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COOPERATIVE
RESEARCH

DETERMINING STIFFNESS COEFFICIENTS AND ELASTIC MODULI OF PAVEMENT MATERIALS FROM DYNAMIC DEFLECTIONS

in cooperation with the
Department of Transportation
Federal Highway Administration

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16. Abstract

The several methods of computing stiffness coefficients or elastic moduli of materials to be used in computerized pavement design procedures and in other research activities requiring the knowledge of these values are presented in this report. The methods include computer codes for calculating stiffness coefficients and elastic moduli of simple two-layer pavement structures based on the observed surface pavement deflections, a graphical technique of obtaining elastic moduli of simple two-layer pavement structures and two recently developed computer codes for calculating stiffness coefficients of multilayer pavement structures.

The method of solution and the basic equations of each method are presented to assist the prospective user in determining which method best meets his needs.

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DETERMINING STIFFNESS COEFFICIENTS AND ELASTIC MODULI OF PAVEMENT MATERIALS FROM DYNAMIC DEFLECTIONS

by

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G.W. Turman

Research Report Number 207-1

Flexible Pavement Evaluation and Rehabilitation

Research Project 2-8-75-207

conducted for

The Texas State Department of Highways and
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in cooperation with the
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Federal Highway Administration

by the

Texas Transportation Institute
Texas A&M University

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PREFACE

This report is the first of a series issued under Research Study 2-8-75-207, "Flexible Pavement Evaluation and Rehabilitation". This study is being conducted by principal investigators and their staffs of the Texas Transportation Institute as part of the cooperative research program with the Texas State Department of Highways and Public Transportation and the Department of Transportation, Federal Highway Administration.

DISCLAIMER

ACKNOWLEDGMENT

The cooperation and assistance of many individuals in the Texas Transportation Institute given during the preparation of this report is appreciated. Dr. R.L. Lytton's assistance was especially helpful in the final preparation of the report.

LIST OF REPORTS

Report No. 207-1, "Determining Stiffness Coefficients and Elastic Moduli of Pavement Materials from Dynamic Deflections", by C.H. Michalak, D.Y. Lu, and G.W. Turman, is a summary in one document of the various methods of calculating in situ stiffness coefficients and elastic moduli in simple two-layer and multi-layer pavement structures using surface pavement deflections.

ABSTRACT

The several methods of computing stiffness coefficients or elastic moduli of materials to be used in computerized pavement design procedures and in other research activities requiring the knowledge of these values are presented in this report. The methods include computer codes for calculating stiffness coefficients and elastic moduli of simple two-layer pavement structures based on the observed surface pavement deflections, a graphical technique of obtaining elastic moduli of simple two-layer pavement structures and two recently developed computer codes for calculating stiffness coefficients of multi-layer pavement structures.

The method of solution and the basic equations of each method are presented to assist the prospective user in determining which method best meets his needs.

Key Words: Computer program, dynamic deflection, elastic modulus, pavement design, stiffness coefficients, surface deflections.

SUMMARY

Purpose

The principal purpose of this report is to present in one body the several methods of calculating in situ stiffness coefficients and elastic moduli of pavement materials in simple two-layer pavement structures from observed surface deflections. Also presented are two methods recently developed for calculating stiffness coefficients of multi-layer pavement structures from observed surface deflections.

All of the methods of calculating stiffness coefficients or elastic moduli are based on finding the stiffness coefficient or elastic moduli values which predict the observed surface pavement deflections within the established accuracy limits.

All of the methods but one, a graphical method, are available to researchers or other users as computer codes with full documentation of the theory and method of solution available in the references given.

Findings

There is a significant difference in calculated base course stiffness coefficients depending upon which method of calculation is used. The simple two-layer approach (which assumes that the pavement is a base course with a thin surface course or none at all) usually gives base course coefficients that are <u>lower</u> than those obtained by considering the pavement as a multi-layered structure. The values of the subgrade coefficient were not significantly different regardless of the method of calculation used.

The methods of calculating elastic moduli which use all five of the observed surface deflections in the solution process are considered to give more accurate estimates of elastic moduli than those methods which use

only two deflection observations in the solution process.

Conclusions

Two new methods of determining stiffness coefficients in multi-layer pavements using observed surface deflections are recommended to pavement designers and researchers who have need of these values.

IMPLEMENTATION STATEMENT

The methods of calculating stiffness coefficients or elastic moduli of pavement structures from observed surface pavement deflections are available for immediate use by researchers and other users.

Two recently developed methods for calculating stiffness coefficients of multi-layer pavement designs are available and are recommended for use by researchers and other users who need more reliable values of stiffness coefficients than were previously available.

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INTRODUCTION

The increasing use of computer codes such as FPS and RPS in pavement design by the State Department of Highways and Public Transportation in Texas and by pavement designers in other states has created the need for accurate measurements of the many variables that are inputs to these computer codes (1).

One of the variables for which an accurate measurement is needed is the stiffness of the materials that will be considered in selecting the optimal pavement design. This structural value of the pavement material can be either the FPS "stiffness coefficient" or the elastic modulus of the material.

There have been several methods formulated and converted to computer codes for computing the stiffness coefficient or the elastic modulus of a material to be used in the FPS or some other pavement design computer code (2, 3, 4, 5, 6, 7, 8). All of the methods are based on dynamic surface deflections of existing pavements as a predictor of the performance (i.e., life) of the pavement structure, which was shown to be feasible from the results of the WASHO and AASHTO Road Tests (9, 10).

Scrivner, et al., developed an equation for predicting the surface deflections of a pavement subjected to a known load (11). It is this deflection equation which is the basis for the several computer codes that compute stiffness coefficients of pavement materials. The development of this deflection equation is presented in the next section. The equations in the computer codes for computing elastic moduli of pavement materials are from Burmister's theory of elasticity in layered pavements (14).

This report presents summaries of the several methods of computing stiffness coefficients or elastic moduli of pavement materials, including the basic equations and a brief explanation of the method of solution. The user can select the method that best suits his needs and resources and can obtain detailed descriptions and instructions for using the method selected from the references.

DEVELOPMENT OF THE DYNAMIC DEFLECTION EQUATION

The sketch in Figure 1 represents a pavement composed of n layers, including the subgrade. The material in each of these layers is characterized by a stiffness coefficient, a_i, where the subscript, i, identifies the position of the layer in the structure. Layers are numbered consecutively from the top downward, thus, i = 1 for the surfacing layer, and i = n for the foundation layer, which is considered to be of infinite thickness. The thickness of any layer above the foundation is represented by the symbol, D_i.

An important feature of the flexible pavement design procedure in Texas is the use of the Dynaflect* for measuring deflections on existing highways. Descriptions of the instrument and examples of its use in pavement research have been published previously (see reference 1). Suffice it to say here that a dynamic load of 1000 lbs, oscillating sinusoidally at 8 cps, is applied through two steel load wheels to the pavement, as indicated in Figure 2. Five sensors, resting on the pavement at the numbered points shown in the figure, register the vertical amplitude of the motion at those points in thousandths of an inch (or mils).

A deflection basin of the type illustrated in Figure 3 results from the Dynaflect loading. The symbol W_1 represents the amplitude--or deflection--occurring at Point 1, W_2 is the deflection at Point 2, etc.

An empirical equation used in Texas for estimating the dynamic deflection, W_j, from the design variables a_i and D_i was developed from deflection data gathered on the A&M Pavement Test Facility located at Texas A&M University's Research Annex near Bryan. A description of the

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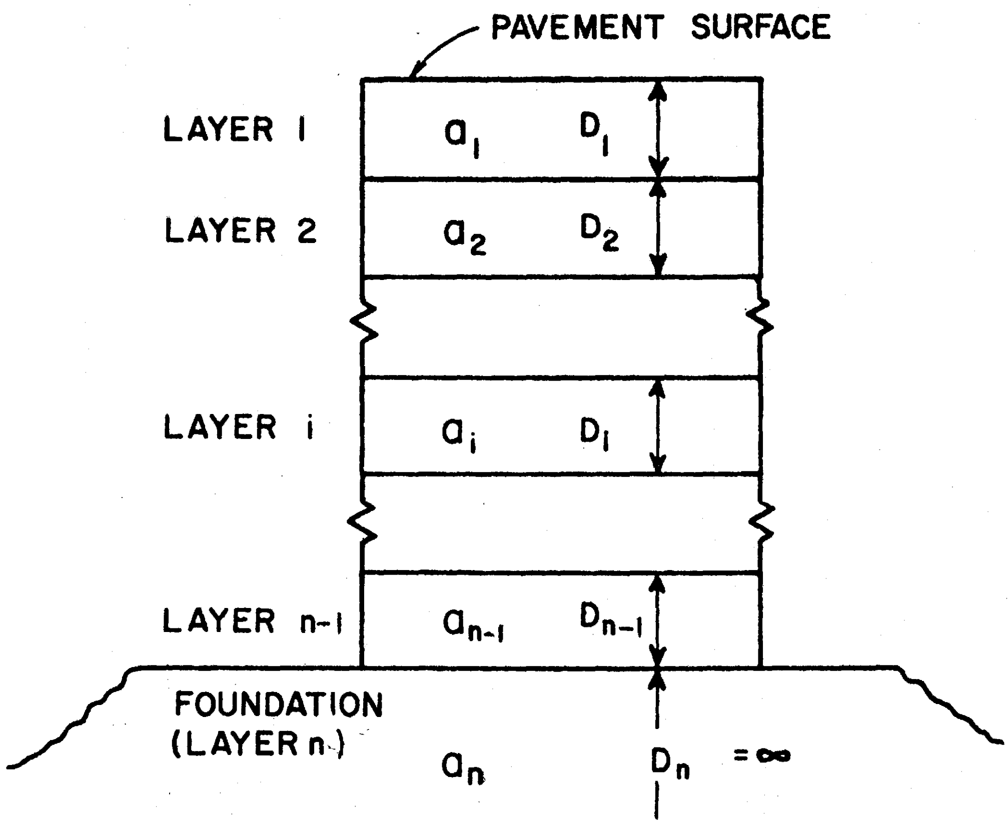

Figure 1: A pavement section of n layers.

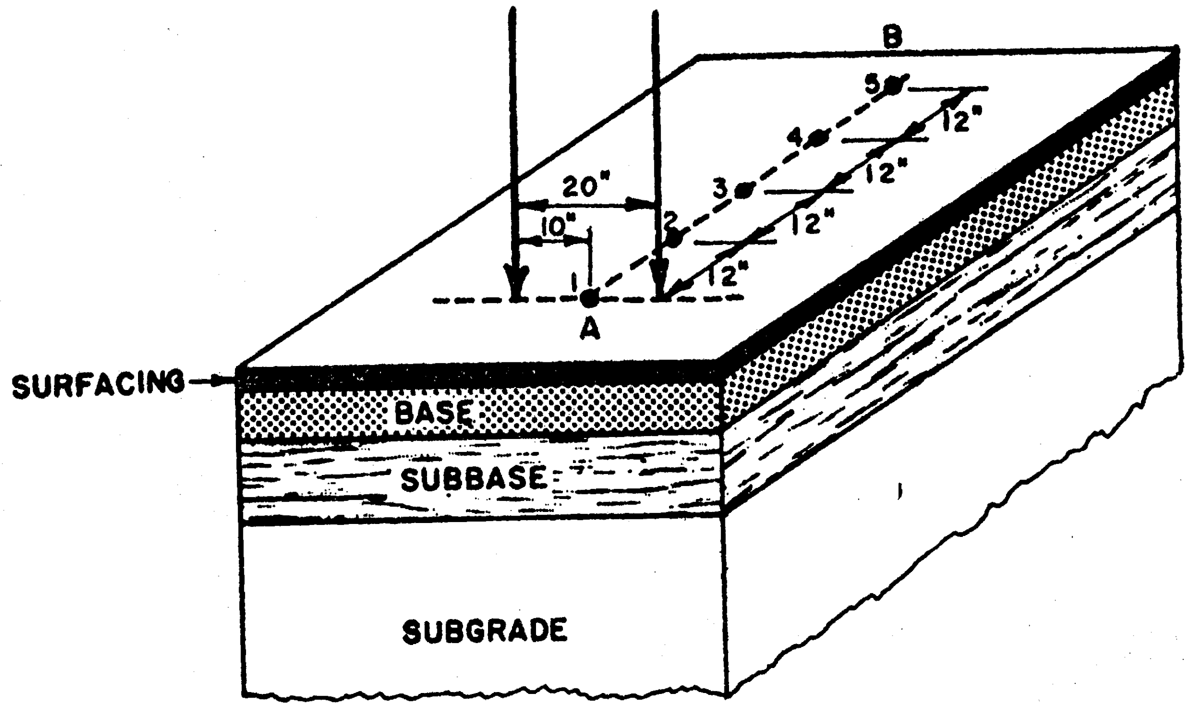

Figure 2: Position of Dynaflect sensors and load wheels during test. Vertical arrows represent load wheels. Points numbered 1 through 5 indicate location of sensors.

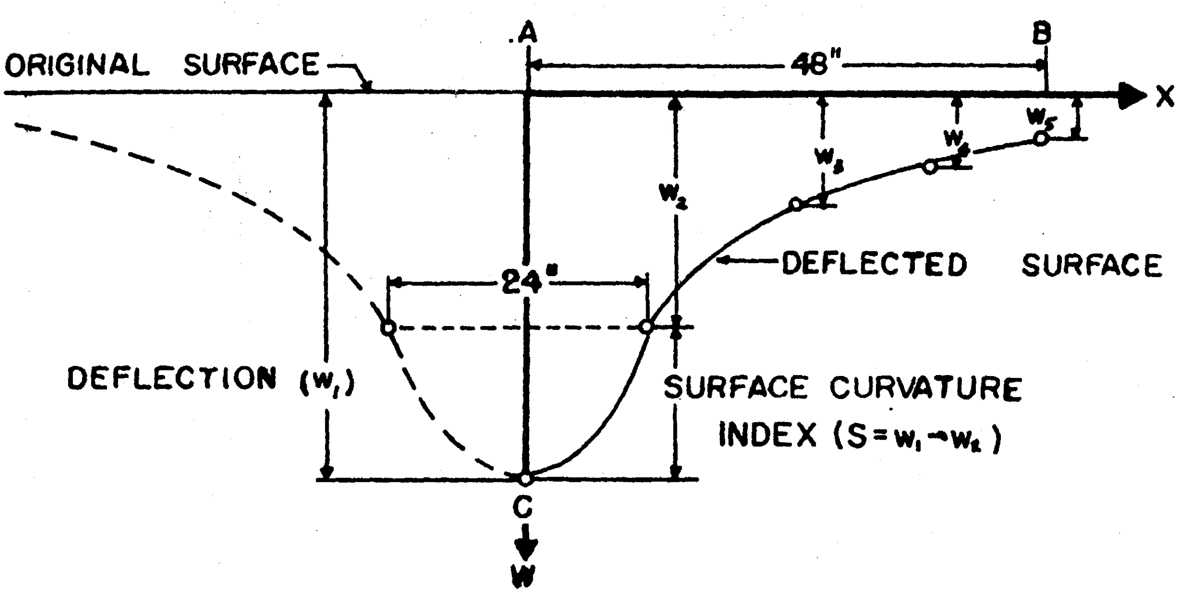

Figure 3: Typical deflection basin reconstructed from Dynaflect readings.

facility is contained in reference (12). The deflection equation, developed in reference (11) is given below:

$$W_j = \sum_{k=1}^{n} \Delta jk \qquad (1)$$

where

W_j = surface deflection in thousandths of an inch (or mils) at geophone j,

n = number of layers, including subgrade, and

$$\Delta jk = \frac{c_0}{a_k^{c_1}} \left[\frac{1}{r_j^2 + c_2\left(\sum_{i=0}^{k-1} a_i D_i\right)^2} - \frac{1}{r_j^2 + c_2\left(\sum_{i=0}^{k} a_i D_i\right)^2} \right]$$

and

c_0 = 0.891087,

c_1 = 4.50292,

c_2 = 6.25,

a_i = stiffness coefficient of layer i ($a_0 = 0$),

D_i = thickness in inches of layer i ($D_0 = 0$ and $D_n = \infty$),

r_j = distance in inches from point of application of either load to the j^{th} geophone.

Measured in situ values of the stiffness coefficient, a, range from about 0.17 for a wet clay to about 1.00 for a strongly stabilized base material. No way has been found for predicting these values with suitable accuracy from laboratory tests. For the present, the stiffness coefficient of a material proposed for use in a new pavement in a particular locality must be estimated from deflection measurements made on the same type of material in an existing pavement located in the same general area.

METHODS OF COMPUTING MATERIAL STIFFNESS COEFFICIENTS

Several computational procedures and computer codes (STIF2, STIF5, SCIMP, SCIMP-PS), which employ the deflection equation (Eq. 1) to calculate stiffness coefficients based on the surface dynamic deflections, have been developed, and are described briefly below.

STIF2

A computer program, STIF2, has been developed to calculate the stiffness coefficient of materials in a special case of a simple structure consisting of a relatively thin surfacing layer (say less than 2 inches) on a base with no subbase layers between base and subgrade (2). In this special case, the surfacing and base layers can be considered one material, with a thickness of D_1 and a stiffness of a_1, resting on an infinite foundation with a stiffness, a_2. Consider two deflections: W_1 and W_2. The equations for these deflections are, according to Eq. 1,

$$W_1 = \frac{c_0}{a_1^{\,c_1}}\left[\frac{1}{r_1^{\,2}} - \frac{1}{r_1^{\,2}+c_2(a_1D_1)^2}\right] + \frac{c_0}{a_2^{\,c_1}}\left[\frac{1}{r_1^{\,2}+c_2(a_1D_1)^2}\right] \quad (2)$$

$$W_2 = \frac{c_0}{a_1^{\,c_1}}\left[\frac{1}{r_2^{\,2}} - \frac{1}{r_2^{\,2}+c_2(a_1D_1)^2}\right] + \frac{c_0}{a_2^{\,c_1}}\left[\frac{1}{r_2^{\,2}+c_2(a_1D_1)^2}\right] \quad (3)$$

By eliminating a_2 between these two equations, the following equation in a_1 can be formed:

$$\frac{W_1 - \frac{c_0}{a_1^{\,c_1}}\left[\frac{1}{r_1^{\,2}} - \frac{1}{r_1^{\,2}+c_2(a_1D_1)^2}\right]}{W_2 - \frac{c_0}{a_1^{\,c_1}}\left[\frac{1}{r_2^{\,2}} - \frac{1}{r_2^{\,2}+c_2(a_1D_1)^2}\right]} - \frac{\left[r_2^{\,2}+c_2(a_1D_1)^2\right]}{\left[r_1^{\,2}+c_2(a_1D_1)^2\right]} = 0 \quad (4)$$

In Eq. 4 all quantities except a_1 are known. The value of a_1 can be found by iteration (trial and error). With a_1 known, a_2 can be found from either Eq. 2 or Eq. 3, as a_2 can be isolated in either of those equations.

In theory, any pair of the deflections W_j can be used to find a_1 and a_2, and the values found from any pair should equal those found from any other pair. In practice, it has been discovered that this rule does not generally hold--the values found by using W_1 and W_2, for example, are, in fact, not precisely the same as those found from W_1 and W_5. The difference is ascribed to experimental error, including the error in assuming that a simple two-layer structure of the type envisioned actually can exist in the case of a real pavement and its foundation. The difference can also be ascribed to imperfections in the mathematical model.

STIF5

Usually, the Dynaflect measures the surface deflection at five geophones. A least square fit of the five deflections would provide better estimates of a_1 and a_2 than those determined by STIF2 which uses two deflections (3). For a two-layer pavement structure, according to Eq. 1,

$$W_j = F_j + B_0 \cdot f_j \qquad (5)$$

where

$$F_j = \frac{c_0}{a_1^{c_1}} \left[\frac{1}{r_j^2} - \frac{1}{r_j^2 + c_2(a_1 D_1)^2} \right]$$

$$B_0 = \frac{c_0}{a_2^{c_1}}$$

$$f_j = \frac{1}{r_j^2 + c_2(a_1 D_1)^2}$$

The constants c_0, c_1, c_2 and the variables a_1, D_1, and r_j are as defined previously. The a_1 and a_2 values can be found by an iteration process such as the one described as follows.

Assume an a_1 value, then F_j and f_j at five geophones can be calculated. B_0 is thus determined by:

$$B_0 = \sum_{j=1}^{5} (W_j - F_j)f_j / \sum_{j=1}^{5} f_j^2 . \qquad (6)$$

In turn, a_2 can be estimated from B_0,

$$a_2 = (c_0/B_0)^{\frac{1}{c_1}} . \qquad (7)$$

Applying the assumed a_1 and the calculated a_2 values in the deflection equation (Eq. 5), the predicted W_j (designated by $\hat{W}_j$) at five geophones can thus be determined. Then the root-mean-square-error can be calculated from

$$RMSE = \sqrt{\frac{1}{5} \sum_{j=1}^{5} (W_j - \hat{W}_j)^2} . \qquad (8)$$

Now assume another a_1 value and repeat the computational procedure to calculate the a_2, $\hat{W}_j$ and RMSE. A Fibonacci search scheme is utilized in the STIF5 program to select the optimal a_1 and a_2 values yielding the minimum RMSE which would best represent the material stiffness based on the dynamic deflection data.

SCIMP

The application of STIF2 and STIF5 programs are restricted to two-layer pavement structures (or three-layer pavements with a relatively thin surfacing layer, say, 10%). For more than two layers, the SCIMP (Stiffness Coefficient in Multi-layer Pavement) program may be used. Given stiffness coefficients of n-2 layers above the subgrade in an n-layer pavement structure, where $n \geq 3$, the SCIMP calculates the stiffness coefficients of one of the n-1 pavement layers and the subgrade. In mathematics, the computational procedures are represented as follows.

According to Eq. 1, the deflection equation can be rewritten as

$$W_j = F_j + B_0 \cdot f_j \tag{5}$$

where,

$$F_j = \sum_{k=1}^{n-1} \frac{c_0}{a_k^{c_1}} \left[\frac{1}{r_j^2 + c_2\left(\sum\limits_{i=0}^{k-1} a_i D_i\right)^2} - \frac{1}{r_j^2 + c_2\left(\sum\limits_{i=0}^{k} a_i D_i\right)^2} \right]$$

$$B_0 = \frac{c_0}{a_n^{c_1}}$$

$$f_j = \frac{1}{r_j^2 + c_2\left(\sum\limits_{i=0}^{n-1} a_i D_i\right)^2} .$$

To illustrate the algorithm, let $n = 5$ and a_2, a_3, a_4 be known. Assume an a_1 value, then F_j and f_j at five geophones can be calculated. B_0 is determined by

$$B_0 = \sum_{j=1}^{5} (W_j - F_j) f_j \Big/ \sum_{j=1}^{5} f_j^2 ; \tag{6}$$

a_5 can thus be estimated from B_0

$$a_5 = (c_0/B_0)^{\frac{1}{c_1}} . \tag{9}$$

The same Fibonacci search scheme as used in STIF5 is utilized here to find the optimal a_1 and a_5 values which yield the minimum RMSE. It should be pointed out that the unknown pavement coefficient can be any one of the pavement layers above the subgrade.

SCIMP-PS

The SCIMP-PS stands for Stiffness Coefficient in Multi-layer Pavements by Pattern Search. The original SCIMP program calculates the stiffness coefficient of one pavement layer and the subgrade, while the stiffness coefficients of other pavement layers of the multi-layer pavement structure must be known. The SCIMP by pattern search determines the stiffness coefficients of all pavement layers and the subgrade. The deflection equation of an n-layer pavement structure (Eq. 1) can be expanded as follows:

$$
\begin{aligned}
W_j = {} & \frac{c_0}{a_1^{c_1}}\left[\frac{1}{r_j^2} - \frac{1}{r_j^2+c_2(a_1D_1)^2}\right] \\
& + \frac{c_0}{a_2^{c_1}}\left[\frac{1}{r_j^2+c_2(a_1D_1)^2} - \frac{1}{r_j^2+c_2(a_1D_1+a_2D_2)^2}\right] \\
& + \cdots\cdots\cdots\cdots \\
& + \frac{c_0}{a_{n-1}^{c_1}}\left[\frac{1}{r_j^2+c_2(\sum\limits_{i=1}^{n-2} a_iD_i)^2} - \frac{1}{r_j^2+c_2(\sum\limits_{j=1}^{n-1} a_iD_i)^2}\right] \\
& + \frac{c_0}{a_n^{c_1}}\left[\frac{1}{r_j^2+c_2(\sum\limits_{i=1}^{n-1} a_iD_i)^2}\right] \\
= {} & c_0 \left\{ (\frac{1}{a_1^{c_1}}\ [\frac{1}{r_j^2}] + (\frac{1}{a_2^{c_1}} - \frac{1}{a_1^{c_1}})[\frac{1}{r_j^2+c_2(a_1D_1)^2}] \right. \\
& \qquad + (\frac{1}{a_3^{c_1}} - \frac{1}{a_2^{c_1}}\ [\frac{1}{r_j^2+c_2(a_1D_1+a_2D_2)^2}] \\
& \qquad + \cdots\cdots\cdots\cdots
\end{aligned}
$$

$$+ \left(\frac{1}{a_n^{c_1}} - \frac{1}{a_{n-1}^{c_1}}\right) \left[\frac{1}{r_j^2 + c_2 (\sum_{i=1}^{n-1} a_i D_i)^2}\right] \Bigg\}$$

$$= c_0 \left\{ \left(\frac{1}{a_1^{c_1}}\right)\left(\frac{1}{r_j^2}\right) + \sum_{m=2}^{n} \left(\frac{1}{a_m^{c_1}} - \frac{1}{a_{m-1}^{c_1}}\right) \left[\frac{1}{r_j^2 + c_2 (\sum_{i=1}^{m-1} a_i D_i)^2}\right] \right\}. \quad (10)$$

The pattern search method is a standard library routine (15) which is programmed to conduct an efficient multi-dimensional search for the set of n variables which minimizes a prediction error whose form is specified by the user. In this application, the pavement stiffness coefficients of all n layers are the variables that are sought. The prediction error (PE) which is minimized by the pattern search is the squared error between observed and calculated deflections, and thus by minimizing the following prediction error a least-squares fit is assured.

$$PE = \sum_{k=1}^{N_0} \sum_{j=1}^{N_d} \left\{ \left(\frac{1}{a_1^{c_1}}\right)\left(\frac{1}{r_j^2}\right) + \sum_{m=2}^{n} \left(\frac{1}{a_m^{c_1}} - \frac{1}{a_{m-1}^{c_1}}\right) \left[\frac{1}{r_j^2 + c_2 (\sum_{i=1}^{m-1} a_i D_i)^2}\right] - \frac{W_{kj}}{c_0} \right\}^2 . \quad (11)$$

where

N_o = number of observations

N_d = number of geophone measurements per test

W_{kj} = the k^{th} observation of surface deflection W_j as defined before.

Comparison

STIF2, STIF5 and SCIMP can be used to predict two unknown stiffness coefficients. One of the two unknowns must be the stiffness coefficient of the subgrade (or the foundation). For STIF2 and STIF5, the other unknown is the stiffness coefficient of the composite layer of materials above the subgrade, that is, the program is restricted to 2-layer pavements. The SCIMP can be used for multi-layer pavements. The SCIMP calculates the stiffness coefficient of any one selected pavement layer and the subgrade, when the stiffness coefficients of all other pavement layers are given. The PS version of the SCIMP, SCIMP-PS, has the versatility to calculate the stiffness coefficients of all pavement layers, and the subgrade. STIF2, STIF5 and SCIMP calculate the stiffness coefficients of each individual observation and average the total observations. The SCIMP-PS minimizes the prediction error of the total observations.

STIF2, STIF5 and SCIMP programs are very economical in numerical computation, in comparison with the SCIMP-PS. Due to the cumbersome computations required in the pattern search routine, the SCIMP-PS program is suggested for a maximum of 5-layer pavements. For more than 5 layers, other searching techniques which can be found in most optimization and operations research textbooks are recommended.

A comparison of example solutions of STIF2, STIF5, SCIMP and SCIMP-PS is shown in Table 1 and Table 2. Table 1 shows the stiffness coefficients obtained for two designs of a black base pavement using each of the four methods to calculate stiffness coefficients. Table 2 shows the stiffness coefficients obtained for two designs of a limestone rock asphalt pavement using each of the four methods to calculate stiffness coefficients.

TABLE 1: SUMMARY OF STIFFNESS COEFFICIENTS OF A BLACK BASE PAVEMENT CALCULATED BY FOUR DIFFERENT METHODS

	SDHPT STIFFNESS COEFFICIENTS		STIF5 COEFFICIENTS		SCIMP COEFFICIENTS					SCIMP-PS COEFFICIENTS				
STATION	AP2	AS2	AP5	AS5	* A1	A2	A3	A4	A5	A1	A2	A3	A4	A5
S1	0.62	0.24	0.58	0.25	0.40	0.49	0.72	0.42	0.25	0.40	0.43	0.72	0.42	0.24**
S2	0.48	0.28	0.53	0.26		0.38			0.25					
S3	0.54	0.26	0.56	0.25		0.43			0.25					
S9	0.55	0.25	0.60	0.23		0.49			0.23					
S10	0.53	0.24	0.53	0.24		0.39			0.23					
S11	0.56	0.23	0.58	0.22		0.46			0.22					
AVERAGE	0.55	0.25	0.56	0.24		0.44			0.24	0.40	0.43	0.72	0.42	0.24
DESIGN:	2-Layers		2-Layers		5-Layers					5-Layers				
PAVEMENT THICKNESSES:	32 Inches		32 Inches		T1=1.0 in., T2=4.0 in., T3=19.0 in., T4=8.0 in.					T1=1.0 in., T2=4.0 in., T3=19.0 in., T4=8.0 in.				
S4	0.61	0.24	0.58	0.25	*0.88	0.45	0.69	0.71	0.24	0.88	0.50	0.69	0.71	0.24
S5	0.84	0.22	0.70	0.24		0.70			0.24					
S6	0.50	0.30	0.61	0.25		0.46			0.25					
S7	0.65	0.22	0.66	0.22		0.58			0.22					
S8	0.52	0.27	0.58	0.25		0.43			0.24					
AVERAGE	0.62	0.25	0.63	0.24		0.52			0.24	0.88	0.50	0.69	0.71	0.24
DESIGN:	2-Layers		2-Layers		5-Layers					5-Layers				
PAVEMENT THICKNESSES:	26 Inches		26 Inches		T1=1.0 in., T2=4.0 in., T3=13.0 in., T4=8.0 in.					T1=1.0 in., T2=4.0 in., T3=13.0 in., T4=8.0 in.				

* Note - The A1, A3, and A4 values were assumed for these problems

**Note - The pattern search method calculates a single set of coefficients that best fits all the data observations

TABLE 2: SUMMARY OF STIFFNESS COEFFICIENTS OF A LIMESTONE ROCK ASPHALT PAVEMENT CALCULATED BY FOUR DIFFERENT METHODS

	SDHPT STIFFNESS COEFFICIENTS		STIF5 COEFFICIENTS		SCIMP COEFFICIENTS					SCIMP-PS COEFFICIENTS				
STATION	AP2	AS2	AP5	AS5	* A1	A2	A3	A4	A5	A1	A2	A3	A4	A5
N1	0.49	0.26	0.50	0.25	2.77	0.38	0.54	0.45	0.24	2.77	0.35	0.54	0.45	0.24**
N2	0.62	0.23	0.69	0.22		1.04			0.22					
N3	0.47	0.26	0.48	0.26		0.35			0.24					
N9	0.43	0.24	0.41	0.24		0.28			0.22					
N10	0.45	0.25	0.45	0.25		0.32			0.23					
N11	0.44	0.29	0.48	0.25		0.36			0.24					
AVERAGE	0.48	0.26	0.50	0.25		0.46			0.23	2.77	0.35	0.54	0.45	0.24
DESIGN:	2-Layers		2-Layers		5-Layers					5-Layers				
PAVEMENT THICKNESSES:	32 Inches		32 Inches		T1=1.0 in., T2=4.0 in., T3=19.0 in., T4=8.0 in.					T1=1.0 in., T2=4.0 in., T3=19.0 in., T4=8.0 in.				
N4	0.47	0.26	0.47	0.25	*0.67	0.43	0.47	0.60	0.25	0.67	0.38	0.47	0.60	0.26**
N5	0.45	0.27	0.49	0.25		0.47			0.25					
N6	0.48	0.26	0.49	0.26		0.48			0.25					
N7	0.41	0.26	0.42	0.26		0.31			0.24					
N8	0.43	0.24	0.43	0.25		0.34			0.23					
AVERAGE	0.45	0.26	0.46	0.25		0.41			0.24	0.67	0.38	0.47	0.60	0.26
DESIGN:	2-Layers		2-Layers		5-Layers					5-Layers				
PAVEMENT THICKNESSES:	26 Inches		26 Inches		T1=1.0 in., T2=4.0 in., T3=13.0 in. T4=8.0 in.					T1=1.0 in., T2=4.0 in., T3=13.0 in., T4=8.0 in.				

* Note - The A1, A3, and A4 values were assumed for these problems

**Note - The pattern search method calculates a single set of coefficients that best fits all the data observations

METHODS OF COMPUTING ELASTIC MODULI

The computer codes for computing elastic moduli of two-layer pavements were developed from Burmister's theory of elasticity in layered pavement (14). All of the methods for computing the elastic moduli of pavement layers described herein are limited to simple two-layer designs consisting of a thin or relatively thin surface layer overlying a base layer, resting on the subgrade. The rigorous mathematical theory involved for more than two layers limits the present methods to the simple two-layer design. All of the methods are based on finding the values of elastic modulus for the subgrade and the base/surface layer which provide the best agreement between the observed surface pavement deflections and the calculated pavement deflections.

ELASTIC MODULUS I

Scrivner, et al. developed the first method of computing the in situ values of elastic modulus of materials for consideration in the FPS system (4).

If the pavement is assumed to consist of a base or surface layer of known thickness resting on a homogeneous subgrade of infinite depth and with Poisson's ratio of 1/2, the equation for the surface deflection of a point according to the theory of elasticity is given by the equation

$$\frac{4\pi E_1}{3P} wr = \int_{x=0}^{\infty} V \cdot J_0(X)dx \qquad (12)$$

where

P = a point load

E_1 = elastic modulus of the upper layer

E_2 = elastic modulus of the subgrade layer

w = the surface deflection of a point on the surface

r = the horizontal distance of the measurement of the deflection w from the load P

x = mr/h, where m is a parameter

$$N = \frac{E_1 - E_2}{E_1 + E_2}$$

$$V = \frac{1 + 4\ Nme^{-2m} - N^2e^{-4m}}{1 - 2\ N(1+2m^2)e^{-2m} + N^2e^{-4m}}$$

By making certain approximations and assumptions described in reference (4), Equation 12 can be reduced to

$$\frac{4\pi E_1}{3P} wr \simeq 1 + \int_{X=0}^{X=10r/h} (V-1)\ J_0(X)dx \tag{13}$$

Equation 13 can then be integrated in the solution process for finding the elastic moduli of the 2-layer pavement structure. A simplified description of how Equation 13 is used to calculate the elastic moduli follows.

The surface deflections w_1 and w_2 of two points located at distances r_1 and r_2 from the load P, and the thickness of the upper layer h are known.

Let F represent the function on the right side of Equation 13. The following equations can then be rewritten

$$\frac{4\pi E_1}{3P} w_1 r_1 \simeq F(E_2/E_1,\ r_1/h) \tag{14}$$

$$\frac{4\pi E_1}{3P} w_2 r_2 \simeq F(E_2/E_1,\ r_2/h) \tag{15}$$

A single equation in which E_2/E_1 is the only unknown can be obtained by dividing Equation 14 by Equation 15 as follows:

$$\frac{w_1 r_1}{w_2 r_2} = \frac{F(E_2/E_1,\ r_1/h)}{F(E_2/E_1,\ r_2/h)} \tag{16}$$

By using a convergent process, a value of E_2/E_1 can be found that satisfies Equation 16 within desired accuracy limits. E_1 can then be calculated from Equation 14 and E_2 can be found from the relation

$$E_2 = E_1 \left(\frac{E_2}{E_1}\right) \tag{17}$$

ELASTIC MODULUS II

Another version of the method by Scrivner for computing in situ values of elastic moduli was developed primarily to compute the in situ moduli of rigid pavements (5). The same equations, assumptions, and approximations described previously hold with the exception that the distance between the observed surface deflections was increased by one foot. This change was felt necessary because in the case of rigid pavements, the difference in the surface deflections of points only one foot apart was not enough to ensure that accurate values of the elastic modulus of a rigid pavement layer could be obtained using elasticity theory.

The two methods of computing in situ values of elastic moduli of pavement structures, described above are available as computer codes.

GRAPHICAL TECHNIQUE

A graphical technique of determining in situ elastic moduli of simple pavement structures from observed surface deflections of the pavement was developed by Swift (6). From the equation for surface deflections at various distances from a point load, the following dimensionless relationships can be written if Poisson's ratio is assumed to be 1/2 for both layers of a simple two-layer system:

$$\frac{wr\ E_2}{P} = \frac{3}{4\pi}\ f\left(\frac{E_1}{E_2}, \frac{r}{h}\right) \tag{18}$$

The terms w, r, P, E_1, E_2, and h are the same as defined earlier. For any value of the ratio E_1/E_2, the quantity $\frac{wr\,E_2}{P}$ is a different function of the ratio r/h. The ratio E_1/E_2 can be evaluated because of this by finding the best match between a given set of measured deflection data and the set of computed deflection data for a certain value of E_1/E_2.

After finding the E_1/E_2 value for which the calculated deflections most closely matches the observed deflections, the E_2 value can be obtained from

$$E_2 = \frac{wr\,E_2}{P}\text{ (Computed)} \div \frac{wr}{P}\text{ (Obs.)} \tag{19}$$

E_1 is obtained from

$$E_1 = E_2 \cdot \frac{E_1}{E_2} \tag{20}$$

The procedure for finding the elastic moduli of two layer pavements using this graphical technique is briefly described as follows. Values of $\frac{wr}{P}$, with w being the observed surface deflections, are plotted versus r using logarithmic scales, as in Figure 4. This curve is then superimposed on a chart containing many curves computed for different E_1/E_2 and r/h ratios (Figure 5). The location on the observed deflections plot r/h = 1.0 is aligned with a similar location on the chart. The plotted curve is then moved vertically up or down until it best matches one of the computed curves on the chart or a best fit between two of the computed curves is found (Figure 6). The ratio E_1/E_2 and the value of E_2 are read directly from the chart. The value of E_1 is calculated from Equation 20 as follows:

$$E_1 = E_2 \cdot \frac{E_1}{E_2}$$

A more detailed explanation of this graphical method for obtaining elastic moduli of pavement materials from surface deflections as well as limitations

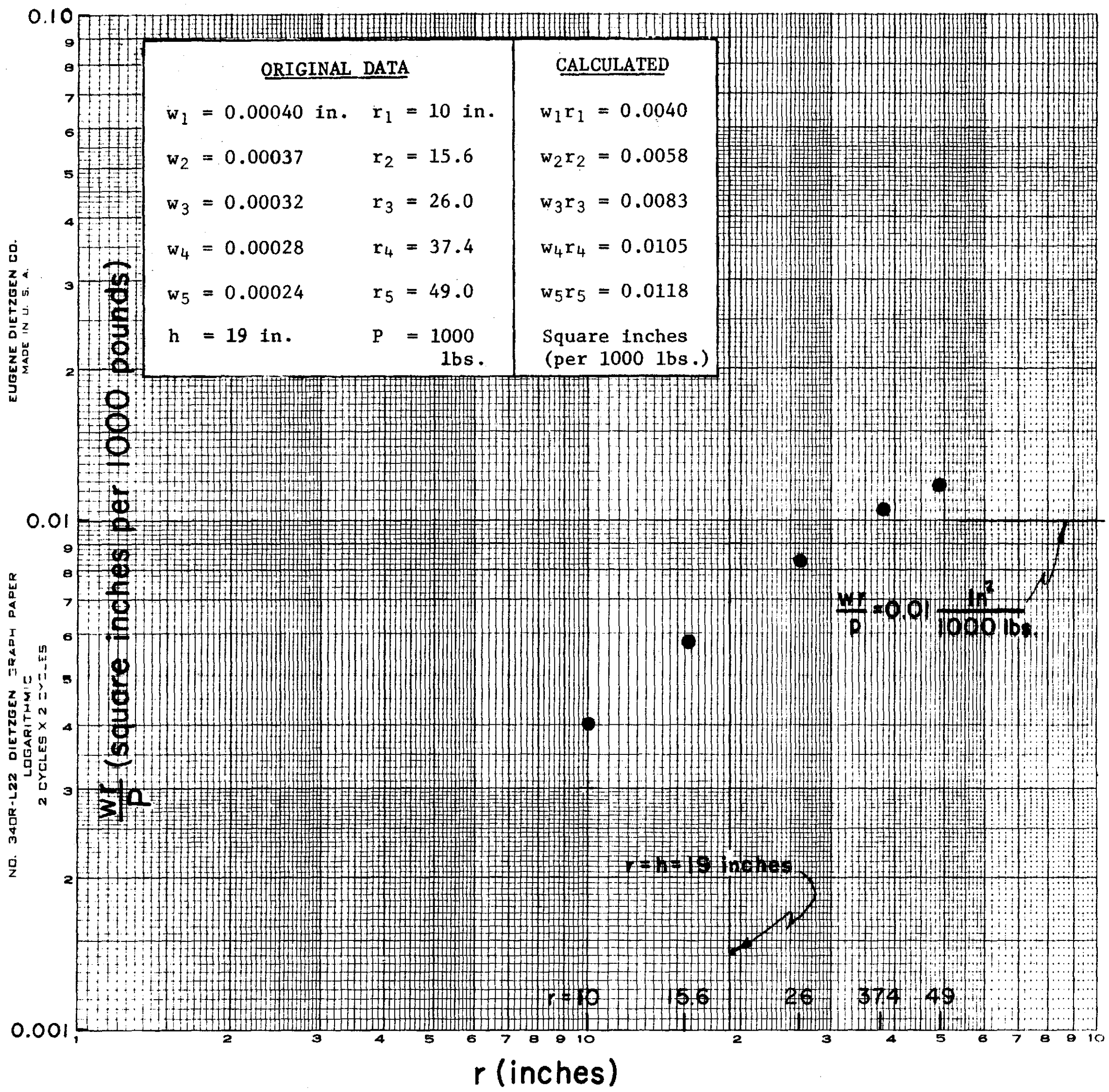

Figure 4: Typical plot of $\frac{wr}{P}$ versus r, derived from measured deflections.

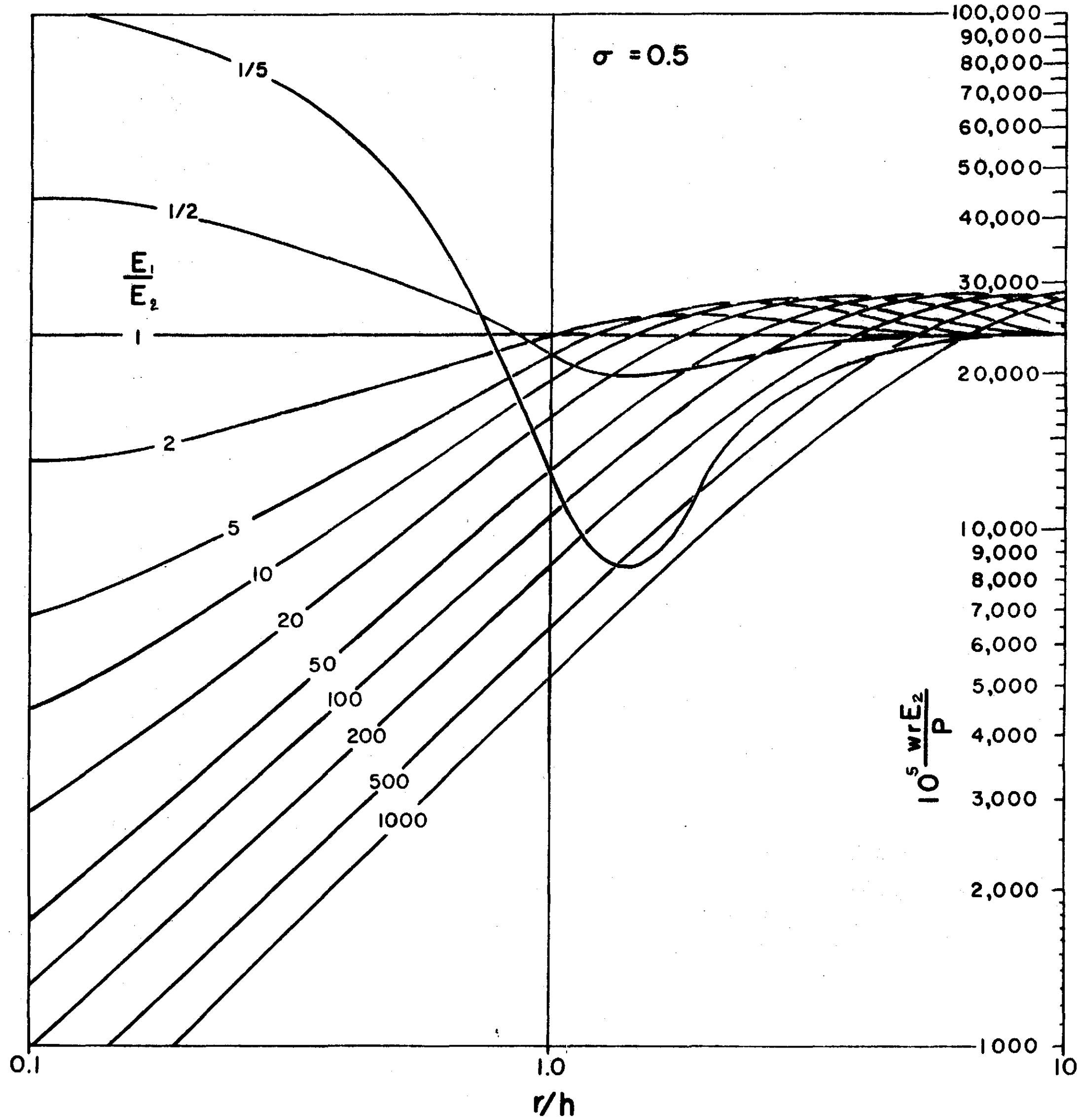

Figure 5: Two-Layer Elastic Deflection Chart.
(Poisson's Ratio, $\sigma = 0.5$)

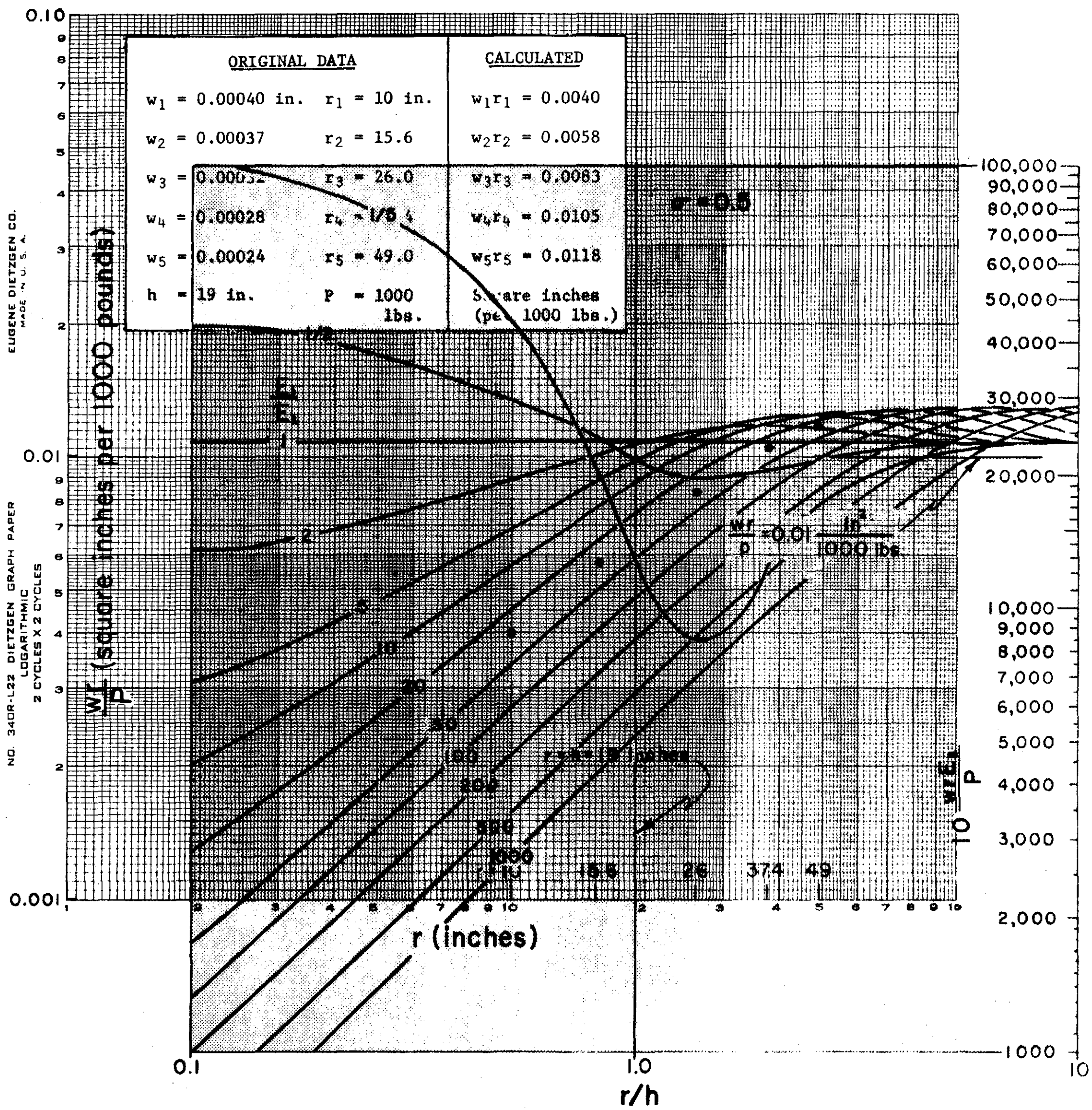

Figure 6: Example showing the chart superimposed in "best fit" position on the deflection plot. In this case, $\frac{E_1}{E_2}$ is found to be equal to 30 and the value of E_2 is found to be 22,000 psi. Accordingly, E_1 is 22, 000 x 30 or 660,000 psi.

on its use can be found in reference (6).

EMPI

An empirical equation for predicting surface pavement deflections of an elastic pavement structure was derived by Swift (7). The results obtained using his equation are in close agreement with results obtained from solutions based on Burmister's equations. The equation for surface deflections of an elastic pavement structure derived by Swift is as follows:

$$w = \frac{3P}{4\pi} \cdot \frac{1}{r} \left[\frac{1}{E_1} + \left(\frac{1}{E_2} - \frac{1}{E_1}\right)\left(\frac{r}{L} + \frac{rx^2}{2L^3} + \frac{3rx^4}{2L^5}\right)\right] \qquad (21)$$

where

$$L = \sqrt{r^2 + X^2}$$

$$X = 2h^3\sqrt{\frac{E_1 + 2E_2}{3E_2}}$$

P, r, and h = same as defined previously.

The advantage of this equation for obtaining predicted surface deflections is the ease of its use and the speed of solution as opposed to the more complicated equations from Burmister.

The empirical equation described above was used by Moore to compute the elastic moduli of simple pavement structures (8). The equation was rewritten in the following form:

$$\hat{w} = \frac{3P}{4\pi E_1} \left[\frac{1}{r} + \left(\frac{E_1}{E_2} - 1\right)\left(\frac{1}{X} + \frac{a^2}{2X^3} + \frac{3a^4}{2X^5}\right)\right] \qquad (22)$$

where

$$X = \sqrt{r^2 + a^2}$$

$$a = 2h^3\sqrt{\frac{1}{3} + {}^{E_1}/E_2}$$

P, r, h, E_1, E_2, and $\hat{w}$ = same as defined previously.

If the surface deflections of the pavement are measured with the Dynaflect, the only unknowns in the above equation are E_1 and E_2. If the set of E_1 and E_2 values can be found such that the predicted surface deflections $\hat{w}$ calculated from the equation approximate the observed surface deflections within the accuracy range specified, then these values can be taken to represent the elastic moduli of the simple pavement system. The "best fit" between the predicted and observed surface deflections was determined to be the minimum value of the root mean square error of the predicted and observed surface deflections as shown below:

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (w_i - \hat{w}_i)^2} \qquad (8)$$

In order to use Equation (22) to calculate the values of E_1 and E_2 which provided the "best fit" between the observed and predicted surface deflections, the equation was written in the general form below:

$$\hat{w} = B_0 \cdot f(r, h, B_1) + \varepsilon$$

where $B_0 = \frac{3P}{4\pi E_1}$

$B_1 = {}^{E_1}/_{E_2}$

ε = a prediction error $(w - \hat{w})$.

The minimum RMSE which determined the best fit was obtained by an iterative process consisting of several steps. A trial value of B_1 was selected first, and then five values of the function f were computed for the values of r at which surface deflections were measured. A B_0 value corresponding to the trial value of B_1 was obtained from the equation below:

$$B_0 = \sum_{i=1}^{5} w_i f_i \Big/ \sum_{i=1}^{5} f_i^2 \qquad (23)$$

The predicted surface deflections for the trial value of B_0 and B_1 were calculated and the RMSE computed.

These steps were repeated until RMSE's for 21 logarithmically spaced trial values of B_1, chosen to cover the entire range of reasonable values of E_1/E_2, were computed. The smallest RMSE value was selected as the starting point of a Fibonacci search technique which determined the B_0 and B_1 values which gave the absolute minimum RMSE. From these two values, the elastic moduli of the individual pavement layers was computed from the following equations:

$$E_1 = \frac{3000}{4\pi\ B_0} \qquad (24)$$

$$E_2 = \frac{3000}{4\pi\ B_0 B_1} \qquad (25)$$

The solution process described above was converted to a computer code which provides a faster means of obtaining elastic moduli from surface deflections than the previous method by Scrivner, et al. (4).

A more detailed explanation of the computer code and certain limitations on its use can be found in reference (8).

EMPIRICAL RELATIONS BETWEEN BASE COURSE ELASTIC MODULUS AND STIFFNESS COEFFICIENT

A pavement evaluation (13) project, conducted by TTI under a joint contract with the City of Houston and Harris County, determined the elastic moduli and stiffness coefficients of a variety of base courses and subgrades within their jurisdictions. In-service pavements were tested by the Dynaflect and analyzed by program EMPI to calculate elastic moduli and program STIF5 to calculate stiffness coefficients. The tests were run during the cold months of the year on materials such as cement stabilized shell, black base, and other stabilized materials whose stiffness coefficients were usually much higher than those normally found in Texas. The stiffness coefficients ranged from 0.68 to 2.14. In addition, samples of base course and subgrade materials were cored and tested in a commercial laboratory to determine the elastic modulus.

The linear correlation of the elastic modulus of base course materials (E) calculated by EMPI and the stiffness coefficient (S) computed by STIF5 of 82 observations can be represented by

$$E = -276{,}242 + 799{,}622\ S$$

$$(N = 82,\ R^2 = 0.787,\ C.V. = 81.5\%,\ S.E. = 338{,}232)$$

A convex quadratic function shows a better fit:

$$E = 80{,}018 - 460{,}141\ S + 526{,}390\ S^2$$

$$(N = 82,\ R^2 = 0.935,\ C.V. = 45.3\%,\ S.E. = 187{,}849)$$

However, the elastic modulus determined in the laboratory is not correlated with the elastic modulus determined by EMPI ($R^2 = 0.046$ by quadratic function), nor correlated with the stiffness coeffieient determined by STIF5 ($R^2 = 0.034$ by quadratic function).

These empirical correlations are useful for converting stiffness coefficients into elastic moduli. Therefore, it is now possible to use the pattern search method in SCIMP-PS to determine stiffness coefficients for an n-layer pavement (5 is the practical maximum) and use the above empirical relation to infer elastic moduli for all of the layers. The accuracy of the result is, of course, limited by the range of data from which the equation is drawn. The linear relation will give negative E's for stiffness coefficients below about 0.34. The quadratic relation gives negative E's for stiffness coefficients below about 0.22.

CONCLUSIONS AND RECOMMENDATIONS

The several methods for computing stiffness coefficients or elastic moduli of materials in existing pavement structures from observed surface deflections have been presented and briefly discussed.

Each method described has been used or is available for use by pavement designers or researchers who need accurate measurements of pavement stiffness coefficients or elastic moduli.

Of the four methods for computing material stiffness coefficents (STIF2, STIF5, SCIMP, SCIMP-PS), STIF5 and SCIMP give the most accurate results. SCIMP has the capability of finding the stiffness coefficient of any selected layer for which the stiffness coefficient volume is unknown. SCIMP-PS is the only method available for calculating all the stiffness coefficients in an n-layer pavement.

The program EMPI gives the most accurate estimates of elastic modulus from surface deflections. The theoretical equation in EMPI for surface deflections agrees closely with results from Burmister's theory and the theoretical equation eliminates the approximations and numerical intregrations which limit the accuracy of ELASTIC MODULUS I and ELASTIC MODULUS II.

A graphical technique for obtaining elastic moduli of simple two layer permanent structures from surface deflections is available also.

The different methods presented herein may be chosen by the user to best suit the user's needs and available data and computational resources.

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APPENDIX A

DOCUMENTATION OF A METHOD OF COMPUTING STIFFNESS COEFFICIENTS IN SIMPLE TWO LAYER PAVEMENT STRUCTURES USING FIVE OBSERVED SURFACE DEFLECTIONS, COMPUTER PROGRAM STIF5.

INTRODUCTION

In 1968 Scrivner and Moore (11) presented an empirical deflection equation developed from a mathematical model fitted to Dynaflect data gathered on a set of experimentally designed pavement test sections. The equation contained a material property constant for each layer called a "layer stiffness coefficient". In addition to the equation, they presented a technique for estimating layer stiffness coefficients for materials in existing two layer pavement structures from measured surface deflections.

Included herein is the documentation of a modification to the technique for estimating layer stiffness coefficients in pavement structures that can be represented as a pavement layer of known thickness resting on an infinitely thick subgrade. The modified technique calculates the two coefficients that give a least squares fit to the entire deflection basin rather than an exact fit of two selected points on the basin. In some cases the latter technique yields deflection predictions which have rather large errors and the modified technique overcomes this problem.

PROGRAM IDENTIFICATION

Title: Documentation of a Method of Computing Stiffness Coefficients in Simple Two Layer Pavement Structures Using Five Observed Surface Deflections, Computer Program STIF5.

Language: FORTRAN IV and IBM 360 Assembly Language

Machine: IBM 360/65

Programmer: G.W. Turman

Availability: Department of Pavement Design
Texas Transportation Institute
Texas A&M University
College Station, Texas 77843

Phone (713) 845-3735

Date: August 1974

Source Deck: Approximately 500 cards

Storage: 110 k bytes

Timing: (1) Compilation time - 0.40 minutes (FORTRAN G Compiler)
(2) Execution Time - dependent on number of data observations, 0.25 minutes for 21 data observations

Output: (1) Program list - approximately 500 lines
(2) Program Output - one page per problem (30 lines per page)

Documentation: Michalak, C.H., Lu, D.Y. and Turman, G.W., "Determining Stiffness Coefficients and Elastic Moduli of Pavement Materials from Dynamic Deflections", Research Report 207-1, Texas Transportation Institute, 1976.

PROGRAM DESCRIPTION

The data for STIF5 is input to the main program as described in the input guide. The deflections at each radial distance are calculated from the geophone deflection readings and multipliers on the appropriate data cards. The Surface Curvature Index (SCI) is also calculated, SCI = W1 - W2. If any W (deflection) is equal to zero, or if any W is greater than its preceding W, the cases are flagged to denote data errors and are not used for further calculations. If the W's are valid observations they are passed to subroutine STIF5 along with the total pavement thickness for the stiffness coefficients and RMSE calculations.

STIF5 returns to the main program the stiffness coefficients for both subgrade (AS5) and pavement (AP5) along with their corresponding RMSE's. The counter N (the number of sets of observations) is incremented and the program reads the next data card and continues the process until all stations in a section are read.

A loop is set up to print the stations numbers, measured and predicted deflections, SCI's, stiffness coefficients for the subgrade and pavement and RMSE's for all data observations. Messages for the following situations are printed for which a data observation is not used in the calculations:

1. Data observation computes a negative SCI in which case the message 'NEGATIVE SCI OTHER CALCULATIONS OMITTED' is printed.

2. Data observation where any W is equal to zero. 'ERROR IN DATA' is printed.

3. When the minimum value for RMSE is where the stiffness coefficient of the pavement is less than .1, the message 'MIN. RMSE AT A1 LESS THAN RANGE SEARCHED' is printed.

4. When the minimum value for RMSE is when the stiffness coefficient

of the pavement is greater than 7.4 the message 'MIN. RMSE AT A1 GREATER THAN RANGE SEARCHED' is printed.

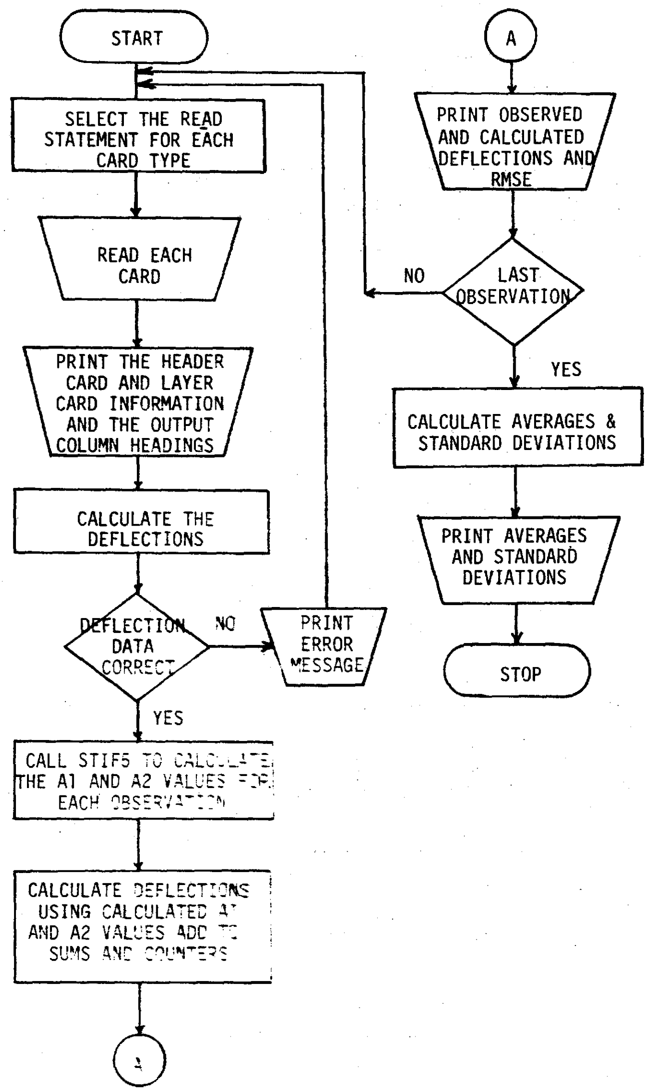
5. If a value for A(1) between .1 and 2.0 does not yield a positive B value (Equation in 3), other calculations are omitted and the message 'MIN. RMSE____ INDICATED AT THE VALUE A1=___. AT THIS POINT THE VALUE OF A2 CANNOT BE CALCULATED' is printed.

After all data and any error messages for a section are printed, the average deflections, SCI's, stiffness coefficients of the subgrade and pavement, standard deviations and RMSE are calculated. These averages are then printed along with the number of points used in calculating each average. Definitions of the heading abbreviations are given next in footnote form.

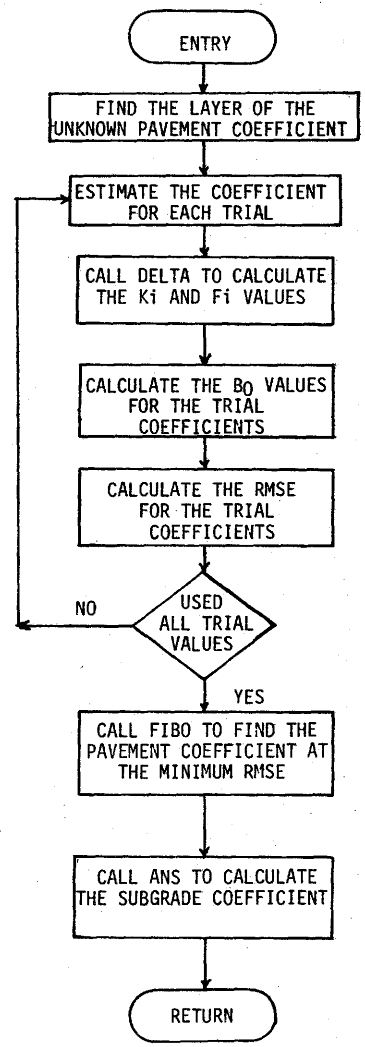
The program then returns to its beginning to read data for another section or terminates execution normally when all data have been read.

For the equations used in STIF5 and an explanation of how they are used to calculate the stiffness coefficients, see page 8 of the main report.

STIF5 (MAIN)

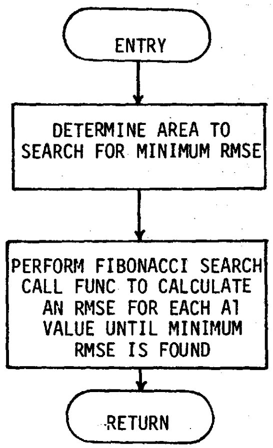


STIF5

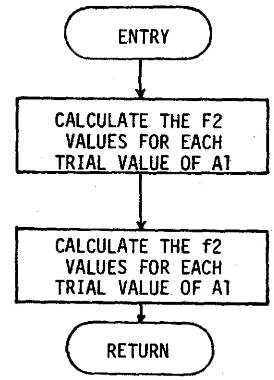


FLOWCHART

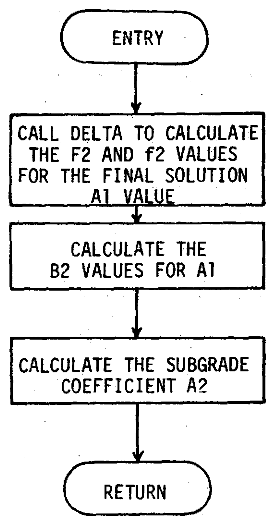
FIBO



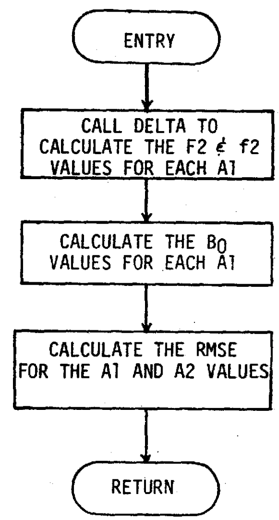
DELTA



ANS



FUNC



PROGRAM LISTING

```
C      STIF5 -- STIFFNESS COEFICIENTS -- MAIN PROGRAM (FIVE DEFLECTIONS)
C
C
       DIMENSION STA(200),W(200,5),D(10),AW(5),AWV(5),AP5(200),
      *AS5(200),LA1(5),LA2(5),LA3(5),LA4(5),LA5(5),LA6(5),A(20),SCI(200),
      *IXDATE(2),COMM(7),REM(200,4),SSW(5),SDW(5),RMSE(200),WC(5),R(5),
      *SSWC(5),AWC(5),AWCV(5),SDWC(5),ISAVSW(200)
       REAL * 8 STA,DAS,DAP,DBLE,RMSE,AVRMS
       ROUND( X,EVEN ) = AINT( ( X + EVEN * .5 ) / EVEN )
      * *  EVEN
    10 CONTINUE
       READ(5,1,END=1000)  NCARD, ( A(I), I = 1 , 20 )
     1 FORMAT( I3, 19A4,A1  )
C      CALL  CORE   ( A,   80 )
       IF(NCARD.EQ.100) GO TO 11
       IF(NCARD.EQ.200) GO TO 12
       IF(NCARD.EQ.300) GO TO 13
    14 I=N + 1
       READ(5,6) CONT,SECT,DM,DAY,YEAR,STA(I),(D(K),K=1,10),
      *(REM(I,J),J=1,4),ICK
     6 FORMAT(3X, A4,4A2,A7,3X,5(F2.1,F3.2),8X,4A4,I2)
       IF(I .EQ. 1 .AND. ICK .GT. 0) GO TO 222
       IF(I .EQ. 1 .AND. PN .EQ. 1.0) GO TO 222
       IF(N .GT. 0) GO TO 555
       IF(LO .GT. 0) GO TO 555
       PRINT 61
    61 FORMAT(/,7X,'LOCATION    W1       W2       W3       W4       W5       SCI
      *AS5     AP5          RMSE ',/)
       GO TO 555
   222 CONTINUE
       PRINT 51
       PRINT 52
       PRINT 53,DIST
       PRINT 54
       CALL DATE(IXDATE)
       PRINT 55,IXDATE
       PRINT 56,DIST,CO1,CO2,CO3,CO4
       PRINT 57, CONT,SECT,JOB,HWY1,HWY2,XLANE,DM,DAY,YEAR,DYNA
       PRINT 58,(COMM(K),K=1,7),DP
       PRINT 61
   555 CONTINUE
       L = 1
       DO 4 J=1,5
       W(I,J) = D(L) * D(L + 1)
       L = L + 2
     4 CONTINUE
       SCI(I) = W(I,1) - W(I,2)
C
C      TEST FOR W1 OR W2 = 0, AND W1 LESS THAN W2
C
       IF(W(I,1).EQ. 0 .OR. W(I,2) .EQ. 0) GO TO 21
       IF(W(I,1) .LT. W(I,2)) GO TO 22
       DO 7 J=2,4
       IF(W(I,J) .LT. W(I,J+1)) GO TO 23
     7 CONTINUE
       ISW = 1
       CALL STIF5(DBLE(W(I,1)),DBLE(W(I,2)),DBLE(W(I,3)),DBLE(W(I,4)),
      *DBLE(W(I,5)),DBLE(DP),DAS,DAP,RMSE(I),ISW)
       AS5(I) = DAS
       AP5(I) = DAP
       ISAVSW(I) = ISW
```

```
      N = N + 1
      IF(ICK .EQ. 0) GO TO 10
      GO TO 80
   11 READ(5,2) DIST,CO1,CO2,CO3,CO4,CONT,SECT,JOB,HWY1,HWY2,XLANE,DP,
     *DM,DAY,YEAR,DYNA,(COMM(I),I=1,7)
    2 FORMAT( 3X, A2,3A4,A2,A4,A2,A2,A4,A3,A3,F5.2,4A2,7A4 )
      PRINT 51
   51 FORMAT( '1' )
      PRINT 52
   52 FORMAT(35X,'TEXAS HIGHWAY DEPARTMENT' /)
      PRINT 53,DIST
   53 FORMAT(33X,'DISTRICT ',A2,' - DESIGN SECTION' /)
      PRINT 54
   54 FORMAT(18X,'DYNAFLECT DEFLECTIONS AND CALCULATED ',
     *'STIFFNESS COEFFICIENTS'/)
      CALL DATE(IXDATE)
      PRINT 55,IXDATE
   55 FORMAT(24X,'THIS REVISED PROGRAM (MAR. 74) WAS RUN ',2A4/)
      PRINT 56,DIST,CO1,CO2,CO3,CO4
      PRINT 57,CONT,SECT,JOB,HWY1,HWY2,XLANE,DM,DAY,YEAR,DYNA
      PRINT 58,(COMM(K),K=1,7),DP
   58 FORMAT(10X,7A4,2X,'PAV. THICK. = ',F5.2,' INCHES' /)
      N = 0
      LO = 0
      DO 15 J=1,5
      AW(J) = 0.0
      SSW(J) = 0.0
      SDW(J) = 0.0
      AWC(J) = 0.0
      SSWC(J) = 0.0
      SDWC(J) = 0.0
   15 CONTINUE
      ASCI = 0.0
      SSSCI = 0.0
      SDSCI = 0.0
      SSSCIC = 0.0
      ASCIC = 0.0
      AAS5 = 0.0
      SSAS5 = 0.0
      SDAS5 = 0.0
      AAP5 = 0.0
      SSAP5 = 0.0
      SDAP5 = 0.0
      AVRMS = 0.0
      R(1) = 100.
      R(2) = 244.
      R(3) = 676.
      R(4) = 1396.
      R(5) = 2404.
      C = .8911
      C1 = 4.5029
      CC = 6.25
      GO TO 10
C     READ & PRINT INFORMATION ON DATA CARD 2
   12 READ(5,3) (LA1(I),I=1,5),T1,(LA2(I),I=1,5),T2,
     * (LA3(I),I=1,5),T3
    3 FORMAT(3X, 5A4,F4.2,5A4,F4.2,5A4,F4.2)
      PRINT 59,(LA1(I),I=1,5),T1,(LA2(I),I=1,5),T2
      PRINT 59, (LA3(I),I=1,5),T3
   59 FORMAT(16X, 5A4,1X,F5.2,5X,5A4,1X,F5.2/)
      GO TO 10
```

```
C     READ & PRINT INFORMATION ON DATA CARD 3,IF PRESENT
   13 READ(5,3)  (LA4(I),I=1,5),T4,(LA5(I),I=1,5),T5,
     * (LA6(I),I=1,5), T6
      PRINT 59,(LA4(I),I=1,5),T4,(LA5(I),I=1,5),T5
      PRINT 59, (LA6(I),I=1,5),T6
      GO TO 10
   23 CONTINUE
      AS5(I) = 55555
      AP5(I) = 55555
      N = N + 1
      IF(ICK .EQ. 0) GO TO 10
      GO TO 80
   22 CONTINUE
      AS5(I) = 7777777
      AP5(I) = 7777777
      N = N + 1
      IF(ICK .EQ. 0) GO TO 10
      GO TO 80
   21 CONTINUE
      AS5(I) = 888888
      AP5(I) = 888888
      N = N + 1
      IF(ICK .EQ. 0) GO TO 10
   80 CONTINUE
      LO = 0
      MNT = 0
      DO 50 I=1,N
      IF(AS5(I) .EQ. 7777777) GO TO 24
      IF(AS5(I) .EQ. 888888) GO TO 25
      IF(AS5(I) .EQ. 55555) GO TO 26
      ISW = ISAVSW(I)
      GO TO (100,200,300,400) , ISW
  100 CONTINUE
      DO 111 K=1,5
      DAP5 = (C/AP5(I)**C1)*(1./R(K)-(1./(R(K) + (CC*AP5(I)**2*DP**2))))
      DAS5 = (C/AS5(I)**C1)*(1./(R(K) + (CC*AP5(I)**2*DP**2)))
      WC(K) = DAP5 + DAS5
      SSWC(K) = SSWC(K) + WC(K)**2
      AWC(K) = AWC(K) + WC(K)
  111 CONTINUE
      SCIC = WC(1) - WC(2)
      SSSCIC = SSSCIC + SCIC**2
      ASCIC = ASCIC + SCIC
      PRINT 63,STA(I),(W(I,J),J=1,5),SCI(I)
   63 FORMAT(7X,A7,1X,6(2X,F5.3))
      PRINT68,(WC(K),K=1,5),SCIC,AS5(I),AP5(I),RMSE(I)
   68 FORMAT(T16,6(2X,F5.3),2(2X,F4.2),T75,F8.4,/)
      GO TO 110
  200 CONTINUE
      PRINT 163,STA(I)
  163 FORMAT(7X,A7,3X,'MIN. RMSE AT A1 LESS THAN RANGE SEARCHED',/)
      MNT = MNT + 2
      LO = LO + 1
      GO TO 50
  300 CONTINUE
      PRINT 263,STA(I)
  263 FORMAT(7X,A7,3X,'MIN. RMSE AT A1 GREATER THAN RANGE SEARCHED',/)
      MNT = MNT + 2
      LO = LO + 1
      GO TO 50
  400 CONTINUE
```

```
      WRITE(6,363) STA(I),RMSE(I),AP5(I)
  363 FORMAT(7X,A7,3X,'MIN.RMSE(',F8.4,') INDICATED AT THE VALUE A1= ',
     *F4.2,/,17X,'AT THIS POINT THE VALUE OF A2 CANNOT BE CALCULATED')
      MNT = MNT + 2
      LO = LO + 1
      GO TO 50
  110 CONTINUE
      AAS5 = AAS5 + AS5(I)
      AAP5 = AAP5 + AP5(I)
      SSAS5 = SSAS5 + AS5(I)**2
      SSAP5 = SSAP5 + AP5(I)**2
      AVRMS = AVRMS + RMSE(I)
      MNT = MNT + 3
      DO 16 M=1,5
      SSW(M) = SSW(M) + W(I,M)**2
   16 AW(M) = AW(M) + W(I,M)
      ASCI = ASCI + SCI(I)
      SSSCI = SSSCI + SCI(I)**2
      IF(MNT .GE. 30) GO TO 31
      GO TO 50
   31 PRINT 51
      PRINT 56,DIST,CO1,CO2,CO3,CO4
   56 FORMAT( T35,'DIST.        COUNTY'/T36,A2,9X,3A4,A2 /)
      PRINT 57, CONT,SECT,JOB,HWY1,HWY2,XLANE,DM,DAY,YEAR,DYNA
   57 FORMAT(T19,'CONT.   SECT.   JOB   HIGHWAY    DATE',
     * '        DYNAFLECT' / T19,A4,5X,A2,5X,A2,2X,A4,2A3,2X,A2,'-',A2,
     *'-',A2,7X,A2,/)
      PRINT 61
      MNT = 0
      GO TO 50
   24 PRINT 65,STA(I),W(I,1),W(I,2)
   65 FORMAT(7X,A7,1X,2(F7.3),2X,'SCI ZERO OR LESS OTHER CALCULATIONS ',
     *'OMMITED',/)
      MNT = MNT + 2
      LO = LO + 1
      GO TO 50
   25 PRINT 66,STA(I)
   66 FORMAT(7X,A7,3X,'ERROR IN DATA',/)
      MNT = MNT + 2
      LO = LO + 1
      GO TO 50
   26 PRINT 361,STA(I),(W(I,J),J=1,5),SCI(I)
  361 FORMAT(7X,A7,1X,6(2X,F5.3))
      PRINT 67,STA(I)
   67 FORMAT(7X,A7,3X,'NOTE DISCONTINUITY IN DEFLECTIONS',/)
      MNT = MNT + 2
      LO = LO + 1
   50 CONTINUE
C     CALCULATE AVERAGES
      N = N - LO
      PN = N
      DO 17 M=1,5
      AWCV(M) = AWC(M) / N
   17 AWV(M) = AW(M) / N
      ASCIV = ASCI / N
      AAP5V = AAP5 / N
      AAS5V = AAS5 / N
      ARMSV = AVRMS / N
      ASCICV = ASCIC / N
      IF(N .LE. 1) GO TO 999
      DO 112 M=1,5
```

```
      SDWC(M) = SQRT((SSWC(M) - (N * (AWCV(M)**2))) / (N - 1 ))
  112 SDW(M) = SQRT((SSW(M) - (N * (AWV(M)**2))) / (N - 1))
      SDSCIC = SQRT((SSSCIC - (N * (ASCICV**2))) / (N-1))
      SDSCI = SQRT((SSSCI - (N * (ASCIV**2))) / (N - 1))
      SDAS5 = SQRT((SSAS5 - (N * (AAS5V**2))) / (N - 1))
      SDAP5 = SQRT((SSAP5 - (N * (AAP5V**2))) / (N - 1))
      PRINT 81,(AWV(J),J=1,5),ASCIV
   81 FORMAT(/,7X,'AVERAGES',6(2X,F5.3))
      PRINT 70,(AWCV(J),J=1,5),ASCICV,AAS5V,AAP5V,ARMSV
   70 FORMAT(T16,6(2X,F5.3),2(2X,F4.2),T75,F8.4,/)
      PRINT 113,(SDW(J),J=1,5),SDSCI
  113 FORMAT(7X,'STD DEV ',6(F7.3))
      PRINT 114,(SDWC(J),J=1,5),SDSCIC,SDAS5,SDAP5
  114 FORMAT(T16,6(2X,F5.3),2(2X,F4.2),/)
      PRINT 82,N
   82 FORMAT(7X,'NUMBER OF POINTS IN AVERAGES ',I3)
  999 CONTINUE
      PRINT 91
   91 FORMAT(/10X,'W1-5  MEASURED DEFLECTIONS AT GEOPHONES 1,2,3,4',
     *' AND 5')
      PRINT 191
  191 FORMAT(16X,'CALCULATED DEFLECTIONS AT GEOPHONES 1,2,3,4 AND 5')
      PRINT 96
   96 FORMAT( 10X,'SCI   SURFACE CURVATURE INDEX ( W1 MIN',
     * 'US W2)'   )
      PRINT 97
   97 FORMAT(10X,'AS5   STIFFNESS COEFFICIENT OF THE SUBGRADE')
      PRINT 98
   98 FORMAT(10X,'AP5   STIFFNESS COEFFICIENT OF THE PAVEMENT')
      PRINT 198
  198 FORMAT(10X,'RMSE  ROOT MEAN SQUARE OF THE ERRORS BETWEEN')
      PRINT 199
  199 FORMAT(16X,'MEASURED AND CALCULATED DEFLECTIONS')
      DO 333 J=1,5
      AWC(J) = 0.0
      SSWC(J) = 0.0
      SDWC(J) = 0.0
      AW(J) = 0.0
      SSW(J) = 0.0
      SDW(J) = 0.0
  333 CONTINUE
      SSSCIC = 0.0
      ASCIC = 0.0
      ASCI = 0.0
      SSSCI = 0.0
      SDSCI = 0.0
      AAS5 = 0.0
      SSAS5 = 0.0
      SDAS5 = 0.0
      AAP5 = 0.0
      SSAP5 = 0.0
      SDAP5 = 0.0
      AVRMS = 0.0
      LO = 0
      N = 0
      GO TO 10
 1000 CONTINUE
      STOP
      END
      SUBROUTINE STIF5(W1,W2,W3,W4,W5,D1,A2,AB,RMS,ISW)
      IMPLICIT REAL*8(A-H,O-Z)
```

```
      DIMENSION A(30),X(5),W(5),R(5),E(5),AO(5),RMSE(30)
      COMMON/D/R,W,N
      N = 5
      W(1) = W1
      W(2) = W2
      W(3) = W3
      W(4) = W4
      W(5) = W5
      C2 = 6.25
      C0 = .8911
      C1 = 4.5029
      B1 = .2709
      R(1) = 100.
      R(2) = 244.
      R(3) = 676.
      R(4) = 1396.
      R(5) = 2404.
      A(1) = .1
      DLTA = .1
      KNT = 0
      JNT = 0
   11 CONTINUE
      DO 20 J=2,20
   20 A(J) = A(J-1) + DLTA
      DO 30 J=1,20
      A1 = A(J)
      DO 40 I=1,N
      T1 = C0 / (A1**C1)
      T2 = 1. / R(I)
      X1 = (A1*D1) * (A1*D1)
      X(I) = 1. / (R(I)+(C2 * X1))
      AO(I) = T1 * (T2 - X(I))
   40 CONTINUE
      SMXW = 0.0
      SMXSQ = 0.0
      SMESQ = 0.0
      DO 50 I=1,N
      SMXW = SMXW + X(I) * (W(I) - AO(I))
   50 SMXSQ = SMXSQ + X(I) * X(I)
      B = SMXW / SMXSQ
      DO 60 I=1,N
      E(I) = W(I) - ((B * X(I)) + AO(I))
   60 SMESQ = SMESQ + E(I) * E(I)
      AMSE = SMESQ / N
      RMSE(J) = DSQRT(AMSE)
   30 CONTINUE
      K = 20
      TEMP1 = RMSE(1)
      ISUB1 = 1
      DO 51 L=1,K
      IF(RMSE(L) .GT. TEMP1) GO TO 51
      TEMP1 = RMSE(L)
      ISUB1 = L
   51 CONTINUE
      IF(ISUB1 .NE. 1) GO TO 41
      ISW = 2
      GO TO 10
   41 CONTINUE
      IF(ISUB1 .NE. 20) GO TO 52
      A(1) = A(ISUB1 - 1)
      KNT = KNT + 1
```

```
      IF(KNT .NE. 3) GO TO 11
      ISW = 3
      GO TO 10
   52 CONTINUE
      Z1 = A(ISUB1 - 1)
      Z2 = A(ISUB1 + 1)
      NOI = 14
      CALL FIBO(NOI,Z1,Z2,AB,RMS,D1)
      CALL ANS(AB,D1,A2)
      IF(A2 .NE. 22222.) GO TO 10
      ISW = 4
   10 CONTINUE
      RETURN
      END
      SUBROUTINE FIBO(N,X1,X2,X,Y,D1)
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION FIB(20)
      FIB(1) = 1.
      FIB(2) = 2.
      FIB(3) = 3.
      FIB(4) = 5.
      FIB(5) = 8.
      FIB(6) = 13.
      FIB(7) = 21.
      FIB(8) = 34.
      FIB(9) = 55.
      FIB(10) = 89.
      FIB(11) = 144.
      FIB(12) = 233.
      FIB(13) = 377.
      FIB(14) = 610.
      FIB(15) = 987.
      FIB(16) = 1597.
      FIB(17) = 2584.
      FIB(18) = 4181.
      FIB(19) = 6769.
      FIB(20) = 10946.
      DX=(X2-X1)/FIB(N)
      XL=X1
      XR=X2
      N=N-1
      X=XL+FIB(N)*DX
      CALL FUNC(X,VR,D1)
    1 N=N-1
      X=XL+FIB(N)*DX
      CALL FUNC(X,VL,D1)
    2 IF(N.EQ.1) GO TO 4
      IF(VL.GT.VR) GO TO 3
      XR=XR-FIB(N)*DX
      VR=VL
      GO TO 1
    3 XL=XL+FIB(N)*DX
      VL=VR
      N=N-1
      X=XR-FIB(N)*DX
      CALL FUNC(X,VR,D1)
      GO TO 2
    4 IF(VL.GT.VR) GO TO 7
      IF(XL.EQ.X1) GO TO 6
    5 X=XL+DX
      Y=VL
```

```
      RETURN
    6 CALL FUNC(X1,V,D1)
      IF(V.GT.VL) GO TO 5
      X=X1
      Y=V
      RETURN
    7 IF(XR.EQ.X2) GO TO 9
    8 X=XR-DX
      Y=VR
      RETURN
    9 CALL FUNC(X2,V,D1)
      IF(V.GT.VR) GO TO 8
      X=X2
      Y=V
      RETURN
      END
      SUBROUTINE ANS(A1,D1,A2)
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION A(30),X(5),W(5),R(5),E(5),AO(5)
      COMMON/D/R,W,N
      C0 = .8911
      C1 = 4.5029
      C2 = 6.25
      B1 = .2709
      DO 1 I=1,N
      T1 = C0 / (A1**C1)
      T2 = 1. / R(I)
      X1 = (A1*D1) * (A1*D1)
      X(I) = 1. / (R(I) + (C2 * X1))
      AO(I) = T1 * (T2 - X(I))
    1 CONTINUE
      SMXW = 0.0
      SMXSQ = 0.0
      SMESQ = 0.0
      DO 2 I=1,N
      SMXW = SMXW + X(I) * (W(I) - AO(I))
    2 SMXSQ = SMXSQ + X(I) * X(I)
      B = SMXW / SMXSQ
      IF(B .GT. 0.0) GO TO 91
      A2 = 22222.
      GO TO 4
   91 CONTINUE
      CA = 1. / C1
      A2 = (C0 / B)**CA
    4 CONTINUE
      RETURN
      END
      SUBROUTINE FUNC(A1,RMS,D1)
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION A(30),X(5),W(5),R(5),E(5),AO(5)
      COMMON/D/R,W,N
      C0 = .8911
      C1 = 4.5029
      C2 = 6.25
      B1 = .2709
      DO 1 I=1,N
      T1 = C0 / (A1**C1)
      T2 = 1. / R(I)
      X1 = (A1*D1) * (A1*D1)
      X(I) = 1. / (R(I) + (C2 * X1))
      AO(I) = T1 * (T2 - X(I))
```

```
  1 CONTINUE
    SMXW = 0.0
    SMXSQ = 0.0
    SMESQ = 0.0
    DO 2 I=1,N
    SMXW = SMXW + X(I) * (W(I) - AO(I))
  2 SMXSQ = SMXSQ + X(I) * X(I)
    B = SMXW / SMXSQ
    DO 60 I=1,N
    E(I) = W(I) - ((B * X(I)) + AO(I))
 60 SMESQ = SMESQ + E(I) * E(I)
    AMSE = SMESQ / N
    RMS = DSQRT(AMSE)
    RETURN
    END
```

NAME DICTIONARY

A	Dummy array used with subroutine CORE to select the correct input format for each card read
AAP5	Sum of pavement stiffness coefficients
AAS5	Sum of subgrade stiffness coefficients
AAP5V	Average pavement stiffness coefficient
AAS5V	Average subgrade stiffness coefficient
AP5	Stiffness coefficient of the pavement
AS5	Stiffness coefficient of the subgrade
ASCI	Sum of (W1 - W2); W1 - W2 = Surface Curvature Index for measured deflections
ASCIC	Sum of (W1 - W2); W1 - W2 = Surface Curvature Index for predicted deflections
ASCIV	Average Surface Curvature Index for measured deflections
ASCICV	Average Surface Curvature Index for predicted deflections
AW	Array of the sums of geophone deflection
AVRMS	Average of RMSE's
AWCV	Average of the predicted deflections
AWV	Average of measured deflections
C	Assigned value of .8911
C1	Assigned value of 4.5029
CC	Assigned value of 6.25
COMM	Comments related to the project
CONT	SDHPT control number
CORE	Subroutine to re-read a card under format control
CO1,CO2,CO3,CO4	County name
D	Array of measured geophone readings and accompanying multipliers

DAP	Pavement stiffness coefficient as calculated in subroutine STIF5
DAS	Subgrade stiffness coefficients as calculated in subroutine STIF5
DATE	An IBM subroutine that returns the current month, day, and year
DAY	Day the deflections were measured
DIST	District number
DP	Total pavement thickness
DYNA	Dynaflect number
HWY 1, HWY 2	Highway name and number
I	Pointer for data read into storage
ICK	Switch to indicate last data card in each section
ISW	Denotes type of message to be printed for each set of deflections not considered valid
ISAVSW	Array for ISW
IXDATE	Return arguments for subroutine DATE (month, day, year)
LA1	Description of material in layer 1
LA2	Description of material in layer 2
LA3	Description of material in layer 3
LA4	Description of material in layer 4
LA5	Description of material in layer 5
LA6	Description of material in layer 6
LO	Counter for data cards not considered
M	Month the deflections were taken
MNT	Counter to control printing of 20 lines per page
N	Counter for number of data cards read

NCARD	Denotes card type 100 = Project identification card 200 = Existing pavement description card (layers 1, 2, 3) 300 = Existing pavement description card (layers 4, 5, 6) 400 = Data card (geophone readings and multipliers)
R	Array of distances from load wheels
REM	Dummy array to allow reading of standard data cards
SECT	SDHPT section number for the highway
STIF5	Subroutine that takes 5 deflections and pavement thickness and returns with values for A1, A2, RMSE and ISW
SCI	Surface Curvature Index (W1 - W2), in mils, for measured deflections
SCIC	Surface Curvature Index ($\hat{W}1$ - $\hat{W}2$), in mils, for predicted deflections
SDAP5	Standard deviation of the pavement stiffness coefficients
SDAS5	Standard deviation of subgrade stiffness coefficients
SDSCI	Standard deviation of the SCI's of measured deflections
SDSCI5	Standard deviation of the SCI's of predicted deflections
SDW	Standard deviation of the measured deflections
SDWC	Standard deviation of the predicted deflections
SSAP5	Sum of the AP5's squared
SSAS5	Sum of the AS5's squared
SSSCI	Sum of measured deflections SCI's squared
SSSCIC	Sum of predicted deflections SCI's squared
SSW	Sum of measured deflections squared
SSWC	Sum of predicted deflections squared
STA	Station number
T1	Layer 1 thickness
T2	Layer 2 thickness
T3	Layer 3 thickness

T4	Layer 4 thickness
T5	Layer 5 thickness
T6	Layer 6 thickness
W	Array of measured geophone deflections
WC	Array of predicted deflections
XLANE	Traffic lane and direction
YEAR	Year the deflections were taken

INPUT GUIDE

The data input format for the main computer program is the same as that used by several previously written computer programs that compute pavement strength properties from Dynaflect data, namely the Texas State Department of Highways and Public Transportation stiffness coefficient program, ELASTIC MODULUS I, and ELASTIC MODULUS II. Each input data card is read into a storage area and the subroutine CORE is used to select the read statement and data format to read each data card. Subroutine CORE allows a FORTRAN program to read under format control from a storage area which contains alphabetic character codes of a card image. Each data card has a code punched in the first three columns that designate the card type.

100 - Card that indicates the beginning of data cards for each job and contains control information about the job, location, date and total pavement thickness.

200 - Card contains word descriptions and thicknesses of the first three layers of the pavement.

300 - Card contains word descriptions and thicknesses of layers 4, 5 and 6 (if present).

400 or blank - Card contains station number and geophone deflection readings and multipliers for each observation. Two digit numbers in columns 75 and 76 of this card denotes end of data.

CARD TYPE 1: PROBLEM IDENTIFICATION

Variable Name	Variable Definition	Format	Column
DIST	SDHPT district number	A2	4-5
C01	Four characters of county name	A4	6-9
C02	Four characters of county name	A4	10-13
C03	Four characters of county name	A4	14-17
C04	Two characters of county name	A2	18-19
CONT	SDHPT control number	A4	20-23
SECT	SDHPT section number	A2	24-25
JOB	SDHPT job number	A2	26-27
HWY1	Four characters of highway number	A4	28-31
HWY2	Three characters of highway number	A3	32-34
XLANE	Lane identification	A3	35-37
DP	Thicknesses of pavement layers 1-4	4F5.3	38-42
DM	Month deflections were measured	A2	43-44
DAY	Day deflections were measured	A2	45-46
YEAR	Year deflections were measured	A2	47-48
DYNA	SDHPT dynalfect number	A2	49-50
COMM	Comments of data recorder	7A4	51-78

CARD TYPE 2: LAYER IDENTIFICATION

Variable Name	Variable Definition	Format	Column
LA1	Name of material in pavement layer one	5A4	4-23
T1	Thickness of layer one	F4.2	24-27
LA2	Name of material in pavement layer two	5A4	28-47
T2	Thickness of layer two	F4.2	48-51
LA3	Name of material in pavement layer three	5A4	52-72
T3	Thickness of layer three	F4.2	73-76

CARD TYPE 3: LAYER IDENTIFICATION

Variable Name	Variable Definition	Format	Column
LA4	Name of material in pavement layer four	5A4	4-23
T4	Thickness of layer four	F4.2	24-27
LA5	Name of material in pavement layer five	5A4	28-47
T5	Thickness of layer five	F4.2	48-51
LA6	Name of material in pavement layer six	5A4	52-72
T6	Thickness of layer six	F4.2	73-76

Note - for a five layer problem, LA5 will be the name of the subgrade material and T5, LA6, and T6 will be blank.

CARD TYPE 4: DEFLECTION DATA

Variable Name	Variable Definition	Format	Column
CONT	SDHPT control number	A4	4-7
SECT	SDHPT section number	A2	8-9
DM	Month deflections were measured	A2	10-11
DAY	Day deflections were measured	A2	12-13
YEAR	Year deflections were measured	A2	14-15
STA	Station (location on highway where deflections were measured)	A7	16-22
D	Dynaflect readings and multipliers	5(F2.1, F3.2)	26-50
RMK	Remarks of data recorder	4A4	59-74
ICK	Check field for last data card	I2	75-76

OUTPUT FORMAT

The output of STIF5 consists of two parts which may include one or more pages per pavement section (depending on the number of deflection measurements per section).

The first part of the output is the input data of the identification information of the pavement section where the surface deflections were measured. This information includes the SDHPT job, control and section number of the pavement section, the highway name and number, date the deflections were measured, total pavement thickness and the materials and thicknesses of the various layers of the pavement.

The second part of the output is a list of the locations (stations) where surface deflections were measured on the pavement section, the observed deflections, followed by the calculated deflections and the subgrade and pavement stiffness coefficients calculated from the observed deflections. Averages and standard deviations of the observed deflections, calculated deflections, and the stiffness coefficients are printed as the final lines of the printed output.

EXAMPLE PROBLEMS

On the following page is a computer printout of the STIF5 program showing the deflection data used and the stiffness coefficients calculated, to illustrate the utilization of STIF5.

TEXAS HIGHWAY DEPARTMENT

DISTRICT 21 - DESIGN SECTION

DYNAFLECT DEFLECTIONS AND CALCULATED STIFFNESS COEFFICIENTS

THIS REVISED PROGRAM (MAR. 74) WAS RUN 101376

DIST.	COUNTY
21	PHARR

CONT.	SECT.	JOB	HIGHWAY	DATE	DYNAFLECT
1234	S1	1	UNKNOWNUNK	3-27-75	99

PAV. THICK. = 32.00 INCHES

HMAC SURFACE	1.00	BLACK BASE	4.00
FLEX. BASE	19.00		
LIME STAB. SUBGRADE	8.00	SUBGRADE	0.0
	0.0		

LOCATION	W1	W2	W3	W4	W5	SCI	AS5	AP5	RMSE
S1	0.285	0.231	0.156	0.123	0.105	0.054			
	0.289	0.219	0.166	0.128	0.098	0.070	0.25	0.58	0.0081
S2	0.380	0.234	0.192	0.135	0.117	0.146			
	0.369	0.260	0.184	0.135	0.101	0.109	0.26	0.53	0.0150
S3	0.330	0.234	0.180	0.123	0.114	0.096			
	0.327	0.240	0.176	0.133	0.101	0.087	0.25	0.55	0.0082
S9	0.350	0.261	0.219	0.171	0.141	0.089			
	0.343	0.275	0.217	0.170	0.133	0.067	0.23	0.60	0.0082
S10	0.420	0.310	0.207	0.165	0.150	0.110			
	0.417	0.308	0.225	0.168	0.126	0.109	0.24	0.53	0.0137
S11	0.450	0.360	0.264	0.225	0.201	0.090			
	0.442	0.363	0.287	0.225	0.174	0.080	0.22	0.58	0.0164
AVERAGES	0.369	0.272	0.203	0.157	0.138	0.097			
	0.365	0.277	0.209	0.160	0.122	0.087	0.24	0.56	0.0116
STD DEV	0.060	0.053	0.037	0.039	0.035	0.030			
	0.057	0.052	0.045	0.037	0.029	0.019	0.01	0.03	

NUMBER OF POINTS IN AVERAGES 6

W1-5	MEASURED DEFLECTIONS AT GEOPHONES 1,2,3,4 AND 5
	CALCULATED DEFLECTIONS AT GEOPHONES 1,2,3,4 AND 5
SCI	SURFACE CURVATURE INDEX (W1 MINUS W2)
AS5	STIFFNESS COEFFICIENT OF THE SUBGRADE
AP5	STIFFNESS COEFFICIENT OF THE PAVEMENT
RMSE	ROOT MEAN SQUARE OF THE ERRORS BETWEEN MEASURED AND CALCULATED DEFLECTIONS

APPENDIX B

DOCUMENTATION OF A METHOD OF COMPUTING STIFFNESS COEFFICIENTS IN MULTI-LAYER PAVEMENTS, COMPUTER PROGRAM SCIMP.

Page

INTRODUCTION

The Flexible Pavement Design System (FPS) developed in Research Study 2-8-62-32 and currently in use in Texas requires a stiffness parameter of the materials to be considered as an input to the computer program (1). Several methods for determining this stiffness parameter (either elastic modulus or stiffness coefficient) of pavement materials have been reported previously (2, 4, 5). This report describes a procedure for finding two unknown stiffness coefficients in an existing pavement consisting of up to five layers.

PROGRAM IDENTIFICATION

Title: Stiffness Coefficients in Multi-layer Pavements (SCIMP)

Language: Fortran IV

Machine: IBM 360/65

Programmer: C.H. Michalak

Availability: Texas Transportation Institute
Pavement Design Program
Texas A&M University
College Station, Texas 77843
Phone (713)845-3735

Date: April, 1975

Source Deck: Approximately 500 cards

Computer Storage: 110k bytes

Timing: (1) Compilation time - 0.40 minutes (Fortran G compiler)
(2) Execution time - 0.25 minutes for 21 data observations

Output: (1) Program list - about 500 lines
(2) Program output - one page per problem (30 lines per page)

DOCUMENTATION OF A METHOD OF COMPUTING STIFFNESS COEFFICIENTS IN SIMPLE TWO LAYER PAVEMENT STRUCTURES USING FIVE OBSERVED SURFACE DEFLECTIONS, COMPUTER PROGRAM STIF5.

PROGRAM DESCRIPTION

For convenience, the computer program used to calculate two unknown stiffness coefficients in a multi-layer pavement is called SCIMP, for Stiffness Coefficients in Multi-layer Pavements.

The computer code for SCIMP is written in FORTRAN for an IBM 360/65 computer. It uses a re-read routine to permit transfer of the input data from a buffer area in core after the appropriate data format has been determined. Any convenient routine that will "read" data from a buffer area can be used or the user can bypass this feature. The data input and the "re-read" feature will be explained more fully on pg. B-10 where the READIT subroutine is described.

The computer code is written to allow for several problems in succession to be run by initially zeroing all counters and internal data storage areas at the start of each new problem. The input data format is common to the Texas State Department of Highways and Public Transportation stiffness coefficient program, ELASTIC MODULUS I, and ELASTIC MODULUS II (2,4,5) computer programs.

Subroutine READIT is called from the main program to read each data card and to compute the observed surface deflections. The deflections are checked for accuracy (W(I) > W(I+1), W(I) > 0) and are passed to subroutine STIF5 where they are used to calculate the two unknown stiffness coefficients. Subroutine STIF5 returns an indicator switch which indicates a valid solution or specifies the condition for which a solution was not found. If a valid solution is indicated, the predicted surface deflections are calculated and the appropriate counters are incremented for determining average values of the observed and predicted deflection data, surface curvature index, stiffness coefficients, RMSE's and the variances of these values. The computer code is repeated until all the data cards for a particular problem have been read and the stiffness coefficients for each set of observed surface deflections have been calculated.

The averages and variances of the observed and predicted surface deflections, surface curvature index, stiffness coefficients, and RMSE's are computed and printed and the program either returns to its beginning to work the next problem or terminates normally.

As many problems as desired can be worked in one run time, with the only limitation being the amount of computer time specified by the user.

SUBROUTINE STIF5

This subroutine creates an array of values of A_1, the unknown pavement stiffness coefficient, from which the Fibonacci search routine determines the A_1 value which gives the minimum RMSE within the accuracy limits specified.

The code is written so that a range of A_1 values from 0.1 to 7.4 in 0.1 increments will be used to calculate a root mean square error, RMSE, between the observed and the predicted surface deflections.

Subroutine DELTA is called to calculate the f_i and F_i terms from equations (5) and (6) for any A_1 value being used and the RMSE is calculated and stored. After the predetermined number of A_1 values have been used to calculate RMSE's, the smallest RMSE value is found. The A_1 values of the RMSE's which bracket this smallest RMSE are used as the range of values for a Fibonacci search to find the A_1 value that gives the minimum RMSE within the accuracy limits specified.

Subroutine ANS is then called to calculate the stiffness coefficient of the subgrade from equation (9). Subroutine STIF5 then returns to the main program with an indicator switch which tells if the solution is a valid answer or indicates the conditions for which a solution was not obtained.

SUBROUTINE FIBO

This subroutine utilizes a Fibonacci search technique to determine the A_1 value that gives the minimum RMSE.

Since the absolute minimum RMSE will likely be different from the smallest RMSE selected from the array of RMSE's calculated in subroutine STIF5, the A_1 values that bracket this smallest RMSE value are used as the range for a Fibonacci search to find the true minimum RMSE.

The Fibonacci search technique is a convergence scheme based on the Fibonacci number series to search for a minimum between two points (16). The two points that define the range of the search are the A_1 values of the RMSE's that bracket the smallest RMSE found in subroutine STIF5.

SUBROUTINE ANS

The subgrade coefficient, A_5, is calculated in this subroutine. After the A_1 value of the pavement coefficient giving the minimum RMSE is found by the Fibonacci search routine, this value is used in subroutine DELTA to calculate the f_i and F_i terms from equations (5) and (6). Equation (5) is transformed to solve for B_o as shown below:

$$B_o = \frac{\sum_{i=1}^{5} (\hat{w}_i - f_i)}{\sum_{i=1}^{5} F_i}$$

From equation (9), the subgrade coefficient is calculated after the following transformation has been made:

$$A_5 = \left(\frac{C_o}{B_o}\right)^{\frac{1}{C_1}} \qquad (4)$$

SUBROUTINE FUNC

This subroutine is used with the Fibonacci search to calculate the RMSE value for each trial value of A_1.

Subroutine DELTA is called to calculate the f_i and F_i terms used in calculating the predicted deflections, $\hat{w}_i$, from equations (5) and (6). B_o is calculated from equation (6), except the observed surface deflections w are used instead of $\hat{w}$. With B_o, and f_i and F_i terms known, the predicted deflections are calculated from equation (5). The RMSE between the observed surface deflections and the predicted surface deflections is calculated and is tested in the Fibonacci search routine to determine if the RMSE value obtained with the current A_1 value is within the accuracy limits specified.

SUBROUTINE READIT

The input data cards are read and the program output headings are printed in this subroutine.

The main program calls subroutine READIT to read each data card. The data cards are of four types, according to the code numbers punched in the first three columns of the data card. The code numbers and card types are defined below:

100 - the card contains identification information such as county name, SDHPT control, section, and job number, highway name and location, date deflections were taken, the individual layer thicknesses, and the known coefficients

200 - the names of the materials in the first three pavement layers are given on this card

300 - the names of the materials in layers four, five, and six (if present) are given on this card

400 - the card contains the dynaflect sensor readings and multipliers used to calculate the pavement surface deflections at an individual location (the first three columns can also be left blank on these cards).

Each data card is read into an array or buffer storage area as eighty individual character variables. The card code is tested and the particular data input format corresponding to the card code is selected. A subroutine called CORE is then called to transmit the data from the buffer area according to the variable names and the data format. Any convenient routine that will "re-read" data cards from a buffer area according to a data format can be used instead of subroutine CORE. It is also possible to avoid using subroutine CORE by having a blank card with the same card code preceding the actual data card and reading the data cards directly into the program. This is more desirable for small amounts of data as the use of subroutine CORE or any other re-read routine adds greatly to the computer time needed to work a problem.

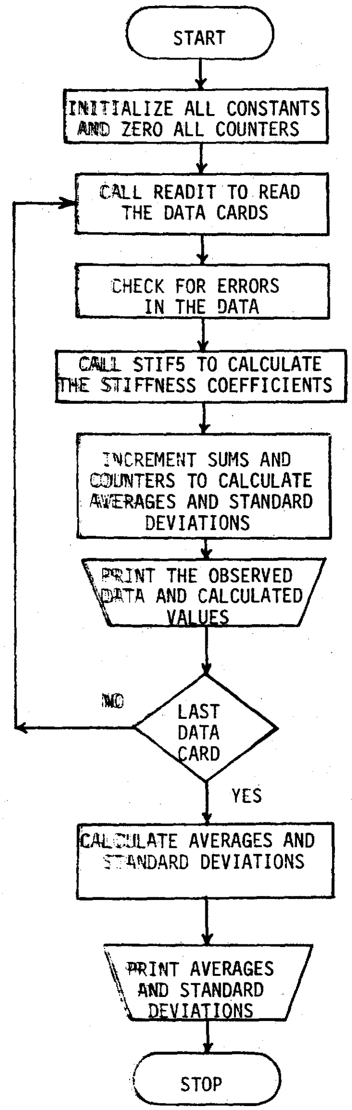
As the header and layer identification cards are read the information on these cards is printed on the program output. The Dynaflect sensor readings are converted to the pavement surface deflections and these values are returned to the main program.

SUBROUTINE DELTA

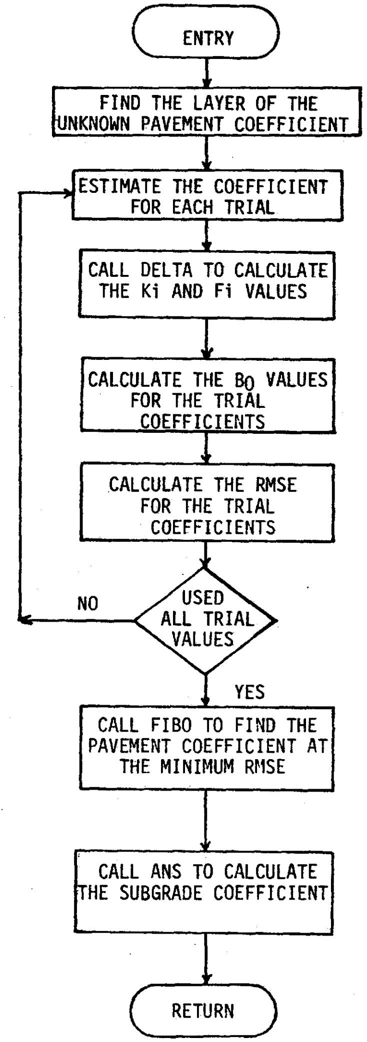
The subroutine calculates the f_i and F_i terms of equations (5) and (6) for each trial value of A_1 used.

FLOWCHART

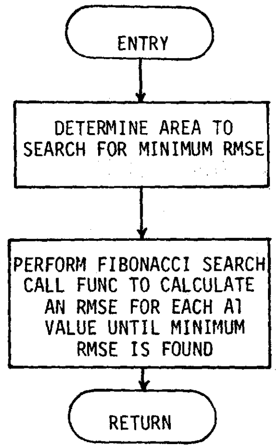
SCIMP
(MAIN)



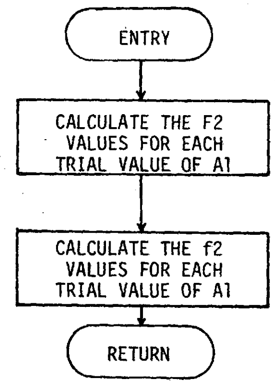
STIF5



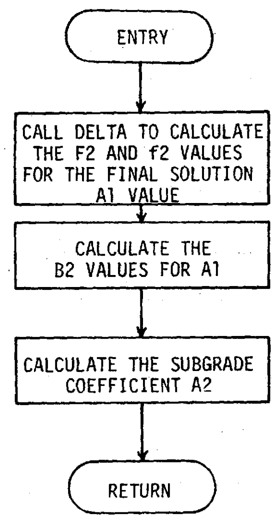
FIBO



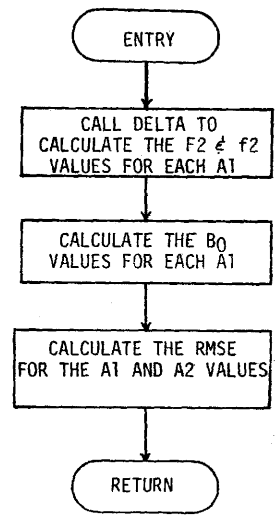
DELTA



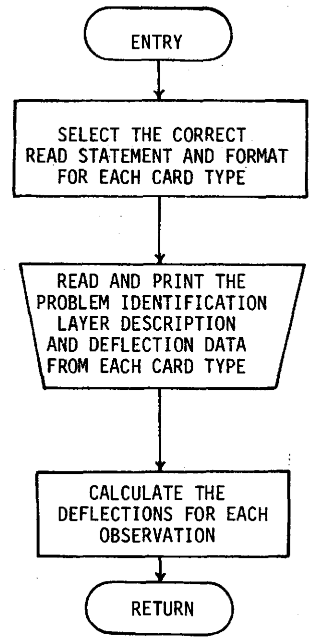
ANS



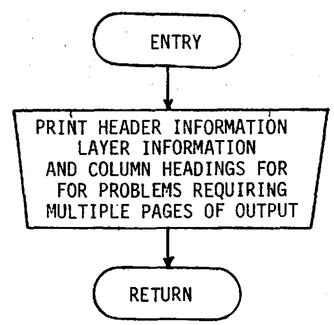
FUNC



READIT



HEADNG



PROGRAM LISTING

```
C
C
      IMPLICIT REAL*8(A-H,O-Z)
C
      DIMENSION AW(5), AWC(5), AVGCOF(5), COEF(5), DCOF(3), DP(4),
     * SAD(5), SDW(5), SDWC(5), SDCOF(5), SMCOF(5), SSW(5), SSWC(5),
     + SSCOF(5), W(5), WC(5)
      DIMENSION AWV(5), AWCV(5), COF(5)
      COMMON /FIB1/ FIB(20)
      COMMON /CONS/ C, C1, CC
      COMMON /RAD/ R(5)
      COMMON /POINT/ IUNK
C
      ROUND( X,EVEN ) =IDINT( ( X + EVEN * .5 ) / EVEN )
     * *  EVEN
C
      R(1) = 100.
      R(2) = 244.
      R(3) = 676.
      R(4) = 1396.
      R(5) = 2404.
      C = .8911
      C1 = 4.5029
      CC = 6.25
      FIB(1) = 1.0
      FIB(2) = 2.0
      DO  1 J = 3, 20
      FIB(J) = FIB(J-1) + FIB(J-2)
    1 CONTINUE
C
    5 CONTINUE
C
      N = 0
      LINES = 0
      DO 10 J = 1, 5
      AW(J) = 0.0
      SSW(J) = 0.0
      AWC(J) = 0.0
      SSWC(J) = 0.0
      SMCOF(J) = 0.0
      SSCOF(J) = 0.0
   10 CONTINUE
      ASCI = 0.0
      SSSCI = 0.0
      SSSCIC = 0.0
      ASCIC = 0.0
      AVRMS = 0.0
C
   15 CONTINUE
      CALL READIT( W, DP, COEF, STA, ICK )
C
C     CHECK FOR ERRORS IN THE DATA
C
      DO 17 J = 1, 4
      IF( W(J) .EQ. 0.0 ) GO TO 30
      IF( W(J) .LT. W(J+1) ) GO TO 32
   17 CONTINUE
      IF( W(5) .EQ. 0.0 ) GO TO 30
      ISW = 1
      CALL STIF5( W, DP, COEF, RMSE, ISW )
      GO TO (100,200,300,400) , ISW
```

```
100 CONTINUE
    N = N + 1
    SAD(1) = 0.0
    DO 19 J = 2, 5
    SAD(J) = (DSQRT(SAD(J-1))+COEF(J-1)*DP(J-1))**2
 19 CONTINUE
    DO 20 K = 1, 5
    DCOF(K) = (C/COEF(K) ** C1)
    WC(K) = 0.0
 20 CONTINUE
    DO 26 K = 1, 5
     COF(1) = DCOF(1) * (1./R(K) - (1./(R(K) + CC * SAD(1))))
    DO 22 J = 2, 4
     COF(J) = DCOF(J) * (1./(R(K) + CC * SAD(J)) - (1./(R(K) +
   =  CC * SAD(J+1))))
 22 CONTINUE
     COF(5) = DCOF(5) * (1./(R(K) + CC * SAD(5)))
    DO 24 J = 1, 5
    WC(K) = WC(K) +  COF(J)
 24 CONTINUE
 26 CONTINUE
    DO 28 I = 1, 5
    SMCOF(I) = SMCOF(I) + COEF(I)
    SSCOF(I) = SSCOF(I) + COEF(I) ** 2
    AWC(I) = AWC(I) + WC(I)
    SSWC(I) = SSWC(I) + WC(I)**2
    SSW(I) = SSW(I) + W(I) ** 2
    AW(I) = AW(I) + W(I)
 28 CONTINUE
    AVRMS = AVRMS + RMSE
    SCI = W(1) - W(2)
    ASCI = ASCI + SCI
    SSSCI = SSSCI + SCI ** 2
    SCIC = WC(1) - WC(2)
    SSSCIC = SSSCIC + SCIC**2
    ASCIC = ASCIC + SCIC
    PRINT 63, STA, (W(J), J = 1, 5), SCI
 63 FORMAT(7X,A7,1X,6(2X,F5.3))
    PRINT 68, (WC(K),K=1,5), SCIC, (COEF(K),K=1,5), RMSE
 68 FORMAT(T16,6(F7.3),5(F6.2),F13.4,/)
    COEF(IUNK) = 0.0
    COEF(5) = 0.0
    LINES = LINES + 2
    GO TO 34
 30 CONTINUE
    PRINT 65, STA, W(1), W(2)
 65 FORMAT(7X,A7,1X,2(F7.3),2X,'SCI ZERO OR LESS OTHER CALCULATIONS ',
   *'OMMITED',/)
    LINES = LINES + 2
    GO TO 34
 32 CONTINUE
    PRINT 66, STA
 66 FORMAT(7X,A7,3X,'ERROR IN DATA',/)
    LINES = LINES + 2
 34 CONTINUE
    IF( LINES .LT. 30 ) GO TO 36
    LINES = 0
    IPRT = 2
    CALL HEADNG( IPRT )
 36 CONTINUE
    IF( ICK .EQ. 0 ) GO TO 15
```

```
C       CALCULATE AVERAGES
        PN = N
        DO 38 M = 1, 5
        AVGCOF(M) = SMCOF(M)/N
        AWV(M) = AW(M)/N
        AWCV(M) = AWC(M)/N
   38 CONTINUE
        ASCIV = ASCI / N
        ARMSV = AVRMS / N
        ASCICV = ASCIC / N
        IF( N .LE. 1 ) GO TO 42
        DO 40 M = 1, 5
        SDCOF(M) =DSQRT((SSCOF(M) - (N * (AVGCOF(M)**2)))/(N-1))
        SDWC(M) =DSQRT((SSWC(M) - (N * (AWCV(M)**2))) / (N - 1 ))
        SDW(M) =DSQRT((SSW(M) - (N * (AWV(M)**2))) / (N - 1))
   4) CONTINUE
        SDSCIC =DSQRT((SSSCIC - (N * (ASCICV**2))) / (N-1))
        SDSCI =DSQRT((SSSCI - (N * (ASCIV**2))) / (N - 1))
        PRINT 81,(AWV(J),J=1,5),ASCIV
   81 FORMAT(/,7X,'AVERAGES',6(2X,F5.3))
        PRINT 70, (AWCV(J),J=1,5), ASCICV, (COEF(J),J=1,5),ARMSV
   70 FORMAT( T16, 6(2X,F5.3), 5(2X,F4.2), 5X, F8.4 / )
        PRINT 113,(SDW(J),J=1,5),SDSCI
  113 FORMAT(7X,'STD DEV ',6(F7.3))
        PRINT 114, (SDWC(J),J=1,5), SDSCIC, (SDCOF(J),J=1,5)
  114 FORMAT( T16, 6(2X,F5.3), 5(2X,F4.2), 5X, F8.4 / )
        PRINT 82,N
   82 FORMAT(7X,'NUMBER OF POINTS IN AVERAGES ',I3)
C
   42 CONTINUE
C
        PRINT 91
   91 FORMAT(/10X,'W1-5  MEASURED DEFLECTIONS AT GEOPHONES 1,2,3,4',
     *' AND 5')
        PRINT 191
  191 FORMAT(16X,'CALCULATED DEFLECTIONS AT GEOPHONES 1,2,3,4 AND 5')
        PRINT 96
   96 FORMAT( 10X,'SCI   SURFACE CURVATURE INDEX ( W1 MIN',
     * 'US W2)'    )
        PRINT 97
   97 FORMAT(10X,'AS5   STIFFNESS COEFFICIENT OF THE SUBGRADE')
        PRINT 98
   98 FORMAT(10X,'AP5   STIFFNESS COEFFICIENT OF THE PAVEMENT')
        PRINT 298
  298 FORMAT( 10X, 'ASS5   STIFFNESS COEFFICIENT OF STAB. SUBGRADE')
        PRINT 398
  398 FORMAT( 10X, 'ASB5  STIFFNESS COEFFICIENT OF SUB-BASE')
        PRINT 498
  498 FORMAT( 10X, 'AB5   STIFFNESS COEFFICIENT OF BASE' )
        PRINT 198
  198 FORMAT(10X,'RMSE  ROOT MEAN SQUARE OF THE ERRORS BETWEEN')
        PRINT 199
  199 FORMAT(16X,'MEASURED AND CALCULATED DEFLECTIONS')
        GOTOS
  200 CONTINUE
        PRINT 163, STA
  163 FORMAT(7X,A7,3X,'MIN. RMSE AT A1 LESS THAN RANGE SEARCHED',/)
        LINES = LINES + 2
        GO TO 34
  300 CONTINUE
        PRINT 263, STA
```

```
263 FORMAT(7X,A7,3X,'MIN. RMSE AT A1 GREATER THAN RANGE SEARCHED',/)
    LINES = LINES + 2
    GO TO 34
400 CONTINUE
    PRINT 363, STA, RMSE, COEF(1)
363 FORMAT(7X,A7,3X,'MIN.RMSE(',F8.4,') INDICATED AT THE VALUE A1= ',
   *F4.2,/,17X,'AT THIS POINT THE VALUE OF A2 CANNOT BE CALCULATED')
    LINES = LINES + 2
    GO TO 36
    END
    SUBROUTINE STIF5( W, DP, COEF, RMS,  ISW )
    IMPLICIT REAL*8(A-H,O-Z)
    DIMENSION A(30), AO(5), E(5), RMSE(30), W(5), X(5) , COEF(5)
    DIMENSION DP(4)
    COMMON/POINT/IUNK
    N = 5
    A(1) = .1
    DLTA = .1
    KNT = 0
    JNT = 0
    DO 4 I = 1, 4
    IF( COEF(I) .EQ. 0.0 ) GO TO 5
  4 CONTINUE
  5 CONTINUE
    IUNK = I
 11 CONTINUE
    DO 20 J=2,20
 20 A(J) = A(J-1) + DLTA
    DO 30 J=1,20
    COEF( IUNK ) = A(J)
    CALL DELTA( AO, COEF, DP, X )
    SMXW = 0.0
    SMXSQ = 0.0
    SMESQ = 0.0
    DO 22 I = 1, N
    SMXW = SMXW + X(I) * (W(I) - AO(I))
    SMXSQ = SMXSQ + X(I) * X(I)
 22 CONTINUE
    B = SMXW / SMXSQ
    DO 25 I = 1, N
    E(I) = W(I) - ((B * X(I)) + AO(I))
    SMESQ = SMESQ + E(I) * E(I)
 25 CONTINUE
    AMSE = SMESQ / N
    RMSE(J) = DSQRT(AMSE)
 30 CONTINUE
    K = 20
    TEMP1 = RMSE(1)
    ISUB1 = 1
    DO 35 L = 1, K
    IF(RMSE(L) .GT. TEMP1) GO TO 35
    TEMP1 = RMSE(L)
    ISUB1 = L
 35 CONTINUE
    IF(ISUB1 .NE. 1) GO TO 41
    ISW = 2
    GO TO 80
 41 CONTINUE
    IF(ISUB1 .NE. 20) GO TO 52
    A(1) = A(ISUB1 - 1)
    KNT = KNT + 1
```

```
      IF(KNT .NE. 3) GO TO 11
      ISW = 3
      GO TO 80
   52 CONTINUE
      Z1 = A(ISUB1 - 1)
      Z2 = A(ISUB1 + 1)
      NOI = 14
      CALL FIBO( NOI, Z1, Z2, AB, RMS, DP, COEF ,W )
      CALL ANS( AB, DP, COEF, A2 , W )
      IF( A2 .NE. 22222. ) GO TO 70
      ISW = 4
   70 COEF(5) = A2
   80 CONTINUE
      COEF(IUNK) = AB
      RETURN
      END
      SUBROUTINE FIBO ( N, X1, X2, X, Y, D,S , W )
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION D(4), S(5) ,W(5)
      COMMON /FIB1/ FIB(20)
      COMMON/POINT/IUNK
      DX=(X2-X1)/FIB(N)
      XL=X1
      XR=X2
      N=N-1
      X=XL+FIB(N)*DX
      S(IUNK)=X
      CALL FUNC(X,VR,D, S , W)
    1 N=N-1
      X=XL+FIB(N)*DX
      S(IUNK)=X
      CALL FUNC(X, VL, D, S , W )
    2 IF(N.EQ.1) GO TO 4
      IF(VL.GT.VR) GO TO 3
      XR=XR-FIB(N)*DX
      VR=VL
      GO TO 1
    3 XL=XL+FIB(N)*DX
      VL=VR
      N=N-1
      X=XR-FIB(N)*DX
      S(IUNK)=X
      CALL FUNC(X, VR, D, S , W )
      GO TO 2
    4 IF(VL.GT.VR) GO TO 7
      IF(XL.EQ.X1) GO TO 6
    5 X=XL+DX
      Y=VL
      RETURN
    6 CONTINUE
      S(IUNK)=X1
      CALL FUNC(X1, V, D, S , W )
      IF(V.GT.VL) GO TO 5
      X=X1
      Y=V
      RETURN
    7 IF(XR.EQ.X2) GO TO 9
    8 X=XR-DX
      Y=VR
      RETURN
    9 CONTINUE
```

```
      S(IUNK)=X2
      CALL FUNC(X2, V, D, S , W )
      IF(V.GT.VR) GO TO 8
      X=X2
      Y=V
      RETURN
      END
      SUBROUTINE ANS( A1, DP, COEF, A2, W )
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION A(30), AO(5), COEF(5), DP(4), W(5), X(5)
      COMMON /CONS/ C0, C1, C2
      N = 5
      CALL DELTA( AO, COEF, DP, X )
      SMXW = 0.0
      SMXSQ = 0.0
      SMESQ = 0.0
      DO 20 I = 1, N
      SMXW = SMXW + X(I) * (W(I) - AO(I))
   20 SMXSQ = SMXSQ + X(I) * X(I)
      B = SMXW / SMXSQ
      IF(B .GT. 0.0) GO TO 30
      A2 = 22222.
      GO TO 40
   30 CONTINUE
      CA = 1. / C1
      A2 = (C0 / B)**CA
   40 CONTINUE
      RETURN
      END
      SUBROUTINE FUNC( A1, RMS, DP, COEF, W )
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION A(30), AO(5), COEF(5), DP(4), E(5), W(5), X(5)
      N = 5
      CALL DELTA( AO, COEF, DP, X )
      SMXW = 0.0
      SMXSQ = 0.0
      SMESQ = 0.0
      DO 20 I = 1, N
      SMXW = SMXW + X(I) * (W(I) - AO(I))
   20 SMXSQ = SMXSQ + X(I) * X(I)
      B = SMXW / SMXSQ
      DO 60 I=1,N
      E(I) = W(I) - ((B * X(I)) + AO(I))
   60 SMESQ = SMESQ + E(I) * E(I)
      AMSE = SMESQ / N
      RMS = DSQRT(AMSE)
      RETURN
      END
      SUBROUTINE READIT( W, DP, COEF, STA, ICK )
      IMPLICIT REAL*8( A-H,O-Z)
      DIMENSION A(20),COEF(5),COMM(7),D(10),DP(4),LA1(5),LA2(5),LA3(5),
     1LA4(5),LA5(5),LA6(5),REM(4), W(5)
      COMMON/HEAD/      CO1,CO2,CO3,CO4,CONT,DAY, DIST,DM,    DYNA,HWY1,
     * HWY2, SECT, XLANE, YEAR, JOB
C
    1 CONTINUE
C
      READ(5,1234,END=1000)  NCARD, ( A(I), I = 1 , 20 )
 1234 FORMAT( I3, 19A4,A1 )
C     CALL  CORE  ( A,  80 )
      IF(NCARD.EQ.100) GO TO 11
```

```
      IF(NCARD.EQ.200) GO TO 12
      IF(NCARD.EQ.300) GO TO 13
   14 CONTINUE
      READ(5,6) CONT,SECT,DM,DAY,YEAR,STA    ,(D(K),K=1,10),
     * (REM(J),J=1,4), ICK
    6 FORMAT(3X, A4,4A2,A7,3X,5(F2.1,F3.2),8X,4A4,I2)
      L = 1
      DO 4 J=1,5
      W(J) = D(L)*D(L+1)
      L = L + 2
    4 CONTINUE
      RETURN
   11 READ(5,2) DIST,CO1,CO2,CO3,CO4,CONT,SECT,JOB,HWY1,HWY2,XLANE,
     *DM,DAY,YEAR,DYNA,(COMM(I),I=1,7), (DP(J), J=1,4),(COEF(J),J=1,5)
    2 FORMAT(3X, A2, 3A4,A2,A4,A2,A2,A4,A3,A3, 5X, 4A2,7A4/35X, 9F5.2 )
      IPRT = 1
      CALL HEADNG( IPRT )
      PRINT58,(DP(J),COEF(J),J=1,4),COEF(5)
58    FORMAT(8X,'PAV.',10X,'BASE',8X,'SUBBASE',6X,'STAB SUB',8X,'SUBGRAD
     *E'/ 7X, 4('THICK  COEF.   '), '     COEF.' /4X,4(F8.2,F6.2), F8.2/)
   61 FORMAT(/,7X,'LOCATION    W1      W2      W3      W4      W5      SCI
     *AS5  ASS5  ASB5   AB5   AP5          RMSE   ' / )
      GO TO 1
C     READ & PRINT INFORMATION ON DATA CARD 2
   12 READ(5,3) (LA1(I),I=1,5),T1,(LA2(I),I=1,5),T2,
     * (LA3(I),I=1,5),T3
    3 FORMAT(3X, 5A4,F4.2,5A4,F4.2,5A4,F4.2, 5A4, F4.2 )
      PRINT 59,(LA1(I),I=1,5),T1,(LA2(I),I=1,5),T2,(LA3(I),I=1,5), T3
   59 FORMAT(16X, 5A4,1X,F5.2,5X,5A4,1X,F5.2, 5X, 5A4, 1X, F5.2 / )
      GO TO 1
C     READ & PRINT INFORMATION ON DATA CARD 3,IF PRESENT
   13 READ(5,3)   (LA4(I),I=1,5),T4,(LA5(I),I=1,5),T5,
     * (LA6(I),I=1,5), T6
      PRINT 59,(LA4(I),I=1,5),T4,(LA5(I),I=1,5),T5,(LA6(I),I=1,5), T6
      PRINT 61
      GO TO 1
 1000 CONTINUE
      PRINT 250
  250 FORMAT( '1' )
      STOP
      END
      SUBROUTINE DELTA(AO,COEF,DP,X)
      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION AO(5), COEF(5), DEL(5,5), DP(4), SUM(5), X(5)
      COMMON /CONS/ C0, C1, C2
      COMMON /RAD/ R(5)
      N = 5
      DO 2 K = 1, 4
      SUM(K) = 0.0
      DO 1 L = 1, K
      SUM(K) = SUM(K) +  COEF(L) * DP(L)
    1 CONTINUE
      SUM(K) = SUM(K) * SUM(K)
    2 CONTINUE
      DO 4 I = 1, N
      AO(I) = 0.0
      DEL(I,1) = C0/(COEF(1)**C1) * (1./R(I) - 1./(R(I) + C2 * SUM(1)))
      AO(I) = AO(I) + DEL(I,1)
      DO 3 K = 2, 4
      DEL(I,K) = (C0/(COEF(K))**C1) * (1./(R(I) + C2 * SUM(K-1)) -
     = 1./(R(I) + C2 * SUM(K)))
```

```
      AO(I) = AO(I) + DEL(I,K)
    3 CONTINUE
      X(I) = 1./(R(I) + C2 * SUM(4))
    4 CONTINUE
      RETURN
      END
      SUBROUTINE HEADNG( IPRT )
      IMPLICIT REAL*8 (A-H,O-Z)
      COMMON/HEAD/     C01,C02,C03,C04,CONT,DAY, DIST,DM,    DYNA,HWY1,
     * HWY2, SECT, XLANE, YEAR, JOB
      DIMENSION IXDATE(2)
      GO TO ( 50, 70), IPRT
   50 CONTINUE
      PRINT 51
   51 FORMAT( '1' )
      PRINT 52
   52 FORMAT(35X,'TEXAS HIGHWAY DEPARTMENT' /)
      PRINT 53,DIST
   53 FORMAT(33X,'DISTRICT ',A2,' - DESIGN SECTION' /)
      PRINT 54
   54 FORMAT(18X,'DYNAFLECT DEFLECTIONS AND CALCULATED ',
     *'STIFFNESS COEFFICIENTS'/)
C     CALL DATE(IXDATE)
C     PRINT 55,IXDATE
C  55 FORMAT(24X,'THIS REVISED PROGRAM (APR. 75) WAS RUN ',2A4/)
      PRINT 56,DIST,C01,C02,C03,C04
   56 FORMAT( T35,'DIST.        COUNTY'/T36,A2,9X,3A4,A2 /)
      PRINT 57, CONT,SECT,JOB,HWY1,HWY2,XLANE,DM,DAY,YEAR,DYNA
   57 FORMAT(T19,'CONT.    SECT.    JOB    HIGHWAY     DATE',
     * '        DYNAFLECT' / T19,A4,5X,A2,5X,A2,2X,A4,2A3,2X,A2,'-',A2,
     *'-',A2,7X,A2,/)
      RETURN
   70 CONTINUE
      PRINT 51
      PRINT 56,DIST,C01,C02,C03,C04
      PRINT 57,CONT,SECT,JOB,HWY1,HWY2,XLANE,DM,DAY,YEAR,DYNA
      PRINT 61
   61 FORMAT(/,7X,'LOCATION    W1      W2      W3      W4      W5      SCI
     *AS5  ASS5  ASB5   AB5   AP5         RMSE   ' / )
      RETURN
      END
```

NAME DICTIONARY

MAIN PROGRAM VARIABLES

ARMSV - Average RMSE value

ASCI - Sum of SCI (surface curvature index, W1-W2) of the observed surface deflections in mils

ASCIC - Sum of SCI of the calculated surface deflections, mils

ASCICV - Average SCI of calculated surface deflections, mils

ASCIV - Average SCI of measured surface deflections, mils

AVGCOF - Array of the average stiffness coefficient values

AVRMS - Sum of RMSE values

AW - Array of sums of the observed surface deflections, mils

AWC - Array of sums of the calculated surface deflections, mils

AWCV - Array of average values of the calculated surface deflections, mils

AWV - Array of average values of the observed surface deflections, mils

C - A constant in the deflection equation, value 0.8911

CC - A constant in the deflection equation, value 6.25

CI - A constant in the deflection equation, value 4.5029

COEF - Array of the known and unknown stiffness coefficients

COF - Array containing the individual terms of the deflection equation used to calculate the pavement surface deflections

DCOF - A part of the deflection equation defined as $\frac{C_o}{A_i^{C_1}}$

DP - Array of the pavement layer thicknesses, inches

FIB - Array of the Fibonacci numbers used in the Fibonacci search routine

ICK - A non-zero number punched on the last data card to signal the end of the data for a problem

IPRT - Indicates which output headings are to be printed by subroutine HEADING

ISW - Indicates a valid solution for each set of surface deflections, or is used to select a message to be printed to indicate why a solution was not obtained

IUNK - The subscript in the array COEF of the unknown pavement coefficient

LINES - Counter to control number of lines printed on a page

N - The total number of data points for which valid solutions were obtained

NLAY - The total number of layers in the pavement design (subgrade counts as one layer)

NL1 - Number of pavement layers above the subgrade

R - Array of the squared distances of the dynaflect sensors from the dynaflect load, inches

RMSE - Root mean square error between the observed surface deflections, W_i and the calculated surface deflections $\hat{W}_i$

SAD - Array of the squared terms (A_i*D_i) used in the deflection equation to obtain the calculated surface deflections

SCI - Surface curvature index, W_1-W_2, in mils

SDCOF - Array of the standard deviations of the stiffness coefficients

SDSCI - Standard deviation of the surface curvature index of the observed surface deflections

SDSCIC - Standard deviation of the surface curvature index of the calculated surface deflections

SDW - Standard deviation of the observed surface deflections

SDWC - Standard deviation of the calculated surface deflections

SMCOF - Array of the sums of the stiffness coefficients

SSCOF - Array of the sums of the squared values of the stiffness coefficients

SSSCI - Sum of the squared values of surface curvature index of the observed surface deflections

SSSCIC - Sum of the squared values of surface curvature index of the calculated surface deflections

STA - Identifies location of each set of surface pavement deflection observations

SSW - Array of the squared values of the observed surface deflections

SSWC - Array of the squared values of the calculated surface deflections

W - Array of the values of the observed surface deflections, mils

WC - Array of the values to the calculated surface deflections, mils

SUBROUTINE STIF5 VARIABLES

A - Array of initial values of the unknown pavement stiffness coefficient

AB - The value of the unknown pavement stiffness coefficient that gives the minimum RMSE within the accuracy limits specified

AO - Array of the f_i terms for each trial value of the unknown stiffness coefficient, (equation 5)

A2 - The value of the unknown subgrade stiffness coefficient calculated from the final solution value for the unknown pavement stiffness coefficient, AB

AMSE - The root mean square error (RMSE) for a trial value of the unknown pavement stiffness coefficient

B - A trial value of B_o (equation 6)

COEF - Array of the known and unknown stiffness coefficients

DLTA - Incremental value used in selecting the initial values of the unknown pavement stiffness coefficient

DP - Array containing values of the pavement layer thicknesses, in inches

E - The error (W_i-$\hat{W}_i$) between the observed surface deflections and the calculated surface deflections

ISUB1 - Pointer to the smallest RMSE of the initial set of unknown pavement stiffness coefficient values tried

ISW - Indicates a valid solution for each set of surface deflections or is used to select a message to be printed to indicate why a solution was not obtained

IUNK - The subscript in the COEF array of the unknown pavement coefficient

K - Counter to control the number of trial values of the unknown stiffness coefficient to be tried

KNT - Counter to control the number of times the Fibonacci search is used before the search is abandoned

N - Number of surface pavement deflections observed at each measurement location

NLAY - The number of layers (including the subgrade) in the pavement section

NL1 - The number of pavement layers above the subgrade in the pavement section

NO1 - Determines the level of precision of the answer found by the Fibonacci search

RMSE - Root mean square error between the observed and calculated surface deflections for a trial value of the unknown pavement stiffness coefficient

SMESQ - Sum of the squared values of $(W_i - \hat{W}_i)$

SMXSQ - Sum of the $f_i * (W_i - F_i)$ values squared

SMXW - Sum of the $f_i * (W_i - F_i)$ values

TEMP1 - Contains the value of the smallest RMSE of the initial values of the unknown stiffness coefficient tried

W - Array of the observed surface deflections, mils

X - Array of the F_i values for each trial value of the unknown stiffness coefficient, (equation 5)

Z1 - Value of the RMSE just preceeding the smallest RMSE

Z2 - Value of the RMSE just following the smallest RMSE

SUBROUTINE FIBO VARIABLES

D - Array of the pavement layer depths, in inches

DX - The incremental amount to change the unknown stiffness coefficient in the Fibonacci search to find the minimum RMSE

FIB - An array of Fibonacci numbers used in the Fibonacci search routine

IUNK - Pointer to the unknown pavement stiffness coefficient in the COEF array

N - Determines the level of precision of the answer found by the Fibonacci search

NLAY - Total number of layers in the pavement section, including the subgrade

NL1 - Number of pavement layers above the subgrade

S - Array of the known and unknown stiffness coefficients

V - An RMSE calculated from a value of the unknown stiffness coefficient selected in the Fibonacci search

VL - The RMSE value from the Fibonacci search when a value of the unknown stiffness coefficient just smaller than the current value of the unknown stiffness coefficient is tried

VR - The RMSE value from the Fibonacci search when a value of the unknown stiffness coefficient just larger than the current value of the unknown stiffness coefficient is tried

W - Array of the observed surface deflections, in mils

X - The value of the unknown stiffness coefficient selected by the Fibonacci search

XL - The lower limit of values of the unknown stiffness coefficient to be searched

XR - The upper limit of values of the unknown stiffness coefficient to be searched

X1 - The lower limit of values of the unknown stiffness coefficient to be searched

X2 - The upper limit of values of the unknown stiffness coefficient to be searched

Y - An RMSE calculated from a value of the unknown stiffness coefficient selected in the Fibonacci search

SUBROUTINE ANS VARIABLES

A0 - Array of the F_i terms (equation [5]) for the solution value of the unknown pavement stiffness coefficient

A2 - The value of the unknown subgrade stiffness coefficient calculated from the final solution value for the unknown pavement stiffness coefficient

B - The final solution value of B_0 after the unknown pavement stiffness coefficient has been found

CA - A constant, value is 1./4.5029

C0 - A constant, value is 0.8911

C2 - A constant, value is 6.25

COEF - Array of the known stiffness coefficients, including the final solution value of the unknown pavement stiffness coefficient

DP - Array of the pavement layer thicknesses, in inches

N - Number of pavement surface deflections observed at each measurement point

SMESQ - Sum of the squared values of $(W_i-\hat{W}_i)$

SMXW - Sum of $f_i*(W_i-F_i)$ values

W - Array of the observed surface deflections, in mils

X - Array of the F_i values, (equation 5)

SUBROUTINE FUNC VARIABLES

AO - Array of the F_i terms (equation [5]) for any value of the unknown stiffness coefficient

AMSE - The root mean square error (RMSE) for a trial value of the unknown pavement stiffness coefficient

B - A trial value of B_o (equation [6])

COEF - Array of the known and unknown stiffness coefficients

DP - Array of the pavement layer thicknesses, in inches

E - The error $(W_i - \hat{W}_i)$ between the observed surface deflections and the calculated surface deflections

N - Number of surface pavement deflections observed at each measurement point

RMS - The root mean square error (RMSE) for a trial value of the unknown stiffness coefficient

SMESQ - Sum of the squared values of $(W_i - \hat{W}_i)$

SMXSQ - Sum of the squared values of $F_i*(W_i - K_i)$

SMXW - Sum of the $f_i*(W_i - F_i)$ values

W - Array of the observed surface deflections, mils

X - Array of the f_i terms, (equation 5)

SUBROUTINE READIT VARIABLES

A - Array for storing each card image as individual character variables for the in core transfer of data under format control routine (Subroutine CORE)

C01, C02, C03, C04 - A fourteen column field for the county name

COEF - Array of the known stiffness coefficients with the unknown stiffness coefficients left blank or entered as zeroes

COMM - A twenty-eight column field for any comments concerning the deflections

CONT - The SDHPT control number

D - Array of the dynaflect sensor readings and multipliers for calculating the surface deflections, in mils

DAY - Day of month the deflections were measured

DIST - The SDHPT district number

DM - Month the deflections were measured

DP - Array of the pavement layer thicknesses, in inches

DYNA - The SDHPT dynaflect number

HWY1, HWY2 - A seven column field for the highway name

ICK - A non zero value to indicate the last data card for each problem

IPRT - Indicates which output headings are to be printed in subroutine HEADING

IUNK - Pointer to the unknown pavement stiffness coefficient in the COEF array

JOB - The SDHPT job number

LA1 - Name of material in first pavement layer

LA2 - Name of material in second pavement layer

LA3 - Name of material in third pavement layer

LA4 - Name of material in fourth pavement layer

LA5 - Name of material in fifth pavement layer

LA6 - Name of material in sixth pavement layer

NCARD - Code indicating type of card, header, layer identification, or deflection data

NLAY	- Total number of pavement layers (including the subgrade) in the pavement section
NL1	- Number of pavement layers above the subgrade
REM	- A sixteen column field on each deflection data card for appropriate remarks
SECT	- The SDHPT section number
STA	- Identifies location of each set of surface pavement deflection observations
T1	- Thickness of pavement layer one, in inches
T2	- Thickness of pavement layer two, in inches
T3	- Thickness of pavement layer three, in inches
T4	- Thickness of pavement layer four, in inches
T5	- Thickness of pavement layer five, in inches
T6	- Thickness of pavement layer six, in inches
W	- Array of the pavement surface deflections, in mils
XLANE	- Identifies the lane the deflections were measured in
YEAR	- Year the deflections were measured

SUBROUTINE DELTA VARIABLES

AO	- Array of the F_i terms (equation [5]) for any value of the unknown stiffness coefficient
COEF	- Array of the known and unknown stiffness coefficients
CO	- A constant, value of 0.8911
C1	- A constant, value of 4.5029
C2	- A constant, value of 6.25
DEL	- Array of the terms used in the calculation of the F_i terms, (equation 5)
DP	- Array of the pavement layer thicknesses, in inches
IUNK	- Pointer to the unknown pavement stiffness coefficient in the COEF array
N	- Number of surface pavement deflections observed at each measurement location
NLAY	- Total number of layers (including the subgrade) in the pavement section
NL1	- Total number of pavement layers above the subgrade
R	- Array of the squared distances of the dynaflect sensors from the dynaflect load, inches
SUM	- Array of A_i*D_i terms used in calculating the F_i terms, (equation 5)
X	- Array of the f_i terms (equation [5]) for any value of the unknown stiffness coefficient used

SUBROUTINE HEADNG VARIABLES

CO1, CO2, CO3, CO4 - A fourteen column field containing the county name

CONT - The SDHPT control number

DAY - Day of the month the deflections were measured

DIST - The SDHPT district number

DM - The month the deflections were measured

DYNA - The SDHPT dynaflect number

HWY1, HWY2 - A seven column field for the highway name

IPRT - Indicates which output headings are to be printed

IXDATE - The date the problem was run

JOB - The SDHPT job number

SECT - The SDHPT section number

XLANE - Identifies the lane the deflections were measured in

YEAR - The year the deflections were measured

INPUT GUIDE

The SCIMP computer program is written to solve one or more problems in each run of the program. The input data for each problem is a set of data cards containing information pertinent to each problem. Each data set is made up of the card types shown in the input guide tables. Each card type is identified by the card code punched in the first three columns of the card. The card types and the information contained on them are listed below:

Card type 1 contains problem identification information and has card code 100 punched in the first three columns. The identification information consists of the SDHPT district number, county name, SDHPT control, section and job number, the highway number, the lane direction, the month, day and year the deflections were measured, the SDHPT dynaflect number, and any comments by the data recorder. Additional information contained on a second card is the pavement layer thicknesses and the known values of stiffness coefficients. Although card type 1 consists of two cards, the information is read as though it were contained on one card.

The second card type has code number 200 punched in the first three columns. It contains the names and thicknesses of the materials in the first three pavement layers.

Card type 3 has code 300 punched in the first three columns. It contains the names and thicknesses of the materials in pavement layers four, five, and six (if these are present).

Card type 4 has code 400 punched in the first three columns, or the card code field can be left blank if desired. This card contains the SDHPT control and section numbers, the month, day, and the year the deflections were measured, the station number (location on the highway) where the deflections were measured, the dynaflect geophone readings and multipliers, and any remarks listed by the data recorder. The card containing the last data observation for each problem has a check field which is coded with any non-blank characters or digits to signal the end of data for each problem.

The normal data input deck for each problem will be one card type 1, one card type 2, one card type 3 and N card types 4, where N is the number of surface deflection observations for the problem. The N^{th} or last card type 4 will have the check field coded to signal the end of data for the problem.

CARD TYPE 1: PROBLEM IDENTIFICATION

Variable Name	Variable Definition	Format	Column
DIST	SDHPT district number	A2	4-5
CO1	Four characters of county name	A4	6-9
CO2	Four characters of county name	A4	10-13
CO3	Four characters of county name	A4	14-17
CO4	Two characters of county name	A2	18-19
CONT	SDHPT control number	A4	20-23
SECT	SDHPT section number	A2	24-25
JOB	SDHPT job number	A2	26-27
HWY1	Four characters of highway number	A4	28-31
HWY2	Three characters of highway number	A3	32-34
XLANE	Lane identification	A3	35-37
DM	Month deflections were measured	A2	43-44
DAY	Day deflections were measured	A2	45-46
YEAR	Year deflections were measured	A2	47-48
DYNA	SDHPT dynalfect number	A2	49-50
COMM	Comments of data recorder	7A4	51-78
	SECOND CARD		
DP	Thicknesses of pavement layers 1-4	4F5.2	36-55
COEF	Values of the known stiffness coefficients (zeroes or blanks indicate unknown values)	5F5.2	56-75

CARD TYPE 2: LAYER IDENTIFICATION

Variable Name	Variable Definition	Format	Column
LA1	Name of material in pavement layer one	5A4	4-23
T1	Thickness of layer one	F4.2	24-27
LA2	Name of material in pavement layer two	5A4	28-47
T2	Thickness of layer two	F4.2	48-51
LA3	Name of material in pavement layer three	5A4	52-72
T3	Thickness of layer three	F4.2	73-76

CARD TYPE 3: LAYER IDENTIFICATION

Variable Name	Variable Definition	Format	Column
LA4	Name of material in pavement layer four	5A4	4-23
T4	Thickness of layer four	F4.2	24-27
LA5	Name of material in pavement layer five	5A4	28-47
T5	Thickness of layer five	F4.2	48-51
LA6	Name of material in pavement layer six	5A4	52-72
T6	Thickness of layer six	F4.2	73-76

Note - for a five layer problem, LA5 will be the name of the subgrade material and T5, LA6, and T6 will be blank.

CARD TYPE 4: DEFLECTION DATA

Variable Name	Variable Definition	Format	Column
CONT	SDHPT control number	A4	4-7
SECT	SDHPT section number	A2	8-9
DM	Month deflections were measured	A2	10-11
DAY	Day deflections were measured	A2	12-13
YEAR	Year deflections were measured	A2	14-15
STA	Station (location on highway where deflections were measured)	A7	16-22
D	Dynaflect readings and multipliers	5(F2.1, F3.2)	26-50
RMK	Remarks of data recorder	4A4	59-74
ICK	Check field for last data card	I2	75-76

OUTPUT FORMAT

The printed output of program SCIMP consists of two parts, the identification information of the pavement section and the deflection data (both observed and calculated values).

The identification information includes the SDHPT job, control and section numbers, the highway name and number, county and district number, the thickness of all pavement layers, the stiffness coefficient values, and the materials in each pavement layer.

The deflection data is listed by location or station where each deflection measurement was made and consists of the observed surface deflections followed by the calculated deflections and the stiffness coefficients (the known and calculated values).

The averages and standard deviations of the deflections (observed and calculated) and the stiffness coefficients are printed as the last line of the output.

EXAMPLE PROBLEMS

On the following page is a computer printout of the SCIMP program showing the deflection data used and the stiffness coefficients calculated to illustrate the utilization of SCIMP.

TEXAS HIGHWAY DEPARTMENT

DISTRICT 21 - DESIGN SECTION

DYNAFLECT DEFLECTIONS AND CALCULATED STIFFNESS COEFFICIENTS

DIST.	COUNTY
21	PHARR

CONT.	SECT.	JOB	HIGHWAY	DATE	DYNAFLECT
1234	S1	1	UNKNOWNUNK	3-27-75	99

PAV. THICK	COEF.	BASE THICK	COEF.	SUBBASE THICK	COEF.	STAB SUB THICK	COEF.	SUBGRADE COEF.
1.00	0.75	4.00	0.0	19.00	0.40	8.00	0.30	0.0

HMAC SURFACE	1.00	BLACK BASE	4.00	FLEX. BASE	19.00
LIME STAB. SUBGRADE	8.00	SUBGRADE	0.0		0.0

LOCATION	W1	W2	W3	W4	W5	SCI	AP5	AB5	ASB5	ASS5	AS5	RMSE
S1	0.285	0.231	0.156	0.123	0.105	0.054						
	0.277	0.236	0.171	0.121	0.087	0.041	0.75	1.71	0.40	0.30	0.27	0.0111
S2	0.380	0.234	0.192	0.135	0.117	0.146						
	0.354	0.282	0.188	0.127	0.088	0.072	0.75	1.30	0.40	0.30	0.27	0.0277
S3	0.330	0.234	0.180	0.123	0.114	0.096						
	0.313	0.260	0.181	0.126	0.089	0.053	0.75	1.51	0.40	0.30	0.27	0.0175
S9	0.350	0.261	0.219	0.171	0.141	0.089						
	0.327	0.291	0.224	0.167	0.125	0.036	0.75	1.92	0.40	0.30	0.24	0.0183
S10	0.420	0.310	0.207	0.165	0.150	0.110						
	0.403	0.330	0.229	0.158	0.112	0.073	0.75	1.33	0.40	0.30	0.26	0.0228
S11	0.450	0.360	0.264	0.225	0.201	0.090						
	0.426	0.379	0.295	0.220	0.165	0.047	0.75	1.81	0.40	0.30	0.23	0.0252
AVERAGES	0.369	0.272	0.203	0.157	0.138	0.098						
	0.350	0.296	0.215	0.153	0.111	0.054	0.75	0.0	0.40	0.30	0.0	0.0204
STD DEV	0.060	0.053	0.037	0.039	0.035	0.030						
	0.056	0.052	0.046	0.038	0.030	0.016	0.0	0.26	0.00	0.00	0.02	

NUMBER OF POINTS IN AVERAGES 6

W1-5	MEASURED DEFLECTIONS AT GEOPHONES 1,2,3,4 AND 5
	CALCULATED DEFLECTIONS AT GEOPHONES 1,2,3,4 AND 5
SCI	SURFACE CURVATURE INDEX (W1 MINUS W2)
AS5	STIFFNESS COEFFICIENT OF THE SUBGRADE
AP5	STIFFNESS COEFFICIENT OF THE PAVEMENT
ASS5	STIFFNESS COEFFICIENT OF STAB. SUBGRADE
ASB5	STIFFNESS COEFFICIENT OF SUB-BASE
AB5	STIFFNESS COEFFICIENT OF BASE
RMSE	ROOT MEAN SQUARE OF THE ERRORS BETWEEN MEASURED AND CALCULATED DEFLECTIONS