	R3	R4	R5	R6	R7	SURFACE(E1)	BASE(E2)	SUBBASE(E3)	SUBGRADE(E4)	ERROR/Sensor
8.010	9,923	6.39	3.31	2.35	2.08	1.87	1.53	1.29	415,803	97,071	3,999,991	31,669	2.11
8.020	9,111	6.35	3.27	2.35	2.08	1.95	1.49	1.21	378,326	86,281	3,999,991	29,558	2.76
8.030	9,031	6.35	3.27	2.35	2.04	1.95	1.46	1.17	374,089	85,748	3,527,455	30,045	3.17
8.040	9,055	6.63	3.27	2.35	2.04	1.95	1.46	1.17	330,905	82,289	3,857,257	30,385	3.10
8.050	9,007	6.27	3.23	2.31	2.04	1.95	1.42	1.13	352,508	93,732	2,933,154	30,780	3.66
8.060	9,007	6.23	3.23	2.31	2.08	1.95	1.42	1.17	370,480	90,917	3,372,013	30,114	3.69
8.070	8,943	6.31	3.23	2.27	2.04	1.99	1.38	1.05	311,291	103,256	2,019,501	31,966	5.33
8.080	8,967	6.23	3.23	2.23	2.04	1.99	1.34	1.05	347,002	96,014	2,224,304	32,248	5.73
8.090	9,167	6.23	3.35	2.35	2.12	1.87	1.53	1.29	453,389	83,573	3,999,991	28,824	1.67
8.100	9,047	6.19	3.35	2.35	2.12	1.87	1.53	1.29	463,205	82,107	3,999,991	28,336	1.67
8.110	9,055	6.15	3.31	2.35	2.08	1.87	1.53	1.29	455,782	84,904	3,999,991	28,462	1.84
8.120	9,047	6.07	3.31	2.31	2.12	1.87	1.53	1.29	467,910	86,427	3,999,991	28,321	2.00
Mean:		6.28	3.28	2.32	2.07	1.92	1.47	1.20	393,391	89,360	3,494,469	30,059	3.06
Std. Dev:		0.14	0.05	0.04	0.03	0.05	0.07	0.09	55,608	6,779	725,192	1,413	1.36
Var Coeff(%):		2.26	1.39	1.70	1.61	2.56	4.53	7.67	14.14	7.59	20.75	4.70	44.58

\* Several of the subbase moduli values hit the user-supplied limit.

Table 12. E Values for Multiple Drops at Same Location (Section 11).

TTI DEFLECTION ANALYSIS SYSTEM													
District: 17										MODULI RANGE(psi)			
County: 21										Thickness(in)		Minimum	Maximum
Highway/Road: TTIANX										Pavement:	1.00	200,000	800,000
										Base:	16.00	20,000	120,000
										Subbase:	0.00	0	0
										Subgrade:	INFINITY	30,000	
Station	Load (lbs)	Measured Deflection (mils):							Calculated Moduli values (psi):				Absolute % ERROR/Sensor
		R1	R2	R3	R4	R5	R6	R7	SURFACE(E1)	BASE(E2)	SUBBASE(E3)	SUBGRADE(E4)	
11.010	8,463	15.16	6.07	3.04	2.04	1.79	1.89	1.37	799,998	59,880	0	28,576	10.63
11.020	8,319	14.19	5.82	3.00	2.08	1.75	1.85	1.29	799,998	65,033	0	28,318	9.49
11.030	8,343	13.95	5.86	3.04	2.04	1.83	2.12	1.41	799,998	68,053	0	27,403	12.13
11.040	8,319	13.87	5.61	3.00	2.08	1.63	1.26	1.09	799,998	61,868	0	31,529	2.81
11.050	8,279	13.71	5.53	2.96	2.08	1.59	1.22	1.05	799,998	61,954	0	32,062	2.34
11.060	8,319	13.83	5.61	3.00	2.12	1.63	1.26	1.09	799,998	62,267	0	31,393	2.56
11.070	8,287	13.71	5.53	2.96	2.12	1.59	1.22	1.05	799,998	62,147	0	31,972	2.24
11.080	8,311	13.67	5.57	3.00	2.12	1.63	1.26	1.05	799,998	62,971	0	31,588	2.00
11.090	8,511	14.31	5.86	3.04	2.08	1.63	1.42	1.17	799,998	61,722	0	31,020	5.23
11.100	8,367	13.83	5.82	3.08	2.04	1.63	1.53	1.29	799,998	64,414	0	29,689	7.81
11.110	8,343	13.91	5.91	3.08	2.00	1.63	1.61	1.41	799,998	64,646	0	29,145	10.13
11.120	8,343	13.71	5.86	3.08	2.04	1.63	1.69	1.41	799,998	66,468	0	28,778	10.44
Mean:		13.99	5.75	3.02	2.07	1.66	1.53	1.22	799,998	63,452	0	30,123	6.48
Std. Dev:		0.42	0.18	0.04	0.04	0.08	0.31	0.15	0	2,315	0	1,644	3.98
Var Coeff(%):		2.99	3.07	1.43	1.87	4.79	20.08	12.65	0.00	3.65	0.00	5.46	61.42

Table 13. E Values for Multiple Drops at Same Location (Section 9).

TTI DEFLECTION ANALYSIS SYSTEM

District: 17									MODULI RANGE(psi)				
County: 21									Thickness(in)		Minimum	Maximum	
Highway/Road: TTIANX									Pavement:	5.00	200,000	800,000	
									Base:	8.00	30,000	200,000	
									Subbase:	0.00	0	0	
									Subgrade:	INFINITY	30,000		
-----													
	Load	Measured Deflection (mils):							Calculated Moduli values (psi):				Absolute %
Station	(lbs)	R1	R2	R3	R4	R5	R6	R7	SURFACE(E1)	BASE(E2)	SUBBASE(E3)	SUBGRADE(E4)	ERROR/Sensor
-----													
9.010	9,167	9.34	5.49	3.08	2.08	1.71	1.26	0.89	484,287	71,425	0	35,045	4.31
9.020	8,815	8.85	5.40	3.08	2.12	1.63	1.30	1.05	461,041	89,276	0	32,408	1.93
9.030	8,791	8.73	5.36	3.08	2.12	1.63	1.26	1.01	511,722	83,816	0	32,739	1.66
9.040	8,775	8.69	5.40	3.08	2.08	1.63	1.26	1.01	547,717	79,214	0	32,772	2.00
9.050	8,751	8.73	5.40	3.08	2.12	1.63	1.26	1.01	529,906	80,526	0	32,566	1.74
9.060	8,679	8.61	5.36	3.04	2.08	1.63	1.26	1.01	528,668	82,394	0	32,503	2.16
9.070	8,695	8.61	5.40	3.08	2.08	1.59	1.26	1.05	558,059	79,195	0	32,380	1.84
9.080	8,719	8.61	5.36	3.08	2.08	1.63	1.26	1.01	548,575	81,009	0	32,576	1.96
9.090	8,871	8.90	5.45	3.12	2.12	1.63	1.30	1.05	491,264	84,334	0	32,507	1.76
9.100	8,735	8.73	5.40	3.08	2.12	1.67	1.22	0.93	604,100	69,802	0	33,149	2.97
9.110	8,719	8.73	5.40	3.08	2.12	1.67	1.26	0.97	534,908	78,841	0	32,584	2.63
9.120	8,663	8.65	5.40	3.08	2.12	1.63	1.26	0.97	576,865	75,029	0	32,485	2.27
-----													
Mean:		8.77	5.40	3.08	2.10	1.64	1.26	1.00	531,426	79,572	0	32,810	2.27
Std. Dev:		0.20	0.04	0.02	0.02	0.03	0.02	0.05	40,243	5,469	0	734	0.75
Var Coeff(%):		2.31	0.69	0.55	0.98	1.84	1.63	4.94	7.57	6.87	0.00	2.24	33.08

minimum the Texas SDHPT should make two drops at each location and that the second one should be used in data analysis.

The second observation from these tables is that the three-layer systems produce repeatable moduli values. However, the four-layer systems backcalculated moduli values (Table 11) for the layers above the subgrade are extremely sensitive to even small changes in bowl shape. The average coefficient of variation of the outermost sensor was 8.4%. The outermost deflections appear to be approaching the accuracy limit of the sensor perhaps indicating that a heavier load is required. Alternatively, it may be feasible to employ more accurate geophones at the outer sensor locations. To minimize the effect of variations in the outer sensor within the MODULUS program it is possible to apply a large weighting factor to the sensors closer to the load.

#### 4.4 Effects of Rigid Layer

Several researchers have found that the placement of a rigid layer within the subgrade has considerable influence on the backcalculated moduli values, the Corp of Engineers recommend a layer placed at 20 feet (2). The existing MODULUS program allows the placement of a rigid layer at any depth in the subgrade. With reference to the data set shown in Table 3, the same data set was rerun using several depths to rigid layer and the effect on the backcalculated subgrade modulus and fitting error between measured and calculated deflections is shown below in Table 14.

Depth to Rigid Layer (inches)	Backcalculated Subgrade Modulus (ksi)	Absolute % Error/Sensor
∞	21.9	5.72
360	17.6	3.76
300	16.8	3.65
240	15.8	3.96
180	14.3	5.61
120	11.8	10.53
60	7.3	25.12

Table 14. Effect of placing a rigid layer at varying depths on FM 2818 data.

The best fit between measured and calculated bowls occurred with a rigid layer placed at approximately 300 inches below the surface. It is

clear from these results that an estimate should be made for the depth to bedrock for each pavement under analysis. This estimate does not need to be precise but simply classifies pavements into groups, i.e., depth to bedrock 0-5 ft., 5-10 ft., 10-15 ft., 15-20 ft., etc. Classifications such as this could be established by reference to a standard geological map or county soils reports.

#### 4.5 Effect of Different Estimated Subgrade Moduli

Programs such as CHEVDEF require a "seed" moduli to be input for each layer so that the error minimization search can begin. Lytton (5) found that the choice of the "seed" value is important; in any search routine the final solution is often a function of the starting point. In the MODULUS program described in this report, the only "seed" modulus given is that of the subgrade; for all other layers an acceptable range of moduli values are supplied. In MODULUS the range of layer moduli are used to generate a range of modular ratios as described earlier in this report.

To evaluate the influence of different input subgrade moduli within the MODULUS program the following was performed. First the BISAR program was run to predict the deflection at FWD sensor locations under known loading (80 psi), layer thicknesses (3 inches HMAC, 10-inch base, and semi-infinite subgrade) and layer moduli (500, 50, 10 ksi and 500, 50, 20 ksi). The calculated FWD deflection bowl was then input into MODULUS and the program ran several times with different estimated subgrade moduli. The results are shown in Tables 15 and 16.

	Surface	Base	Subgrade	% Error in Fitting Input and Calculated Bowls
Input Moduli	500	50	20	
Modulus Backcalculation				
Estimated Subgrade E (ksi)				
5	482.9	51.2	20.0	1.01
10	489.5	51.0	20.0	0.91
20	489.5	51.0	20.0	0.90
30	489.5	51.0	20.0	0.90

Table 15. Reproducibility of MODULUS program with Known Moduli values (500/50/20 ksi)

	Surface	Base	Subgrade	% Error in Fitting Input and Calculated Bowls
Input Moduli	500	50	10	
Modulus Backcalculation				
Estimated Subgrade E (ksi)				
5	430.2	52.6	10.1	1.12
10	494.0	49.6	10.0	1.17
20	505.1	49.3	10.0	1.07
30	496.7	49.5	10.0	1.14

Table 16. Reproducibility of MODULUS program with Known Moduli values (500/50/10 ksi)

When running the MODULUS program the range in surface modulus was (200 to 800 ksi); the range in base modulus was (E subgrade to 100 ksi). The Error presented is the total absolute error between the seven sensors of the input deflection bowl and the bowl backcalculated by the MODULUS program.

This example can be used to estimate the influence of input estimated subgrade moduli. In a typical analysis the designer must estimate the subgrade modulus prior to running the MODULUS program. How close should that estimate be to the actual value? Table 15 and 16 indicate that the modulus values backcalculated are not greatly affected by the user-supplied input subgrade modulus values. Values ranging from 5 ksi to 30 ksi converged to approximately the same set of E values which were very close to the known values. As described in Section 2 of this report, the input subgrade modulus is only used to calculate the range of modular

ratios to be used in generating the deflection database. The actual subgrade modulus is calculated using Equation 13 which is independent of the input value.

It should be noted that when running the MODULUS program, it is essential that a wide enough range of surfacing and base moduli should be used. If the range is too narrow, then messages such as "E1 is very close to limits" or "no feasible solution" are printed. In these cases, the acceptable range of layer moduli should be increased.

## CHAPTER 5

### CONCLUSIONS

This report describes a new modulus backcalculation procedure called MODULUS and describes how this system has to been incorporated into the Texas State Department of Highways and Public Transportation's pavement analysis system. The current program is based on the theory of linear elasticity but the procedure is general and nonlinear analysis programs could be used to build the database (1). The system has been built on microcomputer and implemented by the Texas SDHPT. The initial review of this system has been favorable. The procedure is ideal for use in pavement analysis where numerous deflection bowls are taken at regular intervals along a project.

Further work is underway to validate the backcalculated moduli values. This involves the following two approaches. First, twenty-two experimental pavement sections have been established around the State of Texas. These pavements have been instrumented with temperature and moisture sensors. Pavement layer materials have been taken and returned to the laboratory for triaxial testing. Falling Weight Deflectometer data has been collected at monthly intervals. The laboratory testing phase of this work is complete and the analysis portion is underway and will be reported in the near future.

The second approach involves instrumenting pavement sections with Multi-Depth Deflectometers. By testing the instrumented pavement with FWD, it is possible to measure both the surface and depth deflection profile. Both of these can be used to calculate layer moduli. The preliminary results from the MDD study are presented in Research Report 1123-2(7).



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- 2) Bush, A. J., "Nondestructive Testing of Light Aircraft Pavements, Phase II, Development of the Nondestructive Evaluation Methodology," Report No. FHWA-RD-80-9-11, 1980.
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- 6) AASHTO Guide for Design of Pavement Structures, 1986, AASHTO, Chapter 3 and Appendix J.
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## APPENDIX A

The Modulus Back Calculation program described in this report has been custom-built into a system for the Texas Department of Highways and Public Transportation. The following assumptions were built into the code:

- Designed to accept the field data diskette from a Dynatest FWD.
- Assumes the seven sensors are spaced at one foot intervals.
- Contains several default data bases for commonly found pavement structures in Texas.
- Assumes the weighting factors (Section 2.1) are set to 1.0.
- This version of MODULUS uses the BISAR linear elastic program to generate the deflection data base. Another version of the system is available which uses the CHEVRON program.

Details of the above mentioned system, including a user's manual, are incorporated in this appendix.

### 1. Introduction

#### A. Getting Started

The TTI Deflection Analysis System program is distributed in a 5 1/4" High Density floppy disk. To make backup copies of this diskette use the DISKCOPY command from DOS to insure that all the files are copied to the backup diskette.

Check the disk directory to see if a TTIREAD.ME file exists. If it is there, you can list it either on the screen using the TYPE command, or on the printer via the PRINT command. This file contains the most current information and/or special instructions pertinent to the latest version of the software and it should supersede any information found in the User's Manual.

#### B. System Requirements

Minimum system requirements to run the program are:

- IBM AT or compatible microcomputer

- 640 Kb of RAM
- DOS (version 3.00 or later) operating system
- Math coprocessor chip (80287 or similar)
- 1 High density floppy diskette drive (1.2 Mb)
- A hard disk
- A EGA graphics card with 256 Kb of screen memory and a compatible RGB monitor
- For machines with only a 64K EGA card replace the existing DELINIAT.EXE with DELINIAT.64K by renaming the latter file .EXE

It is recommended that an advanced microcomputer, a 286 or even a 386 based machine, be used in order to minimize program execution time when running analyses comprising more than 20 stations.

### C. File Naming Conventions

The TTI Deflection Analysis Systems program uses several types of files. The type of each of these files is identified by the three letter extension to the filename:

- .LBR: Input/output screen display library.
- .BIS: A file produced by the MODBAC program. It contains information later used by the BISAR program.
- .DA1: These files contain the final results.
- .DA2: The PRMODRES program uses these files to produce summary and detailed output tables which can be sent to a printer.
- TMP.DEF: This file contains input information provided by the user when selecting input option 3. The information is later used by the MODBAC, BISAR, and SERMOD programs.
- BIS.RES: This file stores the normalized deflection bowls that are calculated when the user supplies all input information using input option 3. The file is used by the same programs as TMP.DEF.
- TMP1.DEF: This files contain default information for 24 to to fixed pavement designs. If any of the fixed TMP24.DEF TMP24.DEF designs is selected, the corresponding file is renamed to TMP.DEF and used as the original file.

- BIS1.RES to: Similar to the above. These files are renamed BIS.RES  
BIS24.RES and then used as the original.
- .DAT: Files with this extension store deflection readings  
and corresponding backcalculated moduli for each  
available road section. This data is used by the  
DELINIAT program.
- .EXE: Identifies executable files.
- .FWD: The master data file as obtained from the Falling  
Weight Deflectometer.
- .OUT: These files are produced by the FWDREAD program. They  
contain deflection information extracted from the FWD  
files (.FWD).
- .VAL: A special file containing Poisson Ratio values for  
each pavement layer. This particular file is only  
used for output purposes by the PRMODRES program.
- .BAT: Batch files used for installation of the system in a  
hard disk and for setting up and starting the program.

#### D. Installing the TTI Deflection Analysis System Software

To install the TTI Deflection Analysis System programs in the hard disk, insert the distribution diskette in one of the computer's 1.2 Mb floppy disk drives and then transfer to that drive. For instance, if the 1.2 Mb drive is A:, insert the diskette in the drive, and type:

A: <ENTER>

The distribution disk contains an installation program called INSTALL.BAT. When executed, this batch file creates a special directory in the computer's hard disk and it then copies all the necessary files to that directory. Before running INSTALL.BAT, you must decide what name you want for the directory. Suppose you want to install the program on partition D: of the hard disk and that you want the directory where the program files will reside to be called DEFLECT. To run install with these parameters type:

INSTALL D:\DEFLECT <ENTER>

INSTALL will create a directory called DEFLECT in drive D: and then transfer all the files from the floppy disk to the new directory.

## 2. Running the Program

### Starting the Program

To run the TTI Deflection Analysis System programs, make the DEFLECT subdirectory active by typing CD\DEFLECT after the DOS prompt. If another drive is active, type the letter of the drive where the system has been installed and press <RETURN>; then type CD\DEFLECT.

Once in the DEFLECT directory type DEFLECT followed by <RETURN> to start the program. After a few seconds the Main Program Menu should appear on the screen (Figure A1).

### Main Program Menu Options

The Main Program Menu screen allows the selection of any of the four available programs. To execute any of the programs, use the up/down arrow keys to highlight the selection and press <RETURN>. All menus in this package work in the same way.

The following programs are available:

- Convert FWD data to INPUT data: This program reads in files that have been produced in the field (FWD files) while recording deflection information and converts them to a format that is compatible with the Modulus Backcalculation program. This is a custom-built program handling the FWD data files available with the Texas Dynatest FWD.
- Run Modulus Backcalculation Program: This option allows the user to execute the Modulus Back Calculation (MODULUS) program. This program uses INPUT files (files with the .OUT extension) that have been converted from FWD files using option one above, or it can also process files that have been custom-made using a text editor or similar program.
- Plot Deflection and/or Moduli values: Select this option to produce plots of deflection data or backcalculated moduli values, as a function of project length. The program uses a cumulative difference algorithm to achieve unit delineation for either deflection and moduli data. The delineation approach is useful for identifying

TTI DEFLECTION ANALYSIS SYSTEM

Main Program Menu

- \* 1. Convert FWD data to INPUT data (.FWD to .OUT) \*
- \* 2. Run Modulus Back Calculation program \*
- \* 3. Plot Deflection and/or Moduli values \*
- \* 4. Print results of latest analysis \*
- \* 5. Exit to DOS \*

Use the ^ or v keys or enter the option number and press RETURN

Figure A1. Main Program Menu

TTI DEFLECTION ANALYSIS SYSTEM

FALLING WEIGHT DEFLECTOMETER DATA CONVERSION  
PROGRAM INPUT SCREEN

- DRIVE WHERE FWD FILE RESIDES: X
- FWD DATA FILENAME: XXXXXXXX.FWD
- OUTPUT FILE NAME: XXXXXXXX.OUT
- NUMBER OF DROPS RECORDED AT EACH POINT: X
- NUMBER OF FWD DROP TO USE AT EACH POINT: X
- PROCESS ANOTHER FILE? X

Figure A2. Data conversion screen

units of sections or stations that present similar structural behavior.

- Print results of latest analysis: This option permits the user to skip directly to the Print Menu in order to obtain summary and/or detailed printouts of the last analysis performed by the Modulus Back Calculation program.

To finish a session just select option five to exit to DOS.

### 3. Running the Application Programs

#### **The FWD Conversion Program**

Typically, when a section of road is evaluated using nondestructive testing, the section is divided into stations. The falling weight test, referred to hereafter as a drop, is then performed at each of these stations, as many times as it is required, and the resulting deflection and load information is stored on a computer disk file. The software to perform this is supplied by the FWD supplier. In Texas a .FWD extension is used to denote files containing raw deflection data for any highway.

The format used in the FWD files is highly elaborate and most of the information that they contain is not relevant to the programs contained in the TTI Deflection Analysis System. Consequently, a program that could be able to scan and extract the specific data needed by the system from FWD files to more compact files was developed.

The first option in the Main Program Menu accesses the FWD conversion program. This program extracts the following variables from a FWD file: district number, county number, highway prefix and number, milepoint position of the station, load, and deflection readings (up to seven) for a pre-specified drop along the length of a project. The program then stores this information in a new file and appends to its name the extension .OUT. These files form the actual input to the Modulus Backcalculation program and are hereon referred to as INPUT or OUT files. In general, in Texas FWD data is collected using one of two procedures. One involves two replicate drops. The other uses four drops at different load levels. This program can handle either testing procedure.

To start the FWD conversion program, select option one from the menu and press <RETURN>. A window will appear in the lower part of the screen asking you to verify your choice. Enter <Y> if the choice is correct.

After a few moments, the program input screen (Figure A2) is displayed. There are five fields of required information that the user needs to input before the program can run. These are:

- DRIVE WHERE THE FWD FILE RESIDES: Enter the letter identifier of the drive where the FWD file to be converted is stored. If the FWD file is in the hard disk, enter the letter of the drive from which the program is running. If the file resides in a floppy disk, enter the letter of that drive. Finish this input by pressing <RETURN>.

- FWD DATA FILENAME: In this field enter the name of the FWD file to be converted. Enter the name of the file, up to eight alphanumeric characters, without entering the extension name (it will be automatically appended to the name you entered) and press <RETURN>. In Texas this filename is a combination of county number and highway name.

- OUTPUT FILE NAME: Supply the name of the output file. It can also be up to eight characters long and the .OUT extension will be automatically appended. Again press <RETURN> to finish this input.

- NUMBER OF DROPS RECORDED AT EACH POINT: In this field enter the number of drops (up to eight) performed at each point or station during the test and then press <RETURN>.

- NUMBER OF FWD DROP TO USE AT EACH POINT: At this point, enter the number of the drop to be analyzed. Frequently four drops are recorded at different load levels, e.g., 5,000, 8,000, 12,000, and 15,000 lbs. This option permits the user to select the load level of interest.

Check the input carefully. If a mistake has been made, press the <ESC> key and the cursor will be set back to the beginning of the input process, at the position of the drive letter designator. Press <RETURN> to validate the entries until the incorrect one is reached. To change it just enter the new value or name and press <RETURN> to validate it. Keep on pressing <RETURN> until the last field is reached. If it is also correct, press <RETURN> once again to validate that entry.

Entering this last <RETURN> will start the conversion process, which



should take about 20 to 30 seconds depending on the disk access speed and the length of the file being converted.

When the program has successfully executed, a window with the following message will be displayed:

FILE XXXXXXXX.OUT CONTAINS ### POINTS.

where XXXXXXXX corresponds to the .OUT file name and ### to the number of points or stations stored in the file.

As a last option, the program will prompt to determine if another file is to be processed. Enter <Y> to extract another FWD file. To quit, enter <N> and press <RETURN> in order to go back to the Main Program Menu.

To abort this program, press the <ESC> key if the cursor is positioned in the first input field; otherwise press it twice. These <ESC> key sequences will quit the program and return to the Main Program Menu.

#### **Modulus Backcalculation Program**

Option 2 of the Main Program Menu allows the user to run the Modulus Backcalculation program. Inputs to the program consist of a series of default and temporary files, which are transparent to the user. They are created and read automatically. The only file that is user-supplied is the .OUT file, which was created using option one of the Main Program Menu as explained above.

After selecting and validating option two from the menu, the Input/Output information screen (Figure A3) is displayed. In this screen the user is requested to enter the name of the .OUT file (the file created by option one), and the name of the file that will store the deflection information and the corresponding backcalculated moduli values for each pavement layer. This file is referred hereon as the OUTPUT file and is given the extension .DAT.

Enter first the name of the INPUT (.OUT) file, up to eight characters long, and press <RETURN>. When the cursor moves to the next field, enter the name of the OUTPUT (.DAT) file, also up to eight characters long. If any changes are required, press the <ESC> key to return to the first position of the first field.

If the INPUT file name is incorrect, enter the correct name and press

```
TTI DEFLECTION ANALYSIS SYSTEM

INPUT/OUTPUT FILE INFORMATION

- NAME OF THE INPUT FILE:  XXXXXXXX.OUT

- NAME OF THE OUTPUT FILE: XXXXXXXX.DAT
```

Figure A3. Input/output file information

```
TTI DEFLECTION ANALYSIS SYSTEM

MODULUS BACK CALCULATION MENU

*1. Use an existing fixed design *
*2. Input material types         *
*3. Run a full analysis          *
*4. Return to Main Menu         *

Use the ^ and v keys or enter the option number and press RETURN
```

Figure A4. Modulus backcalculation menu

<RETURN>, otherwise press <RETURN> alone. Repeat this procedure for the OUTPUT filename.

After validation of the OUTPUT file name, the program displays the Modulus Backcalculation Menu screen (Figure A4) which allows the user to select any of three alternative ways of running the program or to return to the Main Program Menu.

The three options have been custom-built to meet the FWD processing needs of the Texas SDHPT. They are:

- USE AN EXISTING FIXED DESIGN: This option lets the user select between 24 designs (12 for infinite subgrade and 12 for finite [rigid layer at 20 ft.] subgrade) for which all input parameters, except for the deflection and load values, have been already calculated and stored in disk files. This option provides the fastest analysis since it only has to perform the Search algorithm in the program.

- INPUT MATERIAL TYPES: For this option the user selects the material types, thicknesses for the pavement layers, and test temperature, and the program assigns the range of acceptable moduli and poisson values to be used in the analysis.

- RUN A FULL ANALYSIS: In this option the user supplies all of the input parameters needed to perform the analysis.

To quit the program while in the menu screen, select option 4 to return to the Main Program Menu.

#### Using the Modulus Backcalculation Menu Options:

The principal difference in the three options of the Modulus Backcalculation menu is that in Option 1, default data bases are used and no runs of the BISAR program are required.

Option 1 - Fixed Designs: Select this option and the program will display the Existing Fixed Designs screen (Figure A5). These layer thicknesses are common in Texas. The moduli values used to build these default databases are shown in Table A1. The screen presents the user with two prompts: First, select the type of subgrade, infinite or finite (rigid layer at 20 ft.), for the analysis. Enter <F> to use a finite subgrade, or <I> for an infinite subgrade. Pressing <RETURN> after the selection validates the choice and moves to the next prompt. Select one of the 12

TTI DEFLECTION ANALYSIS SYSTEM

(1) EXISTING FIXED DESIGNS

TYPE OF SUBGRADE, (I)NFINITE OR (F)INITE: X

- 1) 1" SURFACE TREATMENT, 6" FLEXIBLE BASE
- 2) 1" SURFACE TREATMENT, 8" FLEXIBLE BASE
- 3) 1" SURFACE TREATMENT, 10" FLEXIBLE BASE
- 4) 2" HMAC , 8" FLEXIBLE BASE
- 5) 2" HMAC , 10" FLEXIBLE BASE
- 6) 2" HMAC , 12" FLEXIBLE BASE
- 7) 4" HMAC , 8" FLEXIBLE BASE
- 8) 4" HMAC , 10" FLEXIBLE BASE
- 9) 4" HMAC , 12" FLEXIBLE BASE
- 10) 6" HMAC , 12" FLEXIBLE BASE
- 11) 2" HMAC , 6" BLACK BASE , 8" SUBBASE
- 12) 2" HMAC , 10" BLACK BASE , 8" SUBBASE
- 13) RETURN TO PREVIOUS MENU DESIGN: XX

Figure A5. Existing fixed designs

Design Number (Figure A5)	Asphalt		Base		Subbase		Subgrade
	Min.	Max.	Min.	Max.	Min.	Max.	
1	500	500	5	100	-	-	15
2	500	500	5	100	-	-	15
3	500	500	5	100	-	-	15
4	500	500	5	100	-	-	15
5	500	500	5	100	-	-	15
6	500	500	5	100	-	-	15
7	200	1200	5	100	-	-	15
8	200	1200	5	100	-	-	15
9	200	1200	5	100	-	-	15
10	200	1200	5	100	-	-	15
11	500	500	200	1200	5	100	15
12	500	500	200	1200	5	100	15

Table A1. Modulus defaults for the twelve fixed designs (ksi).

available designs by entering the appropriate number and pressing <RETURN>. If no suitable designs are available for the pavement under analysis, enter option <13> and press <RETURN> to return to the previous menu which will permit selection of an alternate backcalculation option.

Pressing <RETURN> after selecting the desired fixed design choice verifies the selection and starts execution of the program. The screen will clear and the message "The Search Program is Running..." will be displayed. The path and search algorithm in this program takes, in the worst of cases, under two minutes per deflection bowl to reach an optimal solution to the problem. When done, the messages "Program terminated normally", and "Press any key to continue..." are displayed. Press any key to display the Print Results Menu screen. Refer to the section "Print Results Program" later in this manual for instructions on how to obtain printed output of the analysis. When the program has completed printing the analysis results, it automatically returns to the Main Program Menu.

Option 2 - Input Material Types: When this option is selected, the program prompts for the required information using two separate input screens. The first Input Material Types screen (Figure A6), consists of four input fields. In the first field enter the surface layer thickness in inches. Enter the thickness and press <RETURN>. The cursor moves to the second field where the program requests the surface layer material. Enter <1> for crushed limestone aggregate or <2> for crushed river gravel aggregate, and press <RETURN> to continue to the next input field. In this field select whether you want the program to backcalculate an asphalt moduli value or use a fixed value. Enter <1> to use a fixed value, or <2> to perform the calculation, and then press <RETURN>. The last field in this screen prompts for the pavement temperature in degrees Fahrenheit. Enter the temperature value and press <RETURN>. Use the <ESC> key to make changes, as explained previously.

The program has built into it equations for stiffness versus temperature for typical mixes found in Texas (crushed limestone or river gravel mixes). Also equations which represent the reasonable range of stiffnesses are also available. These were generated by analyzing stiffness results and obtained on rutted mixes (low stiffnesses) and badly cracked mixes (high stiffness). In the backcalculation procedure, if the user

# TTI DEFLECTION ANALYSIS SYSTEM

## (2) INPUT MATERIAL TYPES

- HMAC SURFACE LAYER THICKNESS: XXXXX
  - 1 = HMAC WITH CRUSHED LIMESTONE AGGREGATE
  - 2 = HMAC WITH CRUSHED RIVER GRAVEL AGGREGATE X
- DO YOU WANT TO USE THE DEFAULT VALUES  
FOR THE ASPHALT MODULUS?
  - 1 = YES X
  - 2 = NO
- INPUT THE ASPHALT TEMPERATURE (°F): XXXX

Figure A6. Input material types

# TTI DEFLECTION ANALYSIS SYSTEM

## (2) INPUT MATERIAL TYPES

BASE AND SUBBASE TYPES		PREDOMINANT SUBGRADE TYPE
1) CRUSHED LIMESTONE		1) GRAVELLY SOILS
2) ASPHALT BASE		2) SANDY SOILS
3) CEMENT TREATED BASE		3) SILTS
4) LIME TREATED BASE		4) CLAYS, LL < 50
5) IRON ORE GRAVEL		5) CLAYS, LL > 50
6) IRON ORE TOPSOIL		
7) RIVER GRAVEL		
8) CALICHE GRAVEL		
9) CALICHE		

		THICKNESS	
BASE TYPE:	X >	XXXX	SUBGRADE TYPE: X
SUBBASE TYPE:	X >	XXXX	

Figure A7. Input base and subgrade types

wishes to use a fixed default asphalt modulus, which is often the case on these pavements, then a single value is calculated based on the coarse aggregate type and FWD test temperature. However, if an asphalt modulus is to be backcalculated, then an acceptable range of moduli values is generated using the equation for rutted and cracked mixes, and the FWD test temperature. This option was intended for field personnel who are familiar with materials information but who have limited experience with modulus backcalculation techniques.

After validating the pavement temperature with a <RETURN>, the program displays the second Input Material Types screen (Figure A7). In this screen the user selects the material to be used for the base, subbase if any, and subgrade of the pavement sections to be analyzed. The input sequence is organized in five fields. In the first field enter any of the 9 available base material options. The second field takes the base thickness in inches. If a subbase is present, input its type and thickness as for the base. Enter <RETURN> in the subbase type if there is no subbase. In field number five, enter the type of subgrade as per the option list. Changes to the screen can be made using the <ESC> key as described previously. Press <RETURN> to validate the input and to run the program. This time the message "The Bisar Program is running..." appears in the screen to indicate that the program is executing. When BISAR is complete, the data base is generated, and the Path Search algorithm program takes over; the respective message is displayed to indicate that it is executing. Completion of the search phase is confirmed by the "Search program terminated normally!" and "Press any key to continue" messages. Pressing any key leads you to the Print Results Menu.

Option 3 - Run a Full Analysis: This option of the Modulus Back Calculation Program lets the user to specify the thickness, modulus ranges, and Poisson Ratios for up to four layers within a pavement section. In the first four fields in the Full Analysis screen (Figure A8), labelled H1 to H4, enter the pavement thicknesses in inches. H1 represents the surface layer, H2 the base layer, H3 the subbase layer, and H4 the subgrade. Input is done in the same way as for the previous programs; that is, you enter the desired value and validate it by pressing <RETURN>.



# TTI DEFLECTION ANALYSIS SYSTEM

## (3) FULL ANALYSIS

H1	H2	H3	H4
XXXXX	XXXXX	XXXXX	XXXXX

SUBGRADE MODULUS (MOST PROBABLE VALUE IN KSI)  
XXXXXXXXXX

AND POISSON'S RATIO  
XXXXX

MODULUS OF SUBBASE LAYER (IN KSI)

MINIMUM	MAXIMUM
XXXXXXXXXX	XXXXXXXXXX

AND POISSON'S RATIO  
XXXXX

MODULUS OF BASE LAYER (IN KSI)

MINIMUM	MAXIMUM
XXXXXXXXXX	XXXXXXXXXX

AND POISSON'S RATIO  
XXXXX

MODULUS OF SURFACE LAYER (IN KSI)

MINIMUM	MAXIMUM
XXXXXXXXXX	XXXXXXXXXX

AND POISSON'S RATIO  
XXXXX

Figure A8. Full analysis

For a four layer pavement, enter their thicknesses in their respective fields. In the subgrade field, however, indicate whether the layer is infinite or finite. Enter <0> for an infinite subgrade or the thickness of subgrade to the beginning of the rigid layer in the case of a finite subgrade. For a three layer system with no subbase, enter the surface thickness, the base thickness, then zero <0> to indicate the absence of subbase, and the subgrade information. For a two layer pavement, the procedure is the same except that a thickness of <0> is entered for the base layer.

Next, enter the most probable modulus value in ksi and the corresponding Poisson ratio value for the subgrade. Then, depending on the number of layers in the pavement, the cursor automatically moves to the location of either the subbase, base or surface fields. In these fields enter the lower modulus boundary value, the upper boundary value, and the poisson ration value for the layer in question. After entering the value for the surface layer poisson ratio, check all the input values and if necessary, change any values using the <ESC> key sequence as described for all other screens. If satisfied with the input, press <RETURN> to execute the program. The "Bisar Program is Running..." message should now appear on the screen.

When the program is complete, it displays the appropriate message and asks the user to press any key. The Print Results Menu is then displayed and the user can obtain a printout of the analysis results.

#### **Plot Deflection and/or Moduli Values Program**

This program allows the user to analyze pavement response variables, mainly deflection readings and calculated moduli values, from a graphical point of view, along the entire project length. It will also perform a unit delineation analysis using the cumulative difference approach in order to identify units of sections having similar characteristics.

To run this program select option 3 from the Main Program Menu and press <RETURN>. After validating the choice, the Pavement Response Variable Graphic Representation and Delineation Analysis screen is displayed (Figure A9). Here enter the name of the data file containing both the deflection readings and the calculated moduli values for each of

TTI DEFLECTION ANALYSIS SYSTEM

PAVEMENT RESPONSE VARIABLE  
GRAPHIC REPRESENTATION AND DELINEATION ANALYSIS

THE FOLLOWING INFORMATION IS REQUIRED:

- NAME OF THE DATAFILE: XXXXXXXX.DAT
- RESPONSE VARIABLE: XX  
(W = deflection data  
E = moduli values)
- MINIMUM SECTION LENGTH: XXX  
(In miles or fraction  
of a mile, e.g. .5 mi)

Figure A9. Setup for graphics

the pavement layers. These files are characterized by the extension .DAT in their file names; it is automatically appended to the name of the file that was specified in the backcalculation phase. Enter the file name, up to eight characters long and press <RETURN>.

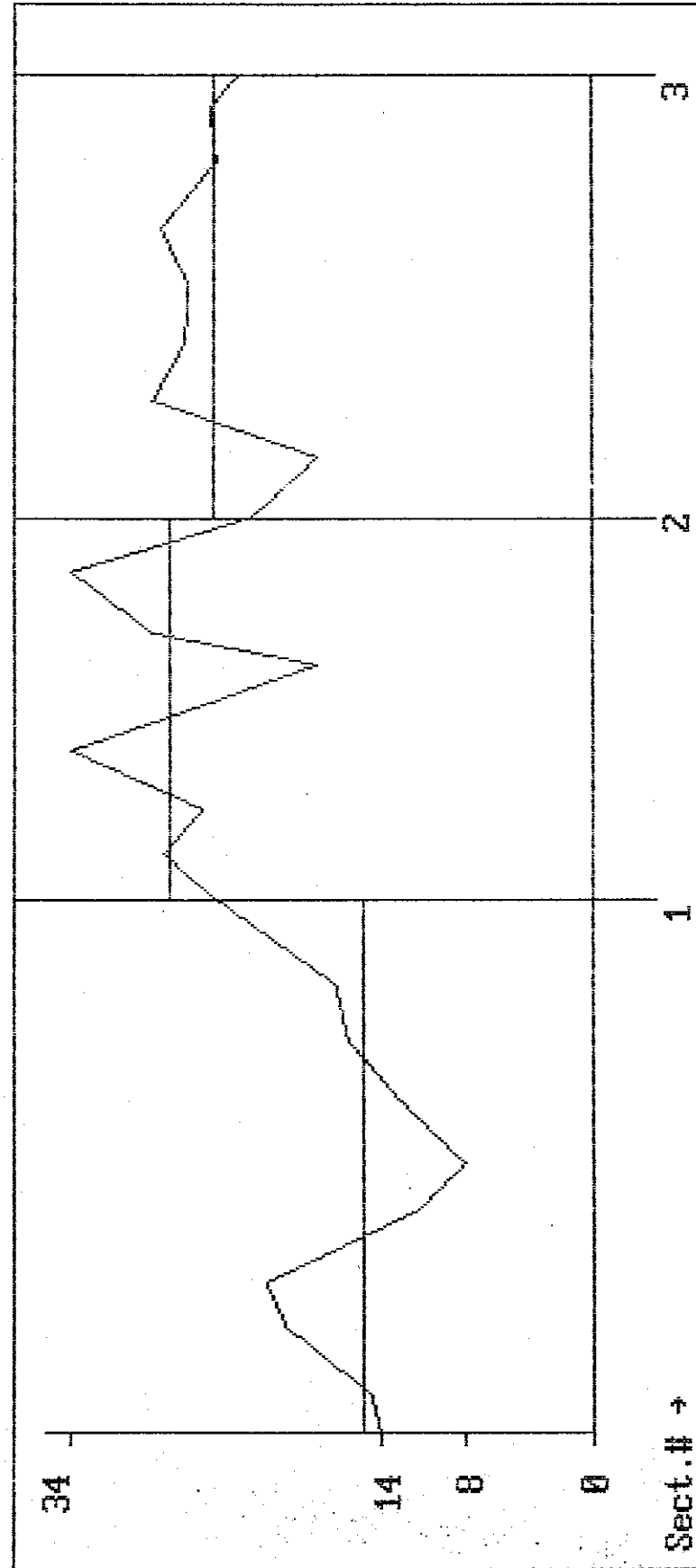
Next, select the response variables to be plotted. There are a maximum of seven deflection readings, and four moduli values for each station. Deflections are identified by a number from 1 to 7, 1 corresponding to the sensor closest to the loading plate, 2 to the second closest, and so on. Moduli values have labels from 8 to 11 where 8 identifies the modulus of the surface layer, 9 the base, 10 the subbase, and 11 the subgrade. Enter the number corresponding to the response variable required, 1 through 7 for deflections or 8 through 11 for moduli values, and press <RETURN>.

The last item of information requested is the minimum section length that will be used by the delineation subroutine to perform the unit delineation of the chosen response variable. If consecutive inflection points in the cumulative difference curve for the response variable being analyzed occur at intervals that are less than the minimum section length entered, the program will ignore them. This feature is provided to avoid the clutter of unit delineations that might occur in projects with unusually high response variable variability.

Enter this value in miles including fractions of a mile, that is, as a decimal value, and press <RETURN>. To make any changes, use the <ESC> sequence as in the other programs.

As soon as the <RETURN> key is pressed, the program starts executing and in a few seconds the screen is cleared and a plot of the selected response variable as a function of distance along the project is produced (Figure A10). At the bottom of the screen a table of statistics for each of the unit delineations is displayed. If there are more than three delineated sections in the plot, press any key to see the statistics for the remaining sections. Press any key until the message "Would you like to combine sections manually or Quit? (C/Q):" appears. To quit the program at this point enter <Q>, otherwise enter <C>. The manual combination routine then prompts for the number of sections the user would like the combination to have. Enter the number and press <RETURN>. To

Road: FM2818 Pavement Response Variable: E4 (Moduli values in KSI)



Press any key to continue

Figure A10. Plot for subgrade moduli values for a section of FM 2818

combine all sections, enter the total number of sections that were delineated in the plot. If the user did not elect to combine all sections, a prompt is displayed asking for the number of the last section to be included as the new section one. The subroutine repeats the last prompt until all of the sections have been accounted for. Then it recalculates and replots the curve showing the new delineations and their respective statistics. Repeat the above sequence for manual combination if there are sections left to combine or quit the program. When the user answers <Q> to the prompt, the user is given the choice of printing the statistics for the latest delineation. Then, the following prompt is displayed: "Enter <R> to analyze other Responses or <Q> to quit to the Main Program Menu:". Selecting <Q> returns to the Main Program Menu while entering <R> redisplay the Pavement Response Variable Graphic Representation and Delineation Analysis screen, allowing the user to select another response variable for graphical analysis.

#### **Print Results Program**

The Print Results of Latest Analysis option in the Main Program Menu gives the user direct access to the same Print Results Menu (Figure A11) that is displayed after any of the three options in the Modulus Back Calculation Program terminate execution, and allows the user to print a results summary table or a detailed estimated deflection report, or both for the analysis that was performed the last time the Back Calculation program was used.

The options in this menu are:

- PRINT DEFLECTION & MODULI SUMMARY TABLE: This option lets the user print a table listing the deflection readings, the calculated moduli values, and the estimated absolute percent error per sensor for each station in the project, with the exception of the ones that do not have a feasible solution to the optimization procedure used in the Modulus Backcalculation program. Also, at the end of the list, statistics are printed for all of the above variables (Figure A12).
- PRINT ESTIMATED DEFLECTION TABLE: Option <2> of the Print Results Menu produces a detailed station by station result report which includes the back calculated deflection values, absolute error and squared error values, force and pressure at the loading plate, and a list of checks

TTI DEFLECTION ANALYSIS SYSTEM

PRINT RESULTS MENU

- \*1. Print Deflection & Moduli summary table \*
- \*2. Print Estimated Deflection table \*
- \*3. Print both of the above tables \*
- \*4. Return to Main Menu \*

Use the ^ and v keys or enter the option number and press RETURN

Figure A11. Print results menu

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District: 17									MODULI RANGE(psi)				
County: 21									Thickness(in)		Minimum	Maximum	
Highway/Road: FM2818									Pavement:	4.00	200,000	1,200,000	
									Base:	10.00	5,000	100,000	
									Subbase:	0.00	0	0	
									Subgrade:	INFINITY		15,000	
Station	Load (lbs)	Measured Deflection (mils):							Calculated Moduli values (psi):				Absolute % ERROR/Sensor
		R1	R2	R3	R4	R5	R6	R7	SURFACE(E1)	BASE(E2)	SUBBASE(E3)	SUBGRADE(E4)	
0.041	11,471	30.60	21.19	12.25	7.48	5.06	3.61	2.89	1,199,997	6,329	0	13,865	2.30
0.104	11,903	42.29	17.34	10.28	6.75	4.86	3.65	2.97	200,000	18,987	0	14,304	6.33
0.214	11,367	38.07	19.93	9.45	4.97	3.16	2.28	1.81	570,002	5,976	0	19,921	7.81
0.295	12,479	39.96	20.70	8.59	4.61	3.24	2.40	2.01	426,476	7,300	0	21,222	4.53
0.418	11,495	44.33	28.32	15.50	8.81	5.77	4.19	3.45	635,776	5,000	0	11,514	3.44
0.501	11,047	61.20	38.45	19.73	11.69	7.43	5.39	4.54	309,656	5,000	0	8,262	6.01
0.604	11,071	34.21	21.19	11.63	7.80	5.34	3.77	3.17	730,667	9,022	0	12,452	4.53
0.708	12,111	29.76	19.45	11.10	6.83	4.66	3.28	2.65	1,199,997	7,551	0	15,919	3.49
0.803	11,271	12.77	11.14	8.51	6.15	4.35	3.03	2.33	1,199,997	95,011	0	16,646	10.39
0.948	11,159	34.13	16.49	6.66	3.40	2.37	1.87	1.65	383,790	8,078	0	24,446	3.17
1.027	11,871	25.74	11.79	4.97	2.91	2.25	1.87	1.65	279,191	27,919	0	27,919	6.33
1.103	11,991	64.01	25.97	6.78	3.48	2.41	1.78	1.41	254,203	7,626	0	25,420	17.43
1.201	11,463	17.95	11.34	5.55	2.91	1.90	1.45	1.20	1,199,997	10,252	0	33,790	3.14
1.348	11,103	35.26	22.89	11.18	5.62	3.40	2.36	1.97	661,153	5,418	0	18,057	8.53
1.402	11,199	18.43	11.51	5.71	3.23	2.21	1.66	1.41	1,199,997	12,960	0	28,624	1.53
1.508	13,343	14.10	9.16	5.06	3.11	2.25	1.78	1.49	1,199,997	34,335	0	33,752	2.69
1.600	11,375	27.39	16.41	8.43	4.57	2.93	2.11	1.73	1,016,626	6,700	0	22,329	4.16
1.706	11,855	56.50	28.03	10.89	5.42	3.48	2.40	2.09	272,247	5,414	0	18,042	11.97
1.801	11,015	19.80	12.40	6.17	3.28	2.17	1.62	1.41	1,199,997	9,126	0	28,522	1.56
1.902	11,111	18.95	12.52	6.58	3.68	2.41	1.74	1.41	1,199,997	11,075	0	26,598	4.33
2.006	11,143	17.71	11.42	5.84	3.48	2.45	1.82	1.53	1,199,997	16,043	0	26,240	1.50
2.100	11,095	26.46	14.34	6.58	3.32	2.09	1.58	1.29	728,880	8,402	0	28,006	6.03
2.213	11,639	48.59	23.09	8.80	3.76	2.33	1.74	1.49	314,318	7,330	0	24,428	16.71
2.303	11,375	25.66	14.99	6.74	3.60	2.45	1.91	1.73	697,100	9,804	0	24,720	1.39
2.359	11,047	22.97	13.85	7.03	4.08	2.81	2.03	1.65	1,071,040	9,657	0	23,175	3.73
Mean:		32.27	18.16	8.80	5.00	3.35	2.45	2.04	774,044	14,013	0	21,927	5.72
Std. Dev:		14.35	6.99	3.49	2.20	1.43	1.00	0.82	390,505	18,294	0	6,841	4.37
Var Coeff(%):		44.47	38.48	39.69	44.06	42.68	40.68	40.07	50.45	130.55	0.00	31.20	76.43

Figure A12. Summary listing



indicating if the moduli values are close to the given limits, if the convexity test fails, or if the solution to the particular station was infeasible (Figure A13).

- PRINT BOTH OF THE ABOVE TABLES: This option prints the summary table first, advances the paper to the beginning of a new page, and then prints the detailed section by section report.

- RETURN TO MAIN MENU: It does just that.

## TTI DEFLECTION ANALYSIS SYSTEM

District: 17 County: 21	Distance (in) from center of loading plate to sensor:							R1 = 0.000	Weight Factor	1.0
Highway/Road: FM2818								R2 = 12.000	Weight Factor	1.0
Radius of loading plate(in): 5.910	POISSON RATIO VALUES							R3 = 24.000	Weight Factor	1.0
Surface thickness(in): 4.000	H1: $\mu = 0.40$							R4 = 36.000	Weight Factor	1.0
Base thickness(in): 10.000	H2: $\mu = 0.35$							R5 = 48.000	Weight Factor	1.0
Subbase thickness(in): 0.000	H3: $\mu = 0.00$							R6 = 60.000	Weight Factor	1.0
Subgrade thickness(in): INFINITY	H4: $\mu = 0.38$							R7 = 72.000	Weight Factor	1.0
Station: 0.041	R1	R2	R3	R4	R5	R6	R7	Plate Load = 11,472 lbs		
Measured Deflection:	30.60	21.19	12.25	7.48	5.06	3.61	2.89	Plate Pressure = 104.550 psi		
Calculated Deflection:	30.04	21.61	12.45	7.33	4.85	3.64	2.99	Absolute Sum of Z ERROR = 16.100		
Z ERROR	1.83	-1.97	-1.60	2.03	4.24	-0.91	-3.55			
Layer:	SURFACE(E1)	BASE(E2)	SUBBASE(E3)	SUBGRADE(E4)	Square Error = 0.005					
Moduli Values (ksi):	1,200.0	6.3	0.0	13.9						
Close to limits?	YES	N/A	N/A	N/A	Failed Convexity Test? NO					
Station: 0.104	R1	R2	R3	R4	R5	R6	R7	Plate Load = 11,903 lbs		
Measured Deflection:	42.29	17.34	10.28	6.75	4.86	3.65	2.97	Plate Pressure = 108.480 psi		
Calculated Deflection:	37.26	19.38	9.86	6.36	4.70	3.75	3.12	Absolute Sum of Z ERROR = 44.300		
Z ERROR	11.90	-11.74	4.07	5.80	3.21	-2.62	-4.94			
Layer:	SURFACE(E1)	BASE(E2)	SUBBASE(E3)	SUBGRADE(E4)	Square Error = 0.037					
Moduli Values (ksi):	200.0	19.0	0.0	14.3						
Close to limits?	YES	N/A	N/A	N/A	Failed Convexity Test? NO					
Station: 0.214	R1	R2	R3	R4	R5	R6	R7	Plate Load = 11,368 lbs		
Measured Deflection:	38.07	19.93	9.45	4.97	3.16	2.28	1.81	Plate Pressure = 103.600 psi		
Calculated Deflection:	34.21	20.65	9.06	4.47	2.99	2.43	2.08	Absolute Sum of Z ERROR = 54.700		
Z ERROR	10.15	-3.60	4.16	9.97	5.39	-6.43	-15.00			
Layer:	SURFACE(E1)	BASE(E2)	SUBBASE(E3)	SUBGRADE(E4)	Square Error = 0.053					
Moduli Values (ksi):	570.0	6.0	0.0	19.9						
Close to limits?	NO	N/A	N/A	N/A	Failed Convexity Test? NO					
Station: 0.295	R1	R2	R3	R4	R5	R6	R7	Plate Load = 12,480 lbs		
Measured Deflection:	39.96	20.70	8.59	4.61	3.24	2.40	2.01	Plate Pressure = 113.730 psi		
Calculated Deflection:	38.23	21.23	8.63	4.33	3.04	2.51	2.16	Absolute Sum of Z ERROR = 31.700		
Z ERROR	4.33	-2.57	-0.46	6.13	6.27	-4.66	-7.27			
Layer:	SURFACE(E1)	BASE(E2)	SUBBASE(E3)	SUBGRADE(E4)	Square Error = 0.018					
Moduli Values (ksi):	426.5	7.3	0.0	21.2						
Close to limits?	NO	N/A	N/A	N/A	Failed Convexity Test? NO					
Station: 0.418	R1	R2	R3	R4	R5	R6	R7	Plate Load = 11,496 lbs		
Measured Deflection:	44.33	28.32	15.50	8.81	5.77	4.19	3.45	Plate Pressure = 104.770 psi		
Calculated Deflection:	42.81	28.70	14.99	8.42	5.63	4.36	3.63	Absolute Sum of Z ERROR = 24.100		
Z ERROR	3.42	-1.34	3.27	4.43	2.35	-3.97	-5.31			
Layer:	SURFACE(E1)	BASE(E2)	SUBBASE(E3)	SUBGRADE(E4)	Square Error = 0.009					
Moduli Values (ksi):	635.8	5.0	0.0	11.5						
Close to limits?	NO	N/A	N/A	N/A	Failed Convexity Test? NO					

Figure A13. Detailed bowl by bowl listing