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16. Abstract

This report gives the theoretical background and a description of a new computer program, which is capable of converting routine Dynaflect deflection measurements obtained on the surface of a two-layer highway pavement system, to give the elastic moduli of the pavement and subgrade layers.

A description of the program and several solutions to example problems are included with the report. The program has been designed to operate at less cost and to eliminate fitting problems encountered in similar existing programs.

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ELASTIC MODULI DETERMINATION
for
SIMPLE TWO-LAYER PAVEMENT STRUCTURES
BASED ON SURFACE DEFLECTIONS

by

William M. Moore

Research Report Number 136-5
Design and Evaluation of Flexible Pavements
Research Study 2-8-69-136

Sponsored by

The Texas Highway Department
In Cooperation with the
U. S. Department of Transportation
Federal Highway Administration

August, 1973

TEXAS TRANSPORTATION INSTITUTE
Texas A&M University
College Station, Texas

Preface

This is the fifth report issued under Research Study 2-8-69-136, "Design and Evaluation of Flexible Pavements," being conducted at the Texas Transportation Institute as part of the cooperative research program with the Texas Highway Department and the Department of Transportation, Federal Highway Administration.

Previous reports from this study are as follows:

(1) "Seasonal Variations of Pavement Deflections in Texas," by Rudell Poehl and Frank H. Scrivner, Research Report 136-1, Texas Transportation Institute, January, 1971.

(2) "A Technique for Measuring the Displacement Vector throughout the Body of a Pavement Structure Subjected to Cyclic Loading," by William M. Moore and Gilbert Swift, Research Report 136-2, Texas Transportation Institute, August, 1971.

(3) "A Graphical Technique for Determining the Elastic Moduli of a Two-Layered Structure from Measured Surface Deflections," by Gilbert Swift, Research Report 136-3, Texas Transportation Institute, November, 1972.

(4) "An Empirical Equation for Calculating Deflections on the Surface of a Two-Layered Elastic System," by Gilbert Swift, Research Report 136-4, Texas Transportation Institute, November, 1972.

The author wishes to thank the many members of the Institute who contributed to this research. Special appreciation is expressed to Mr. Gerald Turman, who wrote the computer program and description in Appendix A, Mr. Danny Y. Lu, who wrote Subroutine FIBO, and Messrs. F. H. Scrivner, Gilbert Swift and C. H. Michalak who provided valuable advice and assistance in many phases of the research.

The support given by the Texas Highway Department is also appreciated, particularly that of Messrs. James L. Brown and L. J. Buttler who suggested the subject of this report.

The contents of this report reflect the views of the author who is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification or regulation.

Abstract

This report gives the theoretical background and a description of a new computer program, which is capable of converting routine Dynaflect deflection measurements obtained on the surface of a two-layer highway pavement system, to give the elastic moduli of the pavement and subgrade layers.

A description of the program and several solutions to example problems are included with the report. The program has been designed to operate at less cost and to eliminate fitting problems encountered in similar existing programs.

Key Words: Deflection, Pavement Evaluation, Elastic Modulus, Nondestructive testing.

Summary

A technique is described for determining the elastic moduli for two-layer highway pavement structures from field deflection measurements. This technique is based upon the "best fit" of the entire measured deflection basin; therefore, the moduli are believed to be more representative of in-situ material properties than those obtained by other existing techniques.

Through an illustrative example, it is shown that the five deflection measurements conventionally made with the Dynaflect are not sufficient to determine a unique set of elastic moduli for some typical highway pavement structures. It is also shown that this ambiguity can be eliminated by taking one additional deflection measurement closer to the load wheels.

A computer program designed to compute moduli from routine deflection measurements is given in Appendix A.

Implementation Statement

A new computer program has been written to permit rapid inexpensive calculation of the elastic moduli of two-layer pavement structures from routine field-measured pavement deflections. These in-situ elastic modulus values are significant for pavement evaluation purposes and are expected to be required in future pavement design systems.

It is recommended that an observation be added to routine field deflection measurements in order to eliminate ambiguities found in the evaluation of some typical highway pavements.

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1. Introduction

This report presents a technique for determining the elastic modulus for each layer in a simple two-layered pavement structure. The thickness of the top layer is known (or measured) and the thickness of the lower layer is assumed to be infinite. The basic concept is to determine the set of values E_1 and E_2 (elastic modulus of pavement subgrade, respectively) which will best predict a measured surface deflection basin in accordance with layered elastic theory.

The technique is somewhat similar to that developed previously by Scrivner, Michalak and Moore (1,2), the chief differences being that the present technique is more rapid and uses the "best fit" of the entire measured deflection basin rather than two arbitrarily selected points of the basin. It is more rapid because it employs the simple empirical equation developed by Swift (3) instead of a conventional, rigorous, mathematical technique for two elastic layers like that developed by Scrivner, et al. The two techniques are similar in that they both assume a point load on a two-layer elastic pavement structure for which the thickness of the top layer is known. Both determine the elastic moduli for the two layers and assume that the layers have a Poisson's ratio of 0.5.

2. Method of Approach

Deflection predictions are based upon the empirical equation given below which was developed by Swift (3).

$$\hat{w} = \frac{3P}{4\pi E_1}\left[\frac{1}{r} + \left(\frac{E1}{E_2} - 1\right)\left(\frac{1}{x} + \frac{a^2}{2x^3} + \frac{3a^4}{2x^5}\right)\right] \qquad (1)$$

in which $x = \sqrt{r^2 + a^2}$

$a = 2h \sqrt[3]{\frac{1}{3}\left(2 + E_1/E_2\right)}$

and P = magnitude of point load

r = horizontal distance from loading point

h = thickness of upper layer

E_1, E_2 = elastic modulus of upper and lower layers respectively

$\hat{w}$ = predicted surface deflection at r

Swift found this equation to closely approximate surface deflections computed using rigorous elastic theory with a Poisson's ratio of 0.5. In this equation deflection is expressed as a function of the following five independent variables: P, r, h, E_1, and E_2. When deflections of a simple pavement structure of known thickness are measured with the Dynaflect, the first three independent variables are known and the last two are unknown. Thus, if one finds the set of values of E_1 and E_2 that best predicts the measured deflections, w_i, these values can be assumed to represent the elastic moduli for the two layers. The criterion selected for determination of the "best fit" is that the root mean square error, RMSE, be minimized, i.e.,

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(w_i - \hat{w}_i\right)^2} \quad \text{is minimum value.}$$

Equation 1 can be written in the following generalized form.

$$\hat{w} = B_o \cdot f\ (r, h, B_1) + \varepsilon \qquad (2)$$

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

$B_1 = E_1/E_2$ and

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

The RMSE is minimized by use of the following step-by-step procedure.

1. A trial value of B_1 is selected.
2. Five values of the function, f, are computed, one for each of the five standard values of r (r = 10.0", 15.6", 26.0", 37.4" and 49.0").
3. B_o is computed using the following equation to obtain the least RMSE for the trial value of B_1.

   $$B_o = \sum_{i=1}^{5} w_i f_i \Big/ \sum_{i=1}^{5} f_i^2$$

4. The RMSE is computed, using the value of B_o computed in step 3.

   $$\text{RMSE} = \sqrt{\frac{1}{5} \sum_{i=1}^{5} \left(w_i - \hat{w}_i\right)^2}$$

5. Steps 1 through 4 are repeated using the search process described below until the values of B_o and B_1 are found which result in minimizing the RMSE.
6. The elastic moduli for the individual layers are then computed using the following equations.

   $$E_1 = \frac{3000}{4\pi B_o}$$

   $$E_2 = \frac{3000}{4\pi B_o B_1}$$

The search process consists of calculating the values of RMSE for each of 21 logarithmically spaced trial values of B_1, which cover the entire range of reasonable values of the ratio, E_1/E_2. These values sufficiently define the RMSE versus B_1 curve to determine the one or two ranges for B_1 within which minima of RMSE occur. The location of the minimum within a range is found to an accuracy of 0.5 percent employing a Fibonacci search technique (4).

In fitting two-layer elastic systems to normal Dynaflect measurements, it is often difficult to distinguish between two alternate sets of elastic moduli which result in similar deflection basins. This problem occurs because there are many cases where two entirely different pairs of elastic moduli will provide nearly equal values of deflections in the range of the standard measurements (r values between 10 and 49 inches). In such cases both alternate sets are determined. A typical example of such a difficult distinction is shown in Table 1. In this table , measured deflection values and sets of computed deflection values for two different pairs of elastic moduli are shown. Both computed sets reasonably predict the measured deflections and are almost alike in the normal measuring range (r = 10 to 49 inches). Figure 1 contains a log-log plot of RMSE versus the trial values of B_1 obtained as described in steps 1 through 4 above. Two distinct minimums are apparent which represent the cases compared in Table 1.

Based upon the step-by-step procedure described previously, a new computer program was developed to determine the "best fit" set of values for the pavement and subgrade moduli. In cases like the example the two

Table 1: Comparison of two cases for predicting measured deflections

		Case 1		Case 2	
r	w	$\hat{w}$	$w-\hat{w}$	$\hat{w}$	$w-\hat{w}$
10.0	1.86	1.83	0.03	1.90	-0.04
15.6	1.35	1.43	-0.08	1.28	0.07
26.0	0.90	0.90	0.00	0.91	-0.01
37.4	0.63	0.60	0.03	0.66	-0.03
49.0	0.50	0.44	0.06	0.51	-0.01

RMSE	0.051	0.038
E_1	195,600 psi	3,600 psi
E_2	11,700 psi	9,400 psi
h	7.5 in	7.5 in

Note: r = horizontal distance in inches

w = measured Dynaflect deflection in 0.001 inches

$\hat{w}$ = predicted deflection in 0.001 inches (from Equation 1) alternate "best fit" sets of moduli are determined. The new program is somewhat similar to several other existing programs used to compute pavement layer stiffness parameters from routine Dynaflect data. Three such existing programs, (1) The Texas Highway Department stiffness coefficient program, (2) Elastic Modulus I and (3) Elastic Modulus II (1,2,5), evaluate the layer stiffness parameters required to precisely fit two points on the measured deflection basin. As might be expected, the calculated basins which result from those programs often have rather large prediction errors at locations removed from the fitted points. The "best fit" technique employed in the new program, "Two-Layer Elastic Moduli for Five Deflections," eliminates this problem and thus is believed to more nearly represent the true material properties within an existing pavement structure insofar as elasticity theory applies to such structures. In addition, the new program has been found to be about ten times faster than the Elastic Modulus programs. Appendix A contains a description and a computer listing of this program.

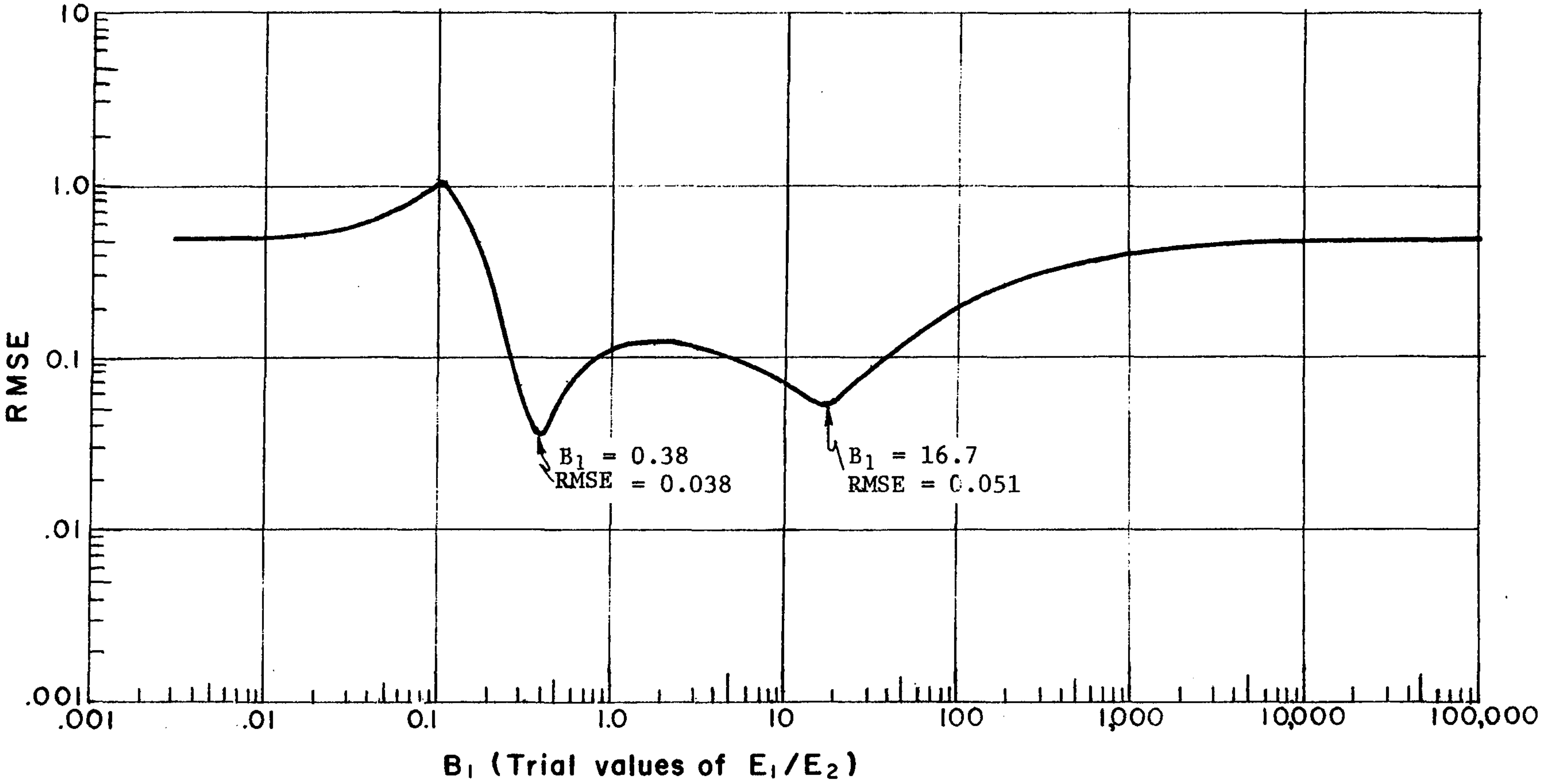

Figure 1: B_1 versus RMSE for typical pavement having alternate possible sets of elastic moduli.

3. Example Solutions

Tables 2a through 2g are computer print-outs based upon the same data used in References 1 and 2. These tables can be compared directly with Tables 6a through 6g in Reference 1 and Tables 5a through 5g in Reference 2. Such a comparison is made in Table 3. Note in this table that six of the seven comparisons appear to have two possible "best fit" solutions based upon the new program.

Table 4 contains solutions based upon the new program for eleven test points taken on rigid pavements at the Houston Intercontinental Airport. These solutions are based upon the same data reported in Reference 2. A direct comparison with the results of Reference 2 is made in Table 5.

```
                              TEXAS HIGHWAY DEPARTMENT

                             DISTRICT 17 - DESIGN SECTION

                DYNAFLECT DEFLECTIONS AND CALCULATED ELASTIC MODULI

                           THIS PROGRAM WAS RUN - 08/28/73

                                DIST.        COUNTY
                                 17          BRAZOS

              CONT.    SECT.    JOB    HIGHWAY     DATE       DYNAFLECT
              1560      1        1     FM 1687   5-21-68          1

                                       PAV. THICK. = 12.50 INCHES

            SEAL COAT                 0.50     RED SANDY GRAVEL     12.00

            GREY & BRWN SAND SUB  0.0

STATION     W1     W2     W3     W4     W5     SCI   ** ES    ** ** EP    **   * RMSE *

 1 - A     1.170 0.770 0.520 0.310 0.219 0.400      20000.      28000.      0.0252
 1 - B     1.140 0.770 0.510 0.310 0.213 0.370      20400.      32400.      0.0221
 2 - A     1.290 0.840 0.490 0.300 0.204 0.450      18700.      18400.      0.0334
 2 - B     1.200 0.840 0.490 0.300 0.201 0.360      19500.      27700.      0.0311
 3 - A     1.140 0.770 0.470 0.300 0.195 0.370      20700.      27100.      0.0214
 3 - B     1.110 0.770 0.460 0.300 0.201 0.340      21000.      30800.      0.0176
 4 - A     1.470 0.960 0.490 0.320 0.222 0.510      16500.      14100.      0.0546
 4 - B     1.380 0.900 0.470 0.310 0.213 0.480      17600.      15200.      0.0458
 5 - A     1.290 0.870 0.500 0.340 0.231 0.420      18300.      21900.      0.0202
 5 - B     1.260 0.800 0.460 0.310 0.219 0.460      19200.      16900.      0.0198

AVERAGES
 W'S,SCI  1.245 0.829 0.486 0.310 0.212 0.416
 POINTS      10    10    10    10    10    10
 STIFF ON TOP SOLUTIONS                             19983.      27983.
 POINTS                                                 6           6
 SOFT ON TOP SOLUTIONS                              18000.      16150.
 POINTS                                                 4           4

   W1     DEFLECTION AT GEOPHONE 1
   W2     DEFLECTION AT GEOPHONE 2
   W3     DEFLECTION AT GEOPHONE 3
   W4     DEFLECTION AT GEOPHONE 4
   W5     DEFLECTION AT GEOPHONE 5
   SCI    SURFACE CURVATURE INDEX ( W1 MINUS W2)
   ES     ELASTIC MODULUS OF THE SUBGRADE FROM W1,W2,W3,W4,& W5
   EP     ELASTIC MODULUS OF THE PAVEMENT FROM W1,W2,W3,W4,& W5
```

Table 2a: Computer print-out for Section 3.

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                         TEXAS HIGHWAY DEPARTMENT

                       DISTRICT 17 - DESIGN SECTION

            DYNAFLECT DEFLECTIONS AND CALCULATED ELASTIC MODULI

                     THIS PROGRAM WAS RUN - 08/28/73

                          DIST.       COUNTY
                           17         BRAZOS

          CONT.   SECT.   JOB   HIGHWAY    DATE      DYNAFLECT
          2824      2      1    FM 2776   5-21-68        1

                                PAV. THICK. =  8.00 INCHES

        SEAL COAT              0.50     ASPHALT STAB. GRAVEL  7.50

        GREY SANDY CLAY SUBG  0.0

STATION    W1     W2     W3     W4     W5     SCI   ** ES   ** ** EP   **   * RMSE *

 1 - A   1.650 1.200 0.870 0.660 0.500 0.450      12000.     293100.      0.0702
         ALTERNATE SOLUTION                        9200.       2800.      0.0409
 1 - B   1.560 1.110 0.810 0.610 0.490 0.450      12900.     299900.      0.0761
         ALTERNATE SOLUTION                        9900.       3000.      0.0297
 2 - A   2.310 1.470 0.930 0.710 0.530 0.840       9200.       5100.      0.0161
 2 - B   2.310 1.410 0.900 0.670 0.510 0.900       9700.       6300.      0.0270
 3 - A   2.430 1.500 0.930 0.670 0.490 0.930       9700.       8100.      0.0213
 3 - B   2.490 1.530 0.930 0.670 0.500 0.960       9600.       9000.      0.0254
 4 - A   2.490 1.470 0.900 0.640 0.480 1.020       9900.      10200.      0.0497
 4 - B   2.430 1.410 0.840 0.610 0.470 1.020      10300.      11100.      0.0625
 5 - A   2.340 1.440 0.870 0.620 0.450 0.900      10400.      10900.      0.0250
 5 - B   2.430 1.470 0.930 0.650 0.470 0.960       9800.       8800.      0.0331

AVERAGES
 W'S,SCI 2.244 1.401 0.891 0.651 0.489 0.843
 POINTS     10    10    10    10    10    10
 STIFF ON TOP SOLUTIONS                           11100.    125040.
 POINTS                                               5          5
 SOFT ON TOP SOLUTIONS                             9586.      6157.
 POINTS                                               7          7

   W1    DEFLECTION AT GEOPHONE 1
   W2    DEFLECTION AT GEOPHONE 2
   W3    DEFLECTION AT GEOPHONE 3
   W4    DEFLECTION AT GEOPHONE 4
   W5    DEFLECTION AT GEOPHONE 5
   SCI   SURFACE CURVATURE INDEX ( W1 MINUS W2)
   ES    ELASTIC MODULUS OF THE SUBGRADE FROM W1,W2,W3,W4,& W5
   EP    ELASTIC MODULUS OF THE PAVEMENT FROM W1,W2,W3,W4,& W5
```

Table 2b: Computer print-out for Section 4.

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                         TEXAS HIGHWAY DEPARTMENT

                       DISTRICT 17 - DESIGN SECTION

              DYNAFLECT DEFLECTIONS AND CALCULATED ELASTIC MODULI

                      THIS PROGRAM WAS RUN - 08/28/73

                        DIST.       COUNTY
                         17         BURLESON

          CONT.    SECT.    JOB    HIGHWAY     DATE         DYNAFLECT
          1399       1       1     FM 1361    5-21-68           1

                                   PAV. THICK. = 12.00 INCHES

        SEAL COAT                0.50     LIME STAB. SANDSTONE 11.50

        TAN SANDY CLAY SUBGR   0.0

 STATION   W1     W2     W3     W4     W5     SCI   ** ES   ** ** EP   **  * RMSE *

  1 - A   1.500 1.110 0.710 0.470 0.330 0.390      14600.     44600.      0.0096
  1 - B   1.560 1.230 0.780 0.480 0.330 0.330      13500.     50800.      0.0315
  2 - A   1.650 1.200 0.670 0.400 0.243 0.450      14100.     22800.      0.0641
  2 - B   1.440 1.050 0.640 0.380 0.246 0.390      15900.     32000.      0.0387
  3 - A   1.500 1.050 0.600 0.370 0.267 0.450      15700.     22600.      0.0345
  3 - B   1.440 0.990 0.580 0.370 0.261 0.450      16400.     22900.      0.0242
  4 - A   1.500 1.050 0.560 0.340 0.216 0.450      15900.     19900.      0.0607
  4 - B   1.380 0.990 0.540 0.330 0.213 0.390      17000.     25000.      0.0501
  5 - A   1.920 1.260 0.650 0.400 0.280 0.660      12700.     11500.      0.0787
  5 - B   1.800 1.140 0.630 0.420 0.310 0.660      13400.     11300.      0.0390

 AVERAGES
  W'S,SCI 1.569 1.107 0.636 0.396 0.270 0.462
  POINTS     10    10    10    10    10    10
  STIFF ON TOP SOLUTIONS                           15388.     30075.
  POINTS                                               8          8
  SOFT ON TOP SOLUTIONS                            13050.     11400.
  POINTS                                               2          2

    W1     DEFLECTION AT GEOPHONE 1
    W2     DEFLECTION AT GEOPHONE 2
    W3     DEFLECTION AT GEOPHONE 3
    W4     DEFLECTION AT GEOPHONE 4
    W5     DEFLECTION AT GEOPHONE 5
    SCI    SURFACE CURVATURE INDEX ( W1 MINUS W2)
    ES     ELASTIC MODULUS OF THE SUBGRADE FROM W1,W2,W3,W4,& W5
    EP     ELASTIC MODULUS OF THE PAVEMENT FROM W1,W2,W3,W4,& W5
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Table 2c: Computer print-out for Section 5.

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                         TEXAS HIGHWAY DEPARTMENT

                        DISTRICT 17 - DESIGN SECTION

              DYNAFLECT DEFLECTIONS AND CALCULATED ELASTIC MODULI

                      THIS PROGRAM WAS RUN - 08/28/73

                          DIST.          COUNTY
                           17            WASHINGTON

         CONT.     SECT.     JOB     HIGHWAY      DATE       DYNAFLECT
          186        5        1      SH 36      5-21-68         1

                                     PAV. THICK. = 19.90 INCHES

       HOT MIX ASPH. CONC.     3.75      SANDSTONE               16.15

       BLACK CLAY SUBGRADE     0.0

STATION    W1     W2     W3     W4     W5     SCI   ** ES  **  ** EP  **   * RMSE *

 1 - A   1.680 1.020 0.610 0.420 0.300 0.660     15000.      12800.      0.0112
 1 - B   1.830 1.080 0.610 0.420 0.310 0.750     14400.      10600.      0.0073
 2 - A   1.740 1.080 0.670 0.470 0.360 0.660     13900.      13600.      0.0135
 2 - B   1.950 1.170 0.690 0.490 0.370 0.780     13000.      13600.      0.0104
 3 - A   1.680 1.080 0.680 0.500 0.380 0.600     13700.      15800.      0.0184
 3 - B   1.710 1.080 0.670 0.480 0.370 0.630     13800.      14500.      0.0143
 4 - A   1.680 1.110 0.750 0.570 0.460 0.570     12600.      19500.      0.0416
 4 - B   1.560 1.080 0.730 0.550 0.440 0.480     13000.      23100.      0.0300
 5 - A   1.500 0.960 0.590 0.440 0.330 0.540     15600.      16900.      0.0151
 5 - B   1.590 0.990 0.600 0.430 0.330 0.600     15200.      14700.      0.0107

AVERAGES
 W'S,SCI 1.692 1.065 0.660 0.477 0.365 0.627
 POINTS     10    10    10    10    10    10
 STIFF ON TOP SOLUTIONS                          13740.      17960.
 POINTS                                              5           5
 SOFT ON TOP SOLUTIONS                           14300.      12520.
 POINTS                                              5           5

   W1     DEFLECTION AT GEOPHONE 1
   W2     DEFLECTION AT GEOPHONE 2
   W3     DEFLECTION AT GEOPHONE 3
   W4     DEFLECTION AT GEOPHONE 4
   W5     DEFLECTION AT GEOPHONE 5
   SCI    SURFACE CURVATURE INDEX ( W1 MINUS W2)
   ES     ELASTIC MODULUS OF THE SUBGRADE FROM W1,W2,W3,W4,& W5
   EP     ELASTIC MODULUS OF THE PAVEMENT FROM W1,W2,W3,W4,& W5
```

Table 2d: Computer print-out for Section 12.

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                         TEXAS HIGHWAY DEPARTMENT

                       DISTRICT 17 - DESIGN SECTION

            DYNAFLECT DEFLECTIONS AND CALCULATED ELASTIC MODULI

                      THIS PROGRAM WAS RUN - 08/28/73

                          DIST.        COUNTY
                           17          ROBERTSON

        CONT.    SECT.    JOB    HIGHWAY    DATE       DYNAFLECT
         49        8       1     US 190    5-21-68         1

                                 PAV. THICK. = 15.20 INCHES

       HOT MIX ASPH. CONC.     1.25      CEM. STAB. LIMESTONE 13.95

       REC SANDY CLAY SUBGR   0.0

STATION    W1     W2     W3     W4     W5     SCI   ** ES   ** ** EP   **   * RMSE *

 1 - A   0.680 0.590 0.490 0.390 0.310 0.090     18600.    347700.      0.0096
 1 - B   0.680 0.600 0.490 0.390 0.310 0.080     18600.    341600.      0.0070
 2 - A   0.720 0.630 0.510 0.390 0.310 0.090     18500.    280900.      0.0060
 2 - B   0.700 0.620 0.490 0.390 0.310 0.080     18700.    302300.      0.0081
 3 - A   0.750 0.650 0.520 0.390 0.300 0.100     18700.    234300.      0.0044
 3 - B   0.760 0.650 0.510 0.390 0.300 0.110     18900.    222000.      0.0072
 4 - A   0.600 0.540 0.450 0.350 0.280 0.060     20300.    411100.      0.0030
 4 - B   0.580 0.520 0.430 0.330 0.264 0.060     21600.    397000.      0.0033
 5 - A   0.620 0.550 0.450 0.350 0.273 0.070     20800.    351900.      0.0030
 5 - B   0.650 0.570 0.470 0.360 0.280 0.080     20100.    325400.      0.0047

AVERAGES
 W'S,SCI 0.674 0.592 0.481 0.373 0.294 0.082
 POINTS     10    10    10    10    10    10
 STIFF ON TOP SOLUTIONS                          19480.    321420.
 POINTS                                             10         10
 NO SOFT ON TOP SOLUTIONS

   W1    DEFLECTION AT GEOPHONE 1
   W2    DEFLECTION AT GEOPHONE 2
   W3    DEFLECTION AT GEOPHONE 3
   W4    DEFLECTION AT GEOPHONE 4
   W5    DEFLECTION AT GEOPHONE 5
   SCI   SURFACE CURVATURE INDEX ( W1 MINUS W2)
   ES    ELASTIC MODULUS OF THE SUBGRADE FROM W1,W2,W3,W4,& W5
   EP    ELASTIC MODULUS OF THE PAVEMENT FROM W1,W2,W3,W4,& W5
```

Table 2e: Computer print-out for Section 15.

```
                                  TEXAS HIGHWAY DEPARTMENT

                                DISTRICT 17 - DESIGN SECTION

                   DYNAFLECT DEFLECTIONS AND CALCULATED ELASTIC MODULI

                              THIS PROGRAM WAS RUN - 08/28/73

                                   DIST.          COUNTY
                                    17            BRAZOS

                CONT.     SECT.     JOB    HIGHWAY     DATE        DYNAFLECT
                1560        1        1     FM 1687   5-21-68           1

                                           PAV. THICK. =  7.50 INCHES

              ASPHALT SURFACING        1.00      ASPH EMUL STAB GRAVL  6.50

              BROWN CLAY SUBGRADE   0.0

STATION    W1     W2     W3     W4     W5      SCI   ** ES    ** ** EP    **   * RMSE *

 1 - A    2.160 1.500 0.960 0.660 0.520 0.660      11000.     104400.      0.0497
          ALTERNATE SOLUTION                        9100.       4400.      0.0328
 1 - B    2.130 1.530 0.960 0.650 0.510 0.600      10900.     117900.      0.0337
 2 - A    1.920 1.410 0.930 0.640 0.490 0.510      11400.     181400.      0.0394
          ALTERNATE SOLUTION                        9300.       3700.      0.0490
 2 - B    1.860 1.350 0.900 0.630 0.500 0.510      11700.     195600.      0.0507
          ALTERNATE SOLUTION                        9400.       3600.      0.0379
 3 - A    2.040 1.470 0.930 0.630 0.490 0.570      11300.     128200.      0.0330
          ALTERNATE SOLUTION                        9400.       4500.      0.0503
 3 - B    2.070 1.500 0.960 0.650 0.500 0.570      11000.     137300.      0.0342
          ALTERNATE SOLUTION                        9100.       4100.      0.0528
 4 - A    2.220 1.620 1.020 0.670 0.490 0.600      10400.     116000.      0.0202
 4 - B    2.220 1.590 1.020 0.650 0.490 0.630      10500.     108500.      0.0292
 5 - A    1.980 1.380 0.900 0.610 0.470 0.600      11800.     122200.      0.0454
          ALTERNATE SOLUTION                        9800.       4600.      0.0329
 5 - B    1.980 1.440 0.930 0.610 0.460 0.540      11500.     141400.      0.0274

AVERAGES
 W'S,SCI 2.058 1.479 0.951 0.640 0.492 0.579
 POINTS     10     10    10     10     10    10
 STIFF ON TOP SOLUTIONS                           11150.     135290.
 POINTS                                              10          10
 SOFT ON TOP SOLUTIONS                             9350.       4150.
 POINTS                                               6           6

   W1     DEFLECTION AT GEOPHONE 1
   W2     DEFLECTION AT GEOPHONE 2
   W3     DEFLECTION AT GEOPHONE 3
   W4     DEFLECTION AT GEOPHONE 4
   W5     DEFLECTION AT GEOPHONE 5
   SCI    SURFACE CURVATURE INDEX ( W1 MINUS W2)
   ES     ELASTIC MODULUS OF THE SUBGRADE FROM W1,W2,W3,W4,& W5
   EP     ELASTIC MODULUS OF THE PAVEMENT FROM W1,W2,W3,W4,& W5
   ***** IN CASES WITH ALTERNATES,RMSES ARE NOT SIGNIFICANTLY DIFFERENT
```

Table 2f: Computer print-out for Section 16.

```
                              TEXAS HIGHWAY DEPARTMENT

                             DISTRICT 17 - DESIGN SECTION

                 DYNAFLECT DEFLECTIONS AND CALCULATED ELASTIC MODULI

                           THIS PROGRAM WAS RUN - 08/28/73

                                 DIST.       COUNTY
                                  17         BRAZOS

           CONT.    SECT.    JOB    HIGHWAY    DATE       DYNAFLECT
            540       3       1     FM 974    5-21-68         1

                                    PAV. THICK. =  8.30 INCHES

         SEAL COAT              0.50     IRON ORE GRAVEL       7.80

         GREY SANDY CLAY SUBG  0.0

STATION    W1     W2     W3     W4     W5      SCI   ** ES    ** ** EP    **   * RMSE *

 1 - A   2.400 1.530 0.960 0.680 0.500 0.870       9400.       6700.      0.0093
 1 - B   2.250 1.440 0.900 0.630 0.480 0.810      10000.       7200.      0.0063
 2 - A   1.770 1.170 0.820 0.600 0.480 0.600      13100.     114900.      0.0832
         ALTERNATE SOLUTION                       10100.       3800.      0.0199
 2 - B   1.800 1.200 0.820 0.620 0.490 0.600      12800.     112800.      0.0831
         ALTERNATE SOLUTION                        9900.       3700.      0.0242
 3 - A   1.650 1.170 0.840 0.640 0.510 0.480      12300.     237500.      0.0796
         ALTERNATE SOLUTION                        9500.       2900.      0.0463
 3 - B   1.590 1.170 0.840 0.610 0.510 0.420      12400.     270900.      0.0657
         ALTERNATE SOLUTION                        9600.       2900.      0.0618
 4 - A   2.250 1.470 0.990 0.750 0.600 0.780      10600.      67800.      0.1032
         ALTERNATE SOLUTION                        8300.       3300.      0.0222
 4 - B   2.340 1.590 1.050 0.790 0.630 0.750       9900.      82800.      0.0939
         ALTERNATE SOLUTION                        7800.       3100.      0.0435
 5 - A   2.220 1.470 0.990 0.710 0.550 0.750       8600.       3700.      0.0269
 5 - B   2.100 1.410 0.960 0.680 0.530 0.690      11200.      83700.      0.0763
         ALTERNATE SOLUTION                        8900.       3600.      0.0337

AVERAGES
 W'S,SCI 2.037 1.362 0.917 0.671 0.528 0.675
 POINTS     10    10    10    10    10    10
 STIFF ON TOP SOLUTIONS                           11757.     138629.
 POINTS                                               7           7
 SOFT ON TOP SOLUTIONS                             9210.       4090.
 POINTS                                              10          10

   W1    DEFLECTION AT GEOPHONE 1
   W2    DEFLECTION AT GEOPHONE 2
   W3    DEFLECTION AT GEOPHONE 3
   W4    DEFLECTION AT GEOPHONE 4
   W5    DEFLECTION AT GEOPHONE 5
   SCI   SURFACE CURVATURE INDEX ( W1 MINUS W2)
   ES    ELASTIC MODULUS OF THE SUBGRADE FROM W1,W2,W3,W4,& W5
   EP    ELASTIC MODULUS OF THE PAVEMENT FROM W1,W2,W3,W4,& W5
   ***** IN CASES WITH ALTERNATES, RMSES OF THE SOFT AND STIFF ON TOP
         SOLUTIONS ARE DIFFERENT AT A 10 PERCENT LEVEL OF SIGNIFICANCE
```

Table 2g: Computer print-out for Section 17.

Table 3: Comparison between Elastic Modulus I, Elastic Modulus II and the new program on flexible pavements.

				Computed Moduli Values					
			Pvmt Thick	Elastic Mod I*		Elastic Mod II*		New Program	
Test Sect	Surfacing	Base	H	E_1	E_2	E_1	E_2	E_1	E_2
3	0.5" ST	12.0" Red sandy grav	15.2	24720	18970	23660	18980	27983	19983
								16150	18000**
4	0.5" ST	7.5" Asph stab Ls	8.0	78900	14900	110475	11800	125040	11100
								6157	9586**
5	0.5" ST	11.5" Lime stab Ss	12.0	32340	14480	23760	14840	30075	15388
								11400	13050**
12	3.7" HMAC	16.2" Crushed Ss	19.9	13900	14420	14920	14010	17960	13740
								12520	14300**
15	1.2" HMAC	14.0" Cement stab Ls	15.2	283180	19990	314100	19120	321420	19480
								No Alternate	
16	1.0" HMAC	6.5" Asph stab grav	7.5	73910	11740	109330	11110	135290	11150
								4150	9350**
17	0.5" ST	7.8" Iron ore grav	8.3	36600	12700	81910	11400	138629	11757
								4090	9210**

*See Table 6 Reference 2.
**Alternate Solutions.

Table 4: Dynaflect deflections and calculated elastic moduli for test points on rigid pavements at the Houston Intercontinental Airport.

Test Point	Pvmt Thick H	Deflections					Calculated Moduli Values		
		W1	W2	W3	W4	W5	E_2	E_1	RMSE
6	12.0	0.400	0.400	0.370	0.340	0.310	15,600	4,928,400	0.0035
10	12.0	0.500	0.470	0.440	0.380	0.330	16,300	2,389,400	0.0046
13	12.0	0.520	0.510	0.470	0.400	0.350	15,300	2,251,200	0.0053
25	12.0	0.400	0.390	0.360	0.330	0.290	17,400	4,052,300	0.0017
28	12.0	0.430	0.410	0.390	0.360	0.330	14,500	4,895,000	0.0041
32	12.0	0.410	0.390	0.360	0.320	0.280	18,900	3,247,900	0.0026
34	12.0	0.400	0.390	0.370	0.340	0.310	15,300	5,253,100	0.0011
49	12.0	0.410	0.400	0.370	0.350	0.350	12,200	8,191,900	0.0104
56	14.0	0.330	0.330	0.310	0.290	0.270	16,500	5,046,300	0.0025
63	12.0	0.390	0.380	0.350	0.320	0.290	17,300	4,451,100	0.0032
69	12.0	0.237	0.234	0.216	0.207	0.198	21,900	12,731,400	0.0039
AVERAGES							16,470	5,221,600	0.0039

Note: Deflection data from Figures 10a through 10k Reference 2.

Table 5: Comparison between Elastic Modulus II and the new program on rigid pavements.

					Calculated Moduli Values			
					Elastic Mod II		New Program	
Point	Pvmt Thick H	General Location	Subbase	Subg	E_2	E_1	E_2	E_1
6	12.0	Runway 14-32	6" Sand Shell	4' Compact	13,000	7,494,800	15,600	4,928,400
10	12.0	Runway 14-32	6" Sand Shell	4' Compact	14,300	3,066,500	16,300	2,389,400
13	12.0	Runway 14-32	6" Sand Shell	4' Compact	11,700	4,137,400	15,300	2,251,200
24	12.0	Taxiway A	6" Sand Shell	4' Compact	15,600	5,085,500	17,400	4,052,300
28	12.0	Taxiway A	6" Sand Shell	4' Compact	14,000	5,154,900	14,500	4,895,000
32	12.0	Taxiway A	6" Sand Shell	4' Compact	17,600	3,674,300	18,900	3,247,900
34	12.0	Taxiway A	6" Sand Shell	4' Compact	13,000	7,494,800	15,300	5,253,100
49	12.0	Taxiway B	6" Sand Shell	4' Compact	15,100	5,099,500	12,200	8,191,900
56	14.0	Taxiway K	9" Soil Cement	4' Compact	13,600	7,831,000	16,500	5,046,300
63	12.0	Taxiway K	9" Soil Cement	4' Compact	16,400	4,952,600	17,300	4,451,100
69	12.0	North Apron	12" Soil Cement	6' Compact	23,000	10,975,400	21,900	12,731,400

4. Implication of Results

As pointed our previously, there are many instances where two entirely different sets of elastic moduli provide nearly equal values of deflections at the locations of the normal set of Dynaflect measurements (r values between 10 and 49 inches). Thus, two alternate sets of elastic moduli may appear to be equivalent solutions in a particular pavement evaluation problem. This phenomena does not imply that point load, two-layer, elastic deflection basins are not unique. In fact, Swift's "Two-Layer Elastic Deflection Chart" (6) clearly demonstrates that each possible two-layer elastic case has its own unique characteristic deflection basin. However, the phenomena does indicate that two alternate cases can become confused when the set of measurement points is not extensive enough.

The distinction between alternate cases could be greatly improved by extending the range of observations to include measurements at values of r that are less than 10 inches and/or greater than 49 inches. For example, at a radius of 5 inches from a point load, the calculated deflections for the two different cases, illustrated in Table 1, would be 2.22 and 6.01, respectively. Thus, a measured deflection at a 5 inch radius from a point load would clearly distinguish between the two possible cases.

With the current configuration of the Dynaflect, 10 inches is the smallest radius that can be used on the symmetry axis (See Figure 2). However, it is possible to obtain measurements closer than 10 inches by employing the principle of superposition. For example, a deflection measured at location number 6, Figure 2, would be the sum of the deflection due to one 500-pound load at a 5 inch radius and another deflection due to a 500 pound load at

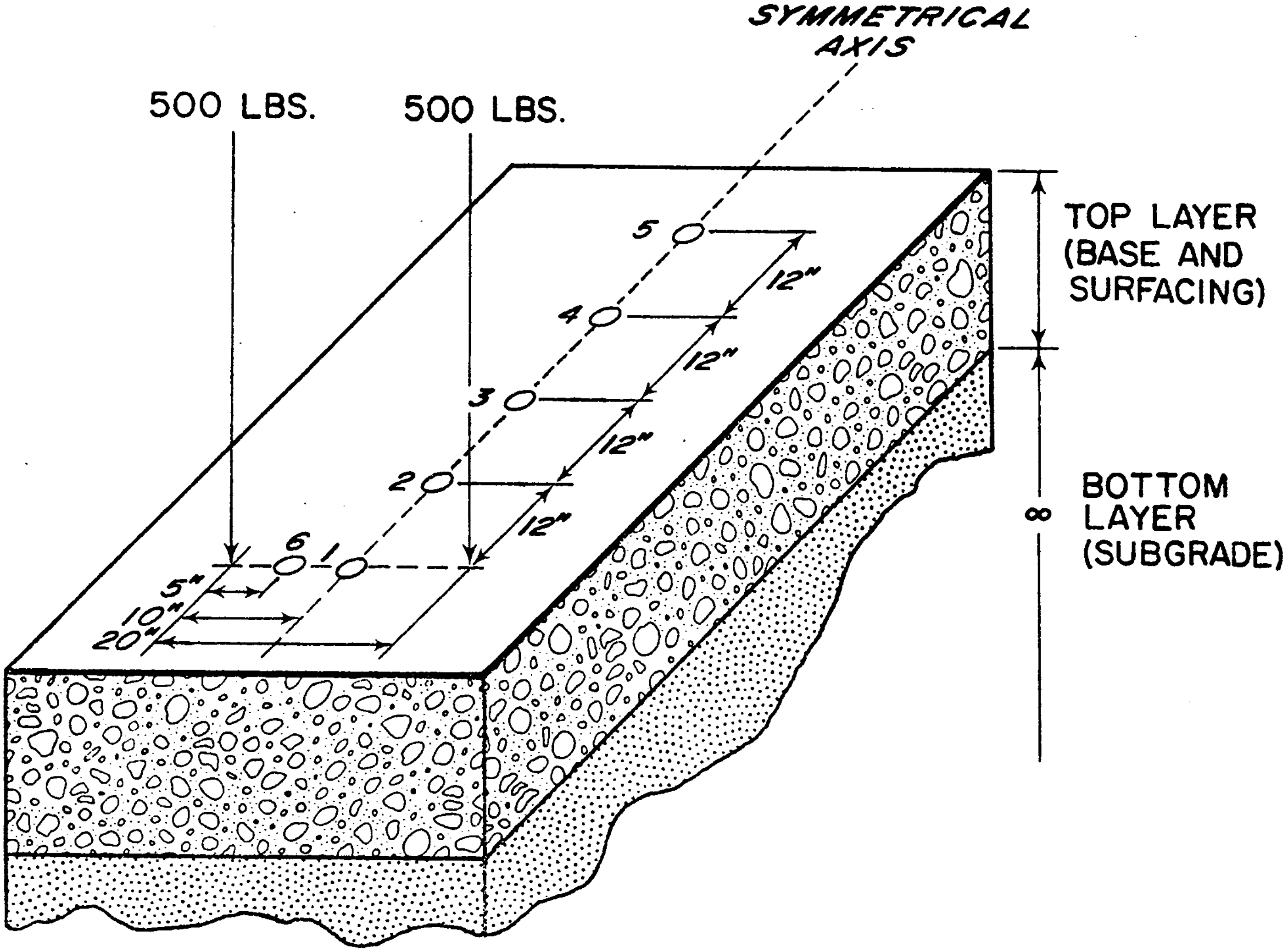

Figure 2: Relative position of Dynaflect loads and sensors. Vertical arrows represent load wheels. Points numbered 1 through 5 indicate location of sensors for standard test. Point 6 indicates the location of a desired additional measurement.

a 15-inch radius. The calculated value of deflection at this point for each of the two cases which were compared above, would be 1.85 and 3.66, respectively. Although this distinction is not as great as the previous comparison for r equal to 5 inches, it is significant enough to clearly distinguish between the two possible cases.

5. Conclusions & Recommendations

1. Because the presented technique for determining elastic moduli for simple two-layer pavement structures fits the entire measured deflection basin, it is believed to be more representative of the true material properties, insofar as elasticity theory applies to such structures, than any other technique known to the author.
2. The five Dynaflect deflection measurements normally made in field testing are not sufficient to determine a unique set of elastic moduli for some two-layer highway pavements.
3. The apparent two alternate solutions for many existing flexible pavement structures could be resolved by making an additional deflection measurement closer to the loading point. It is recommended that the mechanics of accomplishing such a measurement be given immediate consideration for use in future deflection based pavement evaluations.

5. References

1. Scrivner, F. H.; Michalak , C. H.; and Moore, W. M. "Calculation of the Elastic Moduli of a Two Layer Pavement System from Measured Surface Deflections," Research Report No. 123-6, Texas Transportation Institute, Texas A&M University, College Station, Texas, March 1971.

2. Scrivner, F. H.; Michalak, C. H.; and Moore, W. M. "Calculation of the Elastic Moduli of a Two Layer Pavement System from Measured Surface Deflections, Part II ," Research Report No. 123-6A, Texas Transportation Institute, Texas A&M University, College Station, Texas, December, 1971.

3. Swift, Gilbert. "An Empirical Equation for Calculating Deflections on the Surface of a Two-Layered Elastic System," Research Report No. 136-4, Texas Transportation Institute, November, 1972.

4. Pierre, Donald A., Optimization Theory with Application's, John Wiley and Sons, Inc., New York, March 1969, pp. 280-283.

5. "Texas Highway Department Pavement Design System, Part I, Flexible Pavement Designer's Manual," Highway Design Division, Texas Highway Department, Austin, Texas, 1970.

6. Swift, Gilbert. "A Graphical Technique for Determining the Elastic Moduli of a Two-Layered Structure from Measured Surface Deflections," Research Report No. 136-3, Texas Transportation Institute, November, 1972.

APPENDIX A

This Appendix contains a description of a computer program, "Two-Layer Elastic Moduli for Five Deflections," which determines the pavement and subgrade moduli for simple two-layer pavement structures based on surface deflections.

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DESCRIPTION OF THE MAIN PROGRAM

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 Highway Department 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 headings and multipliers for each observation. Two digit numbers in columns 75 and 76 of this card denotes end of data.

The deflections at each radial distance are calculated from the geophone deflection readings and multipliers on each 400 or blank card. 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 converted to inches and passed to subroutine EMPI along with the total pavement thickness for the elastic modulus and RMSE calculations.

EMPI returns to the main program two alternate solutions for pavement and subgrade elastic moduli with their corresponding RMSE's. In cases where only one solution exists, the variables for its alternate solution contain the flag number 99999. The pavement and subgrade moduli are then rounded to the nearest 100 psi. The counter N (the number of valid sets of observations) is incremented and the program reads the next data card to continue the process until all stations in a section are read. When all the data cards for a section have been read, the program prints output headings and initializes the variables used in calculating section averages.

A loop is set up to print the station numbers, deflections, SCI's, subgrade moduli, pavement moduli and RMSE's of all valid 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. Date observation where any W is equal to zero. 'ERROR IN DATA' is printed.

3. Data observation where both alternate pavement and subgrade solutions are "soft on top" (pavement modulus is less than subgrade modulus) or where both solutions are "stiff on top" (pavement modulus is greater than subgrade modulus). The message printed for this occurrence is 'NO SOLUTION'.

For all data observations other than the three mentioned above, elastic moduli for the soft and stiff on top solutions are summed separately. For all observations which have two alternate solutions for pavement and subgrade elastic moduli, the RMSE's of the stiff and soft for each solution are stored in separate arrays for a variance analysis calculation to denote significant differences.

After all data and any error messages for a section are printed, the average deflections, SCI's, subgrade moduli, pavement moduli and RMSE are calculated. If more than two observations in a section have alternate solutions, the program calls Subroutine VARI to calculate an analysis of variance between the RMSE's of the stiff on top solutions and the soft on top solutions to determine if these values are significantly different at the 10% level.

The averages are then printed along with the number of points used in calculating each average. These averages are divided into two groups: the average and points of the stiff on top solutions and the average and points of the soft on top solutions.

Definitions of the heading abbreviations are given next in footnote form. An additional footnote occurs when the variance analysis has been run, denoting whether or not the RMSE's of the alternate pavement and subgrade modulus are significantly different.

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

MAIN PROGRAM VARIABLES

A - Dummy array used with subroutine core to select the correct input format for each card read.

AAP2 - Sum of pavement moduli

AAS2 - Sum of subgrade moduli

AAP2V - Average pavement modulus

AAS2V - Average subgrade modulus

ALRMS - Stiff on top alternate solution RMSE array

AP2 - Elastic modulus of the pavement rounded to nearest 100 psi

AS2 - Elastic modulus of the subgrade rounded to nearest 100 psi

ASCI - Sum of (W1 - W2), WI - W2 = surface curvature index

ASCIV - Average surface curvature index

AW1 - Sum of geophone 1 deflections

AW2 - Sum of geophone 2 deflections

AW3 - Sum of geophone 3 deflections

AW4 - Sum of geophone 4 deflections

AW5 - Sum of geophone 5 deflections

AW1V - Average geophone 1 deflections

AW2V - Average geophone 2 deflections

AW3V - Average geophone 3 deflections

AW4V - Average geophone 4 deflections

AW5V - Average geophone 5 deflections

BLRMS - Soft on top alternate solution RMSE array

CNT - Number of soft on top solutions

CORE - Subroutine to re-read a card under format control

CO1, CO2, CO3, CO4 - County name

D1 - Geophone 1 reading

D2 - Geophone 1 multiplier

D3 - Geophone 2 reading

D4 - Geophone 2 multiplier

D5 - Geophone 3 reading

D6 - Geophone 3 multiplier

D7 - Geophone 4 reading

D8 - Geophone 4 multiplier

D9 - Geophone 5 reading

D10 - Geophone 5 multiplier

DAP - Pavement elastic modulus (unrounded) as calculated in subroutine EMPI

DAS - Subgrade elastic modulus (unrounded) as calculated in subroutine EMPI

DATE - An IBM subroutine that returns the current month, day, and year

DP - Total pavement thickness

E11 - Alternate pavement elastic modulus rounded to nearest 100 psi

E21 - Alternate subgrade elastic modulus rounded to nearest 100 psi

EMPI - Subroutine to calculate pavement and subgrade moduli, RMSE, and alternate if it exists.

HWY1, HWY2 - Highway name and number

I - Pointer for data read into storage

ICK - Switch to indicate last data card

ICONT - Contract number for the highway

IDAY - Day the deflections were taken

IDIST - District number

IDYNA - Dynaflect number

IJOB - THD job number

ISECT - THD section number for the highway

ISW - Switch to indicate whether the two RMSE arrays are significant and to control the footnotes to be printed.

IXDATE - Return arguments from subroutine date (month, day, year)

IYEAR - Year the deflections were taken

JNT, LNT - Number of RMSE's in the two arrays to be tested for significance

KNT - Number of stiff on top solutions

LA1 - Description of materials in layer 1

LA2 - Description of materials in layer 2

LA3 - Description of materials in layer 3

LA4 - Description of materials in layer 4

LA5 - Description of materials in layer 5

LA6 - Description of materials in layer 6

LO - Number of both data errors and no solutions

M - Month the deflections were taken

MNT - Number of solutions printed

N - Counter for number of error free 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)

RATIO - Ratio of AP2/AS2

RATIO1 - Ratio of E11/E21

ROUND - Statement function to round a given value of E1 or E2 to the nearest 100 psi

SCI - Surface curvature index, W1-W2 in mils

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

W1 - Deflection at geophone number 1

W2 - Deflection at geophone number 2

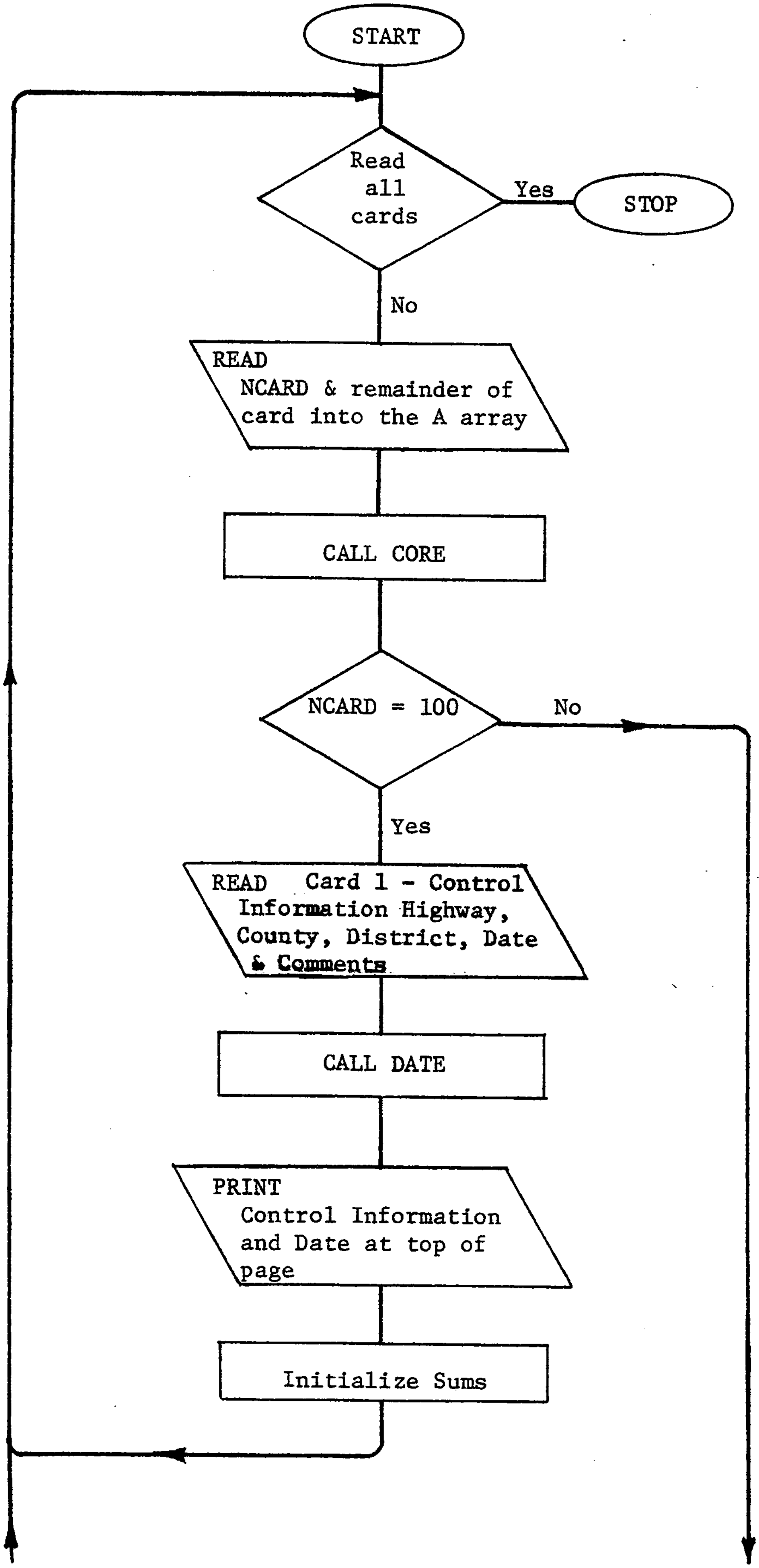
W3 - Deflection at geophone number 3

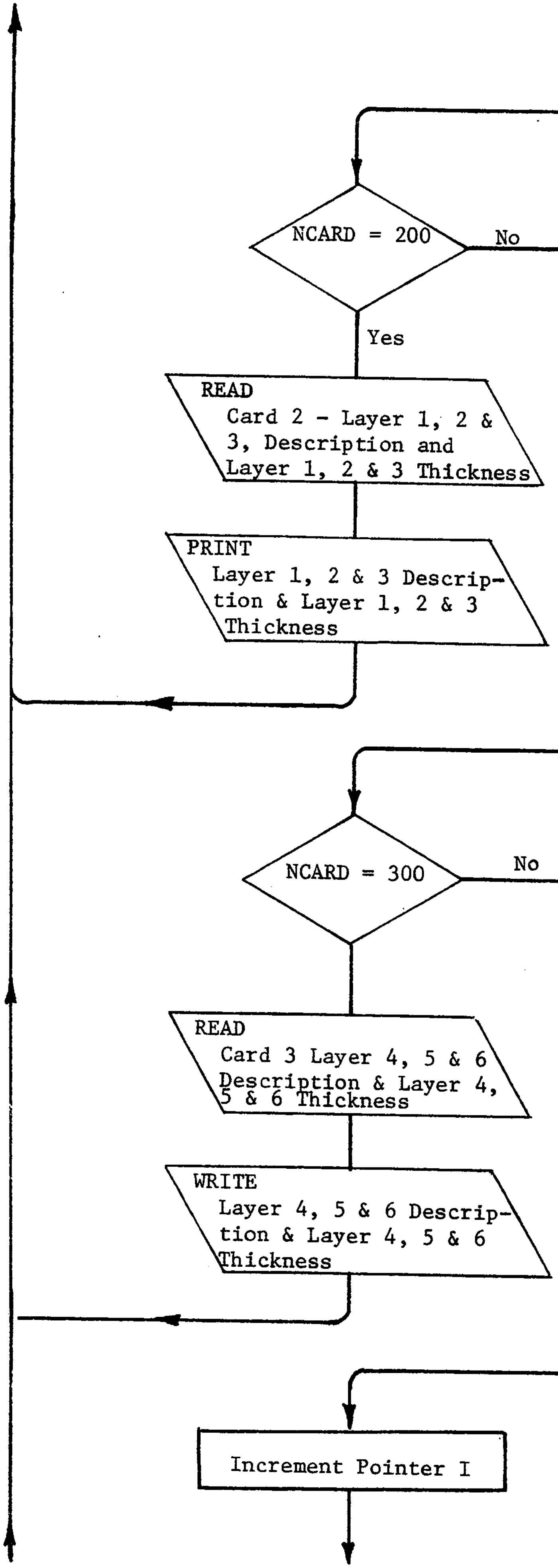
W4 - Deflection at geophone number 4

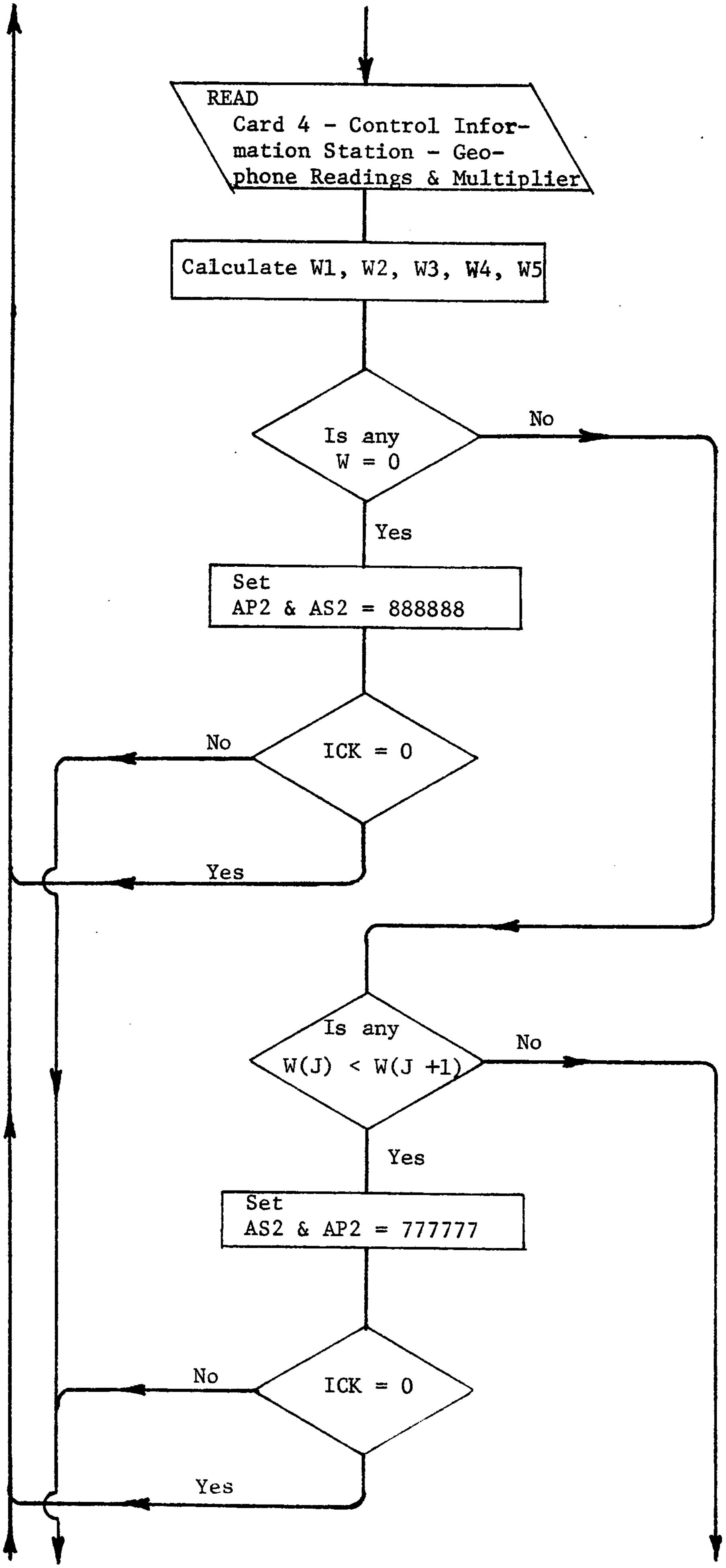
W5 - Deflection at geophone number 5

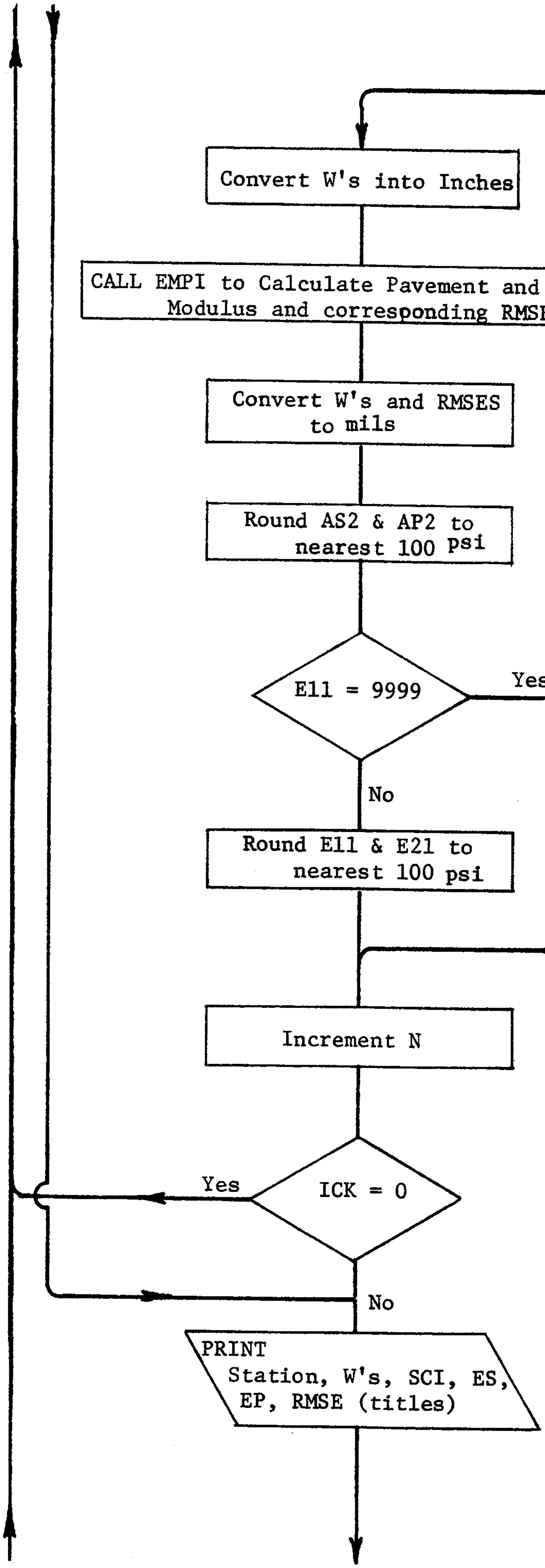
XLANE - Traffic lane and direction

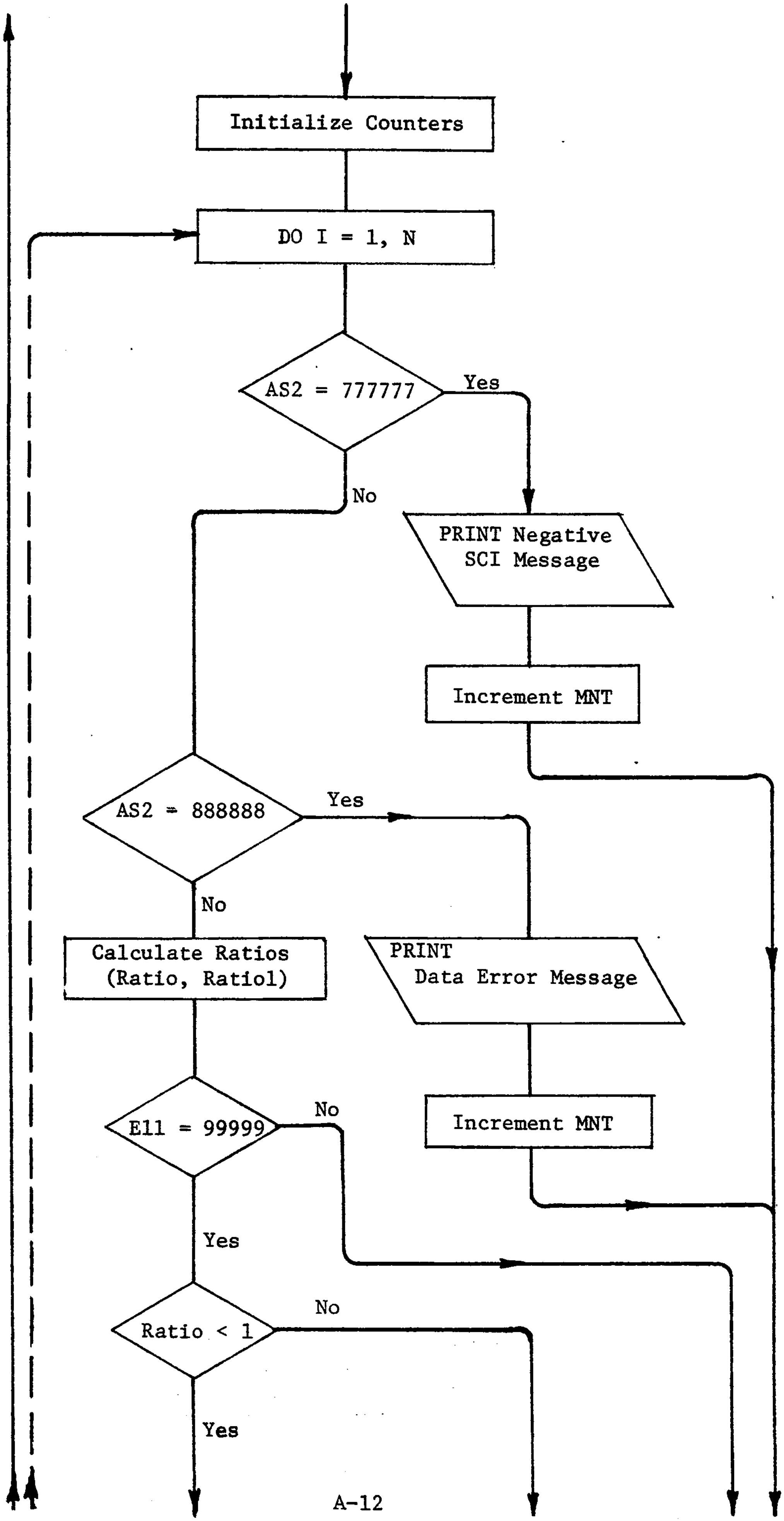
MAIN PROGRAM FLOW CHART

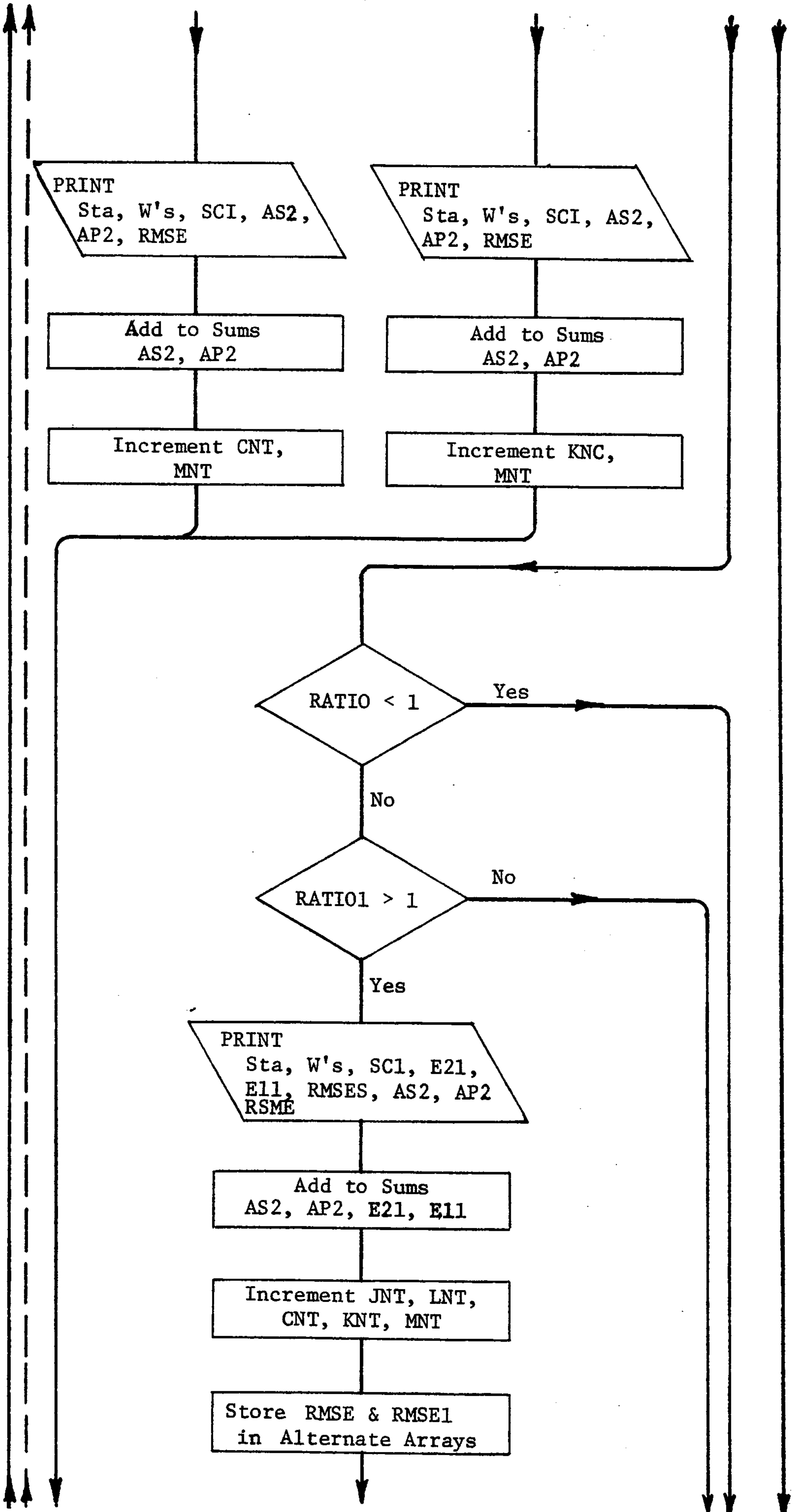


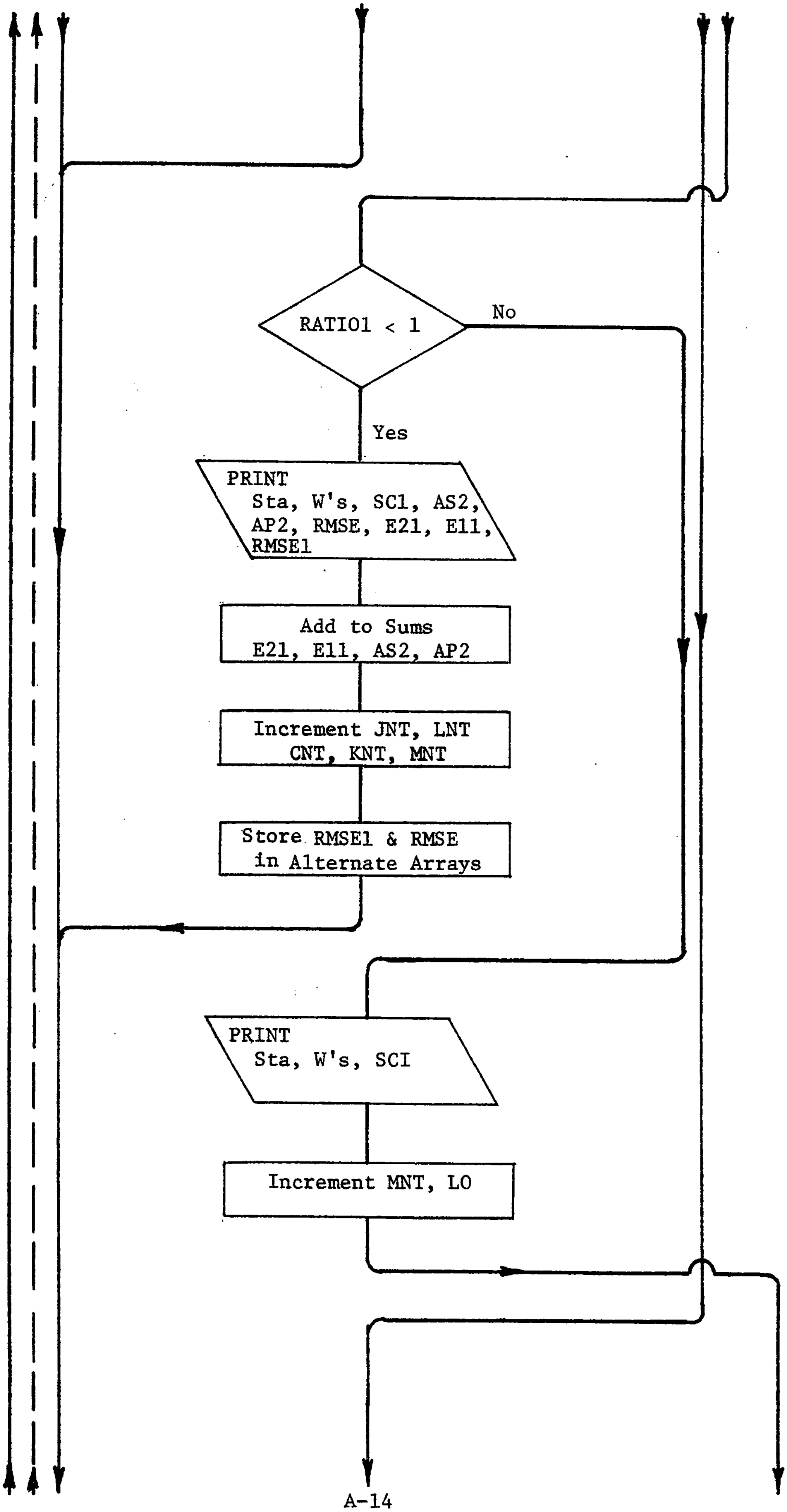

NCARD = 200
No
Yes
READ
Card 2 - Layer 1, 2 & 3, Description and Layer 1, 2 & 3 Thickness
PRINT
Layer 1, 2 & 3 Description & Layer 1, 2 & 3 Thickness
NCARD = 300
No
READ
Card 3 Layer 4, 5 & 6 Description & Layer 4, 5 & 6 Thickness
WRITE
Layer 4, 5 & 6 Description & Layer 4, 5 & 6 Thickness
Increment Pointer I

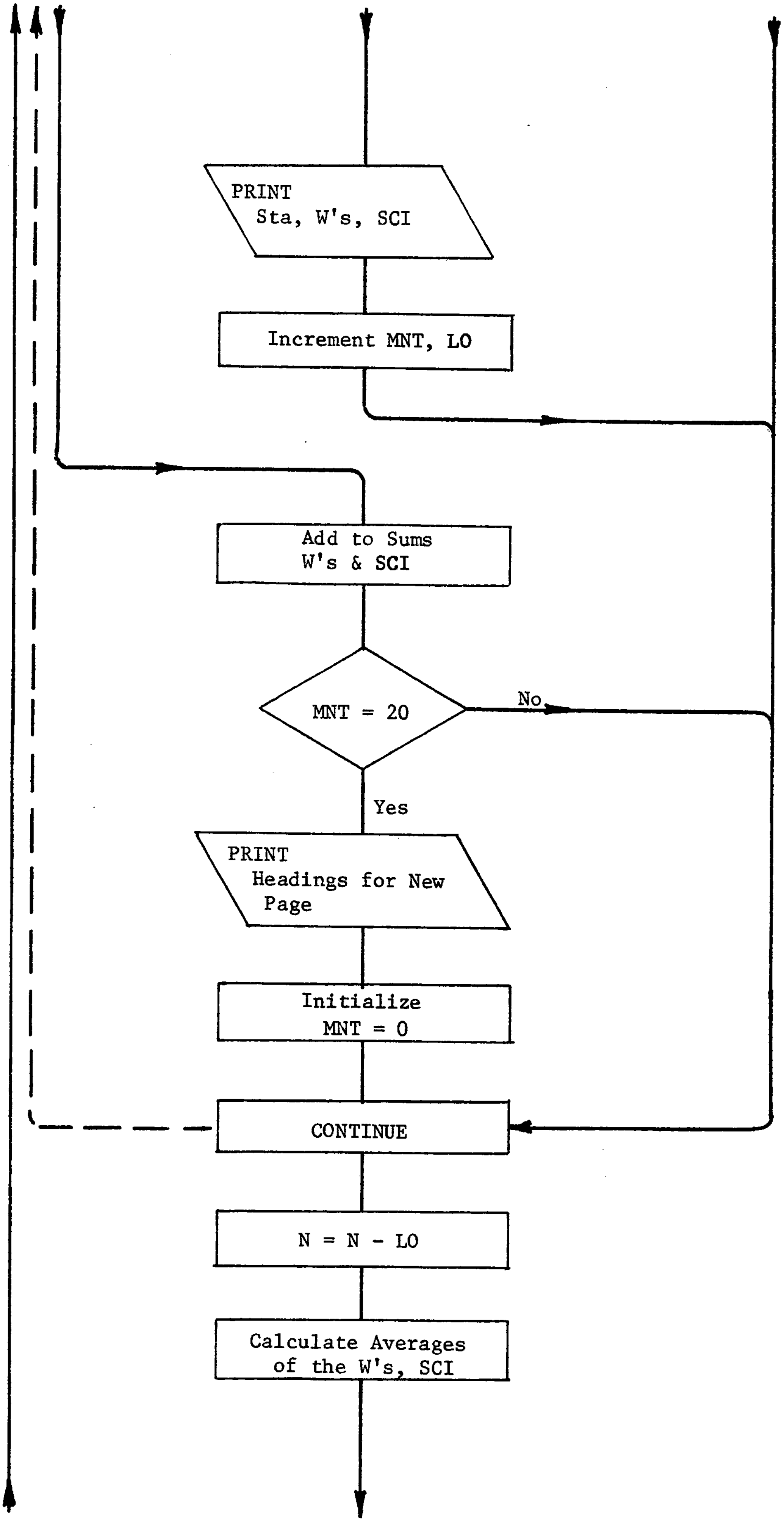

READ
Card 4 - Control Information Station - Geophone Readings & Multiplier
Calculate W1, W2, W3, W4, W5
Is any W = 0
No
Yes
Set AP2 & AS2 = 888888
ICK = 0
No
Yes
Is any W(J) < W(J +1)
No
Yes
Set AS2 & AP2 = 777777
ICK = 0
No
Yes

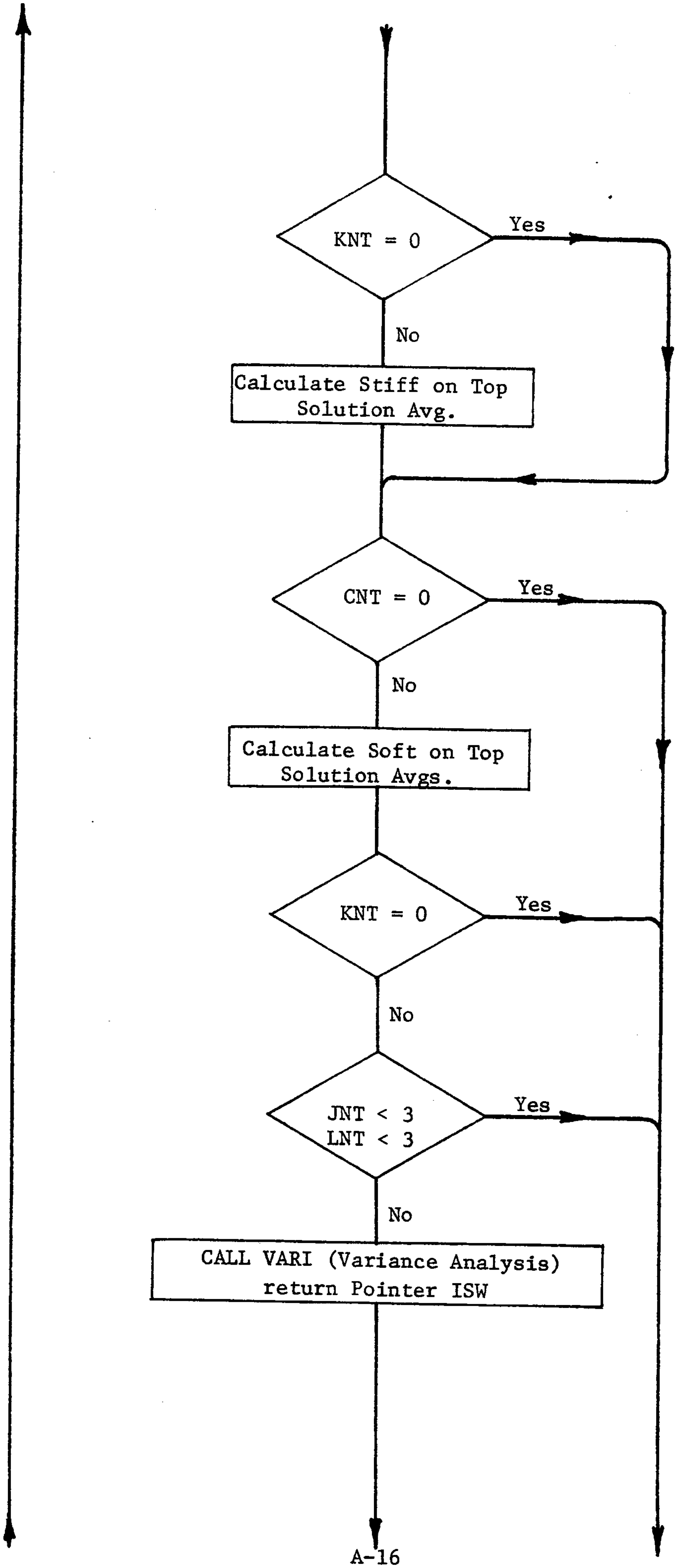

Convert W's into Inches
CALL EMPI to Calculate Pavement and Subgrade Modulus and corresponding RMSES
Convert W's and RMSES to mils
Round AS2 & AP2 to nearest 100 psi
E11 = 9999
Yes
No
Round E11 & E21 to nearest 100 psi
Increment N
ICK = 0
Yes
No
PRINT Station, W's, SCI, ES, EP, RMSE (titles)

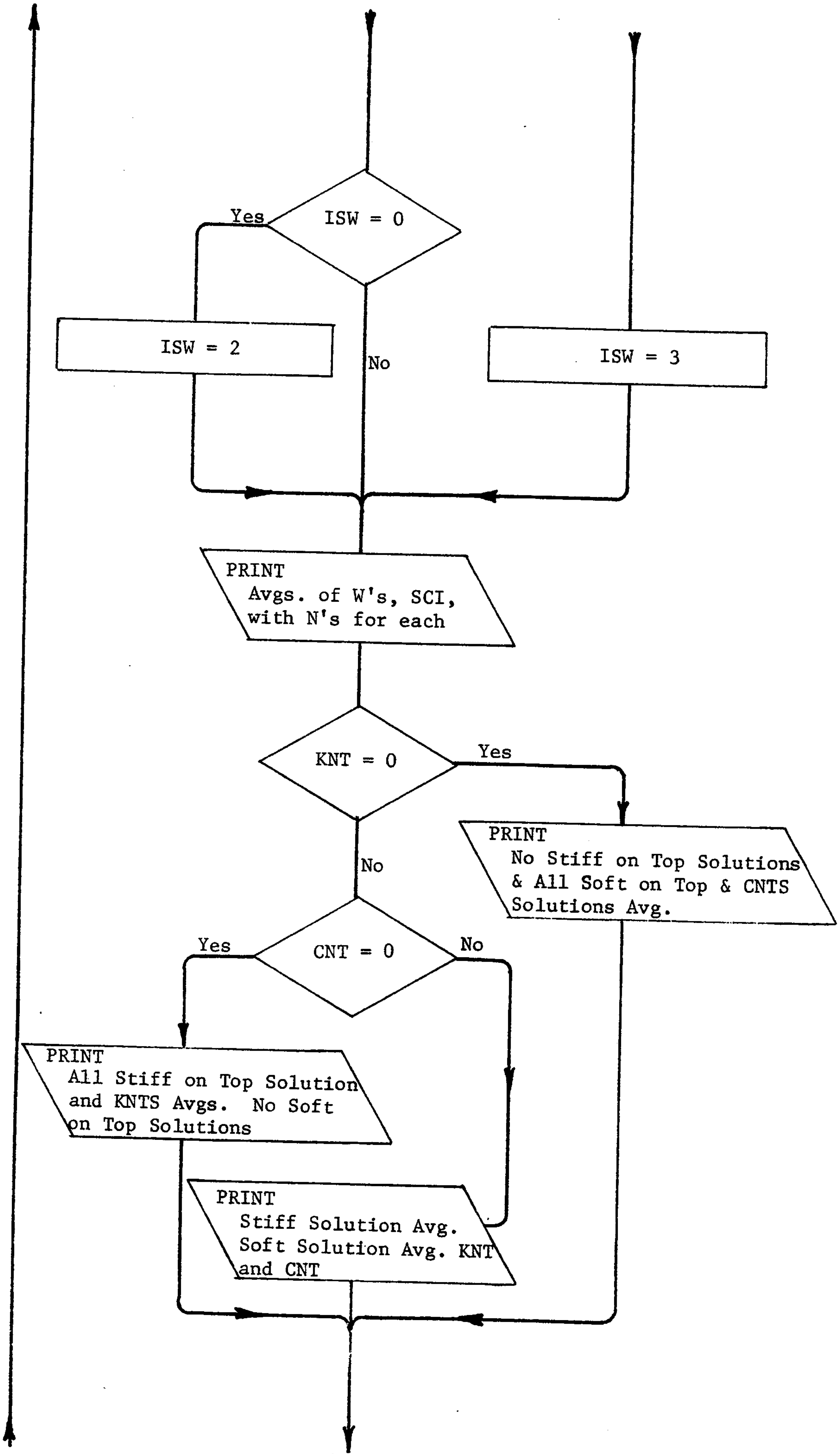

Initialize Counters
DO I = 1, N
AS2 = 777777
Yes
No
PRINT Negative SCI Message
Increment MNT
AS2 = 888888
Yes
No
Calculate Ratios (Ratio, Ratio1)
PRINT Data Error Message
Increment MNT
E11 = 99999
No
Yes
Ratio < 1
No
Yes

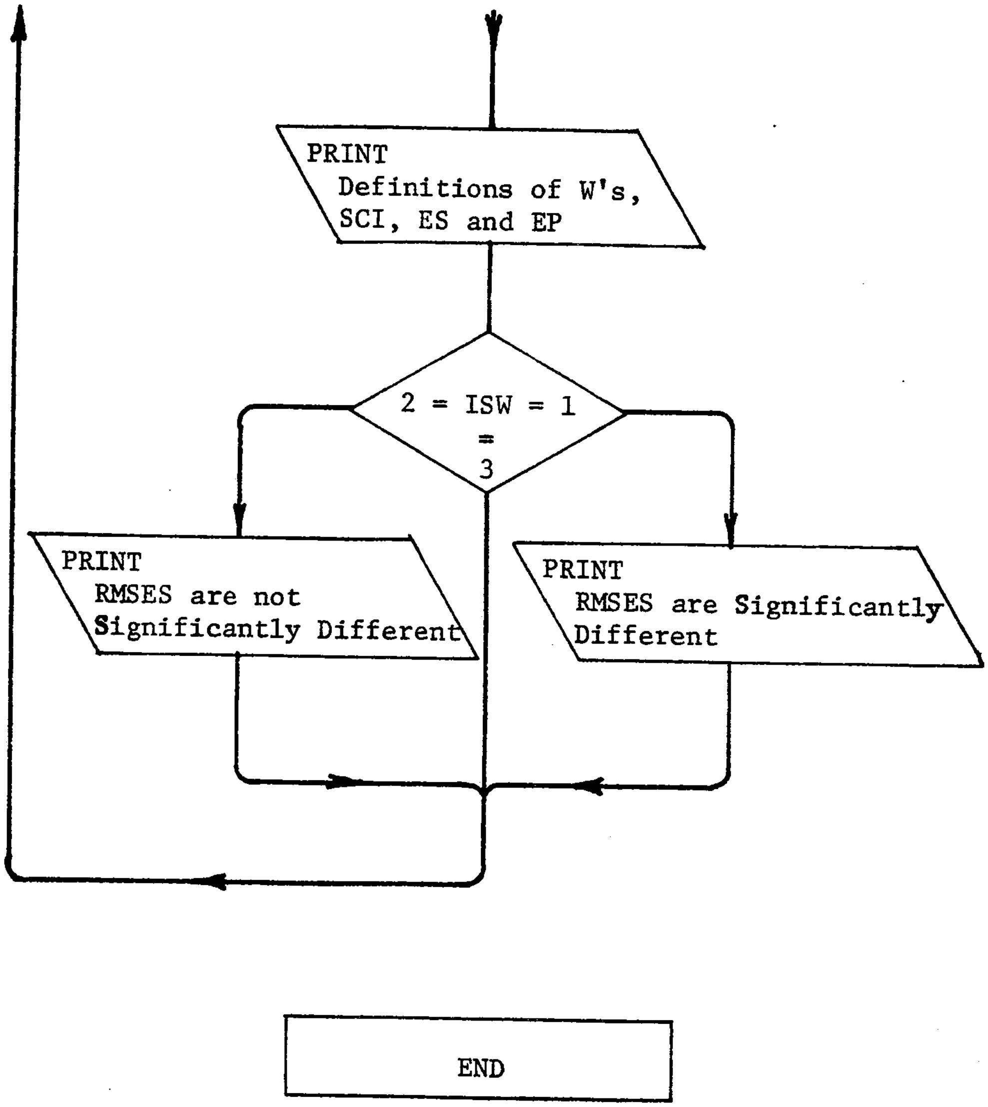

PRINT
Sta, W's, SCI, AS2, AP2, RMSE
PRINT
Sta, W's, SCI, AS2, AP2, RMSE
Add to Sums
AS2, AP2
Add to Sums
AS2, AP2
Increment CNT, MNT
Increment KNC, MNT
RATIO < 1
Yes
No
RATIO1 > 1
No
Yes
PRINT
Sta, W's, SC1, E21, E11, RMSES, AS2, AP2 RSME
Add to Sums
AS2, AP2, E21, E11
Increment JNT, LNT, CNT, KNT, MNT
Store RMSE & RMSE1 in Alternate Arrays


RATIO1 < 1
No
Yes
PRINT
Sta, W's, SC1, AS2,
AP2, RMSE, E21, E11,
RMSE1
Add to Sums
E21, E11, AS2, AP2
Increment JNT, LNT
CNT, KNT, MNT
Store RMSE1 & RMSE
in Alternate Arrays
PRINT
Sta, W's, SCI
Increment MNT, LO


PRINT
Sta, W's, SCI
Increment MNT, LO
Add to Sums
W's & SCI
MNT = 20
No
Yes
PRINT
Headings for New
Page
Initialize
MNT = 0
CONTINUE
N = N - LO
Calculate Averages
of the W's, SCI


KNT = 0
Yes
No
Calculate Stiff on Top Solution Avg.
CNT = 0
Yes
No
Calculate Soft on Top Solution Avgs.
KNT = 0
Yes
No
JNT < 3
LNT < 3
Yes
No
CALL VARI (Variance Analysis) return Pointer ISW


ISW = 0
Yes
No
ISW = 2
ISW = 3
PRINT
Avgs. of W's, SCI, with N's for each
KNT = 0
Yes
No
PRINT
No Stiff on Top Solutions & All Soft on Top & CNTS Solutions Avg.
CNT = 0
Yes
No
PRINT
All Stiff on Top Solution and KNTS Avgs. No Soft on Top Solutions
PRINT
Stiff Solution Avg. Soft Solution Avg. KNT and CNT


PRINT
Definitions of W's, SCI, ES and EP
2 = ISW = 1
=
3
PRINT
RMSES are not Significantly Different
PRINT
RMSES are Significantly Different
END

DESCRIPTION OF EMPI SUBROUTINE

This subroutine uses the five deflections and the pavement thickness and calculates pavement and subgrade moduli solutions from the empirical equation along with the corresponding RMSE (Root Mean Squares of the Errors). Due to the nature of data, two solutions for pavement and subgrade moduli sometimes exist.

EMPI calculates both solutions according to the following procedure.

1. An array of $\log_{10}$ numbers from -2.5 to 7.0 with 0.5 intervals is built. The anti-log of each number is then used as the ratio of E_1/E_2 to calculate an array of RMSE's.

2. This array of RMSE's is searched and the three lowest values are found along with their corresponding locations in the array.

	RMSE	Location
lowest	TEMP1	ISUB1
2nd lowest	TEMP2	ISUB2
3rd lowest	TEMP3	ISUB3

3. The locations of these three RMSE's are then checked to determine whether or not there are one or two significant minimums.

If only one significant minimum exists all three locations of RMSE will be consecutive.

If two significant minimums exist one of the locations of RMSE will be separated from the other two.

4. The vicinity of each distinct minimum is searched using a Fibonacci search subroutine. This search will find the minimum value of a unimodal function between two points on its curve. It should be noted that the RMSE versus E_1/E_2 curve is not a unimodal function in its

entirety; however, it has been found to be unimodal between any three consecutive points in the stored array in the vicinity of a minimum. The subroutine returns to the program the minimum RMSE value and the corresponding value of the ratio E_1/E_2.

5. Next the ratio (E_1E_2) that corresponds to the minimum RMSE is sent to a subroutine ANA. ANS calculates the pavement (E1) and subgrade (E2) moduli using this value for the ratio (E_1E_2).

6. Two sets of pavement and subgrade moduli along with their respective RMSE's are alswys sent back to the main program in the following form.

1st Solution E1 - Pavement modulus
E2 - Subgrade modulus
RMSE - Root mean square of the errors
*2nd Solution E11 - Pavement modulus
E21 - Subgrade modulus
RMSE1 - Root mean square of the errors

*If only one distinct minimum exists, values for E11, E21 and RMSE1 will be 99999.

SUBROUTINE EMPI VARIABLES

B - Sum of the XW's divided by sum of the X's squared (See equation)

DLTA - Intervals on $\log_{10}$ scale

E1 - Pavement elastic modulus

E2 - Subgrade elastic modulus

E11 - Alternate pavement elastic modulus

E21 - Alternate subgrade elastic modulus

E(I) - Errors between recorded deflections and calculated deflections

EX - X (See equation)

EXSQ - X^2 (See equation)

H - Total pavement thickness

ISUB1 - Location of lowest RMSE in array

ISUB2 - Location of second lowest RMSE in array

ISUB3 - Location of third lowest RMSE in array

K - Number of RMSE's in array to find three lowest

MSE - Mean square of the errors

N - Number of deflections in each case

NOI - Number of points to be tested in Fibonacci search.

RATIO - Ratio of E1/E2

R(I) - Distances from the point at which load is applied

RLDG - Array of $\log_{10}$ numbers to be searched

RMSE - Root mean square of the errors

SMESQ - Sum of the errors squared

SMXSQ - Sum of the X's squared

SMXW - Sum of the X's times the W's

TEMP - Minimum RMSE of the Fibonacci search.

TEMP1 - Lowest RMSE in array

TEMP2 - Second lowest RMSE in array

TEMP3 - Third lowest RMSE in array

TEMPO - Minimum RMSE of the alternate solution of the Fibonacci search

TX1, TX2, TX3 - Location of RMSE that is the left boundary in the Fibonacci search

TX11, TX21, TX31 - Location of RMSE that is the right boundary in the Fibonacci search

W(I) - Vertical deflections

X(I) - $\frac{1}{r}$ + (RATIO - 1) * XTWO (See equation)

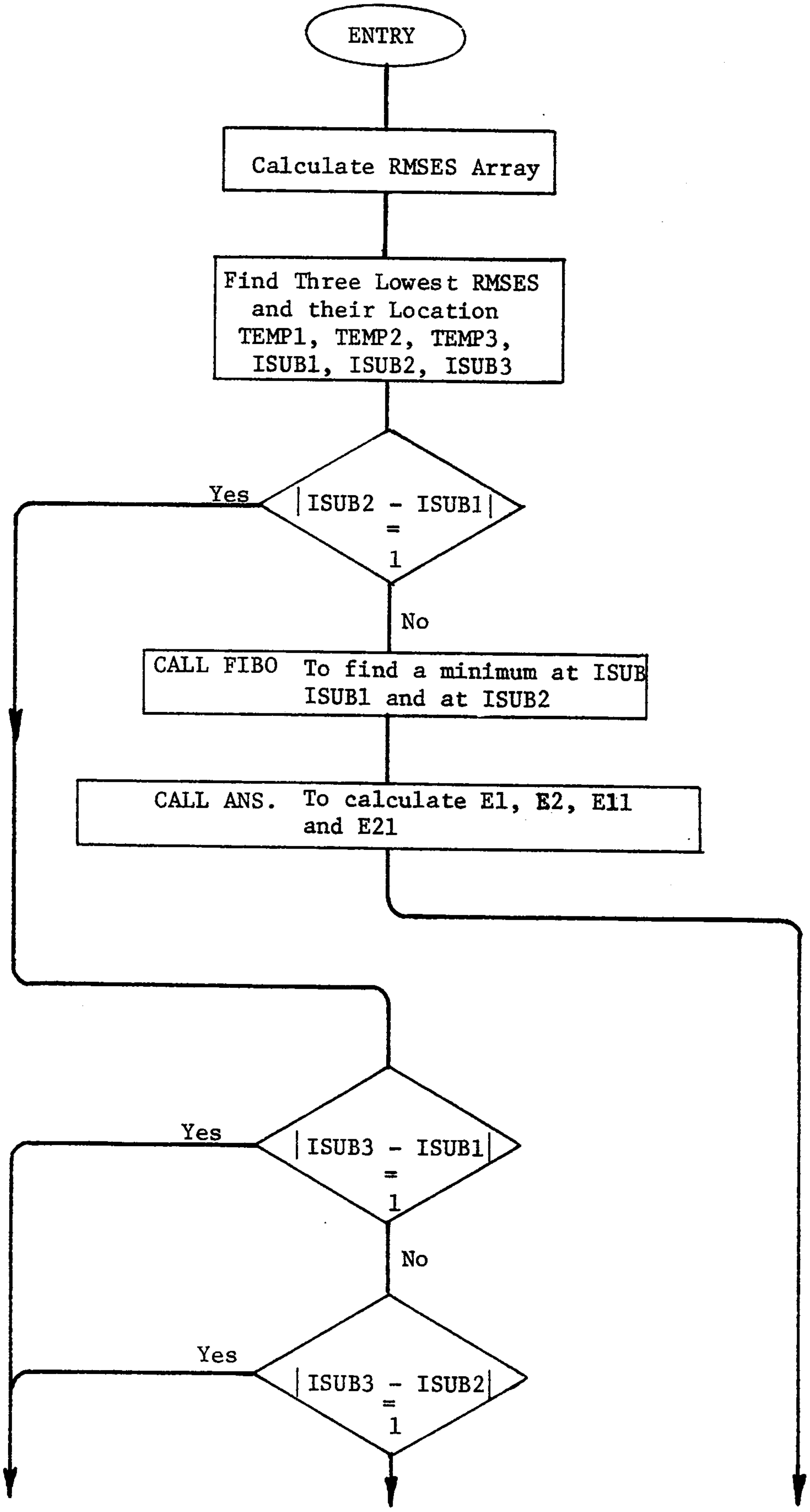
XL - L (See equation)

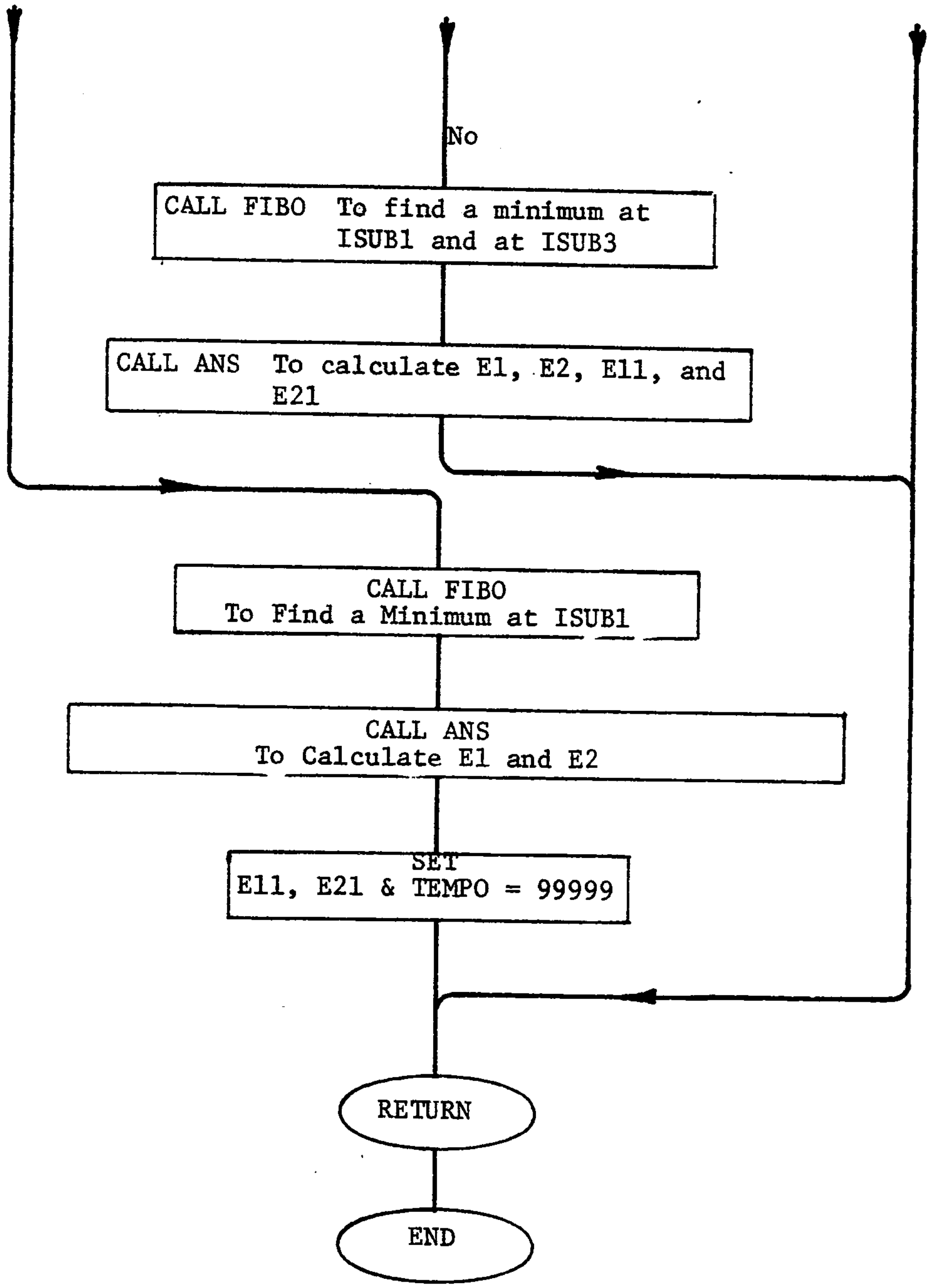
XL3 - L^3 (See equation)

XL5 - L^5 (See equation)

XTWO - $\frac{1}{L} + \frac{X^2}{2L^3} + \frac{3X^4}{2L^5}$ (See equation)

SUBROUTINE EMPI FLOW CHART




No
CALL FIBO To find a minimum at ISUB1 and at ISUB3
CALL ANS To calculate E1, E2, E11, and E21
CALL FIBO To Find a Minimum at ISUB1
CALL ANS To Calculate E1 and E2
SET E11, E21 & TEMPO = 99999
RETURN
END

SUBROUTINE VARI

VARI is a variance analysis subroutine to determine whether or not there is a significant difference between the array of soft on top alternate RMSE's and the array of stiff on top alternate RMSE's at a 10% level of significance.

SUBROUTINE VARI VARIABLES

AMSBS - Mean square between sets

AMSWS - Mean square within sets

CNT - Number of soft on top solutions

F - Ratio of AMSBS over AMSWS

IDFBS - Degrees of freedom between sets

IDFWS - Degrees of freedom within sets

KNT - Number of stiff on top solutions

N - Total number of RMSE's tested

RMSE - Array of stiff on top alternate RMSE's

RMSE1 - Array of soft on top alternate RMSE's

SSBS - Sums of squares between sets

SSQ(1) - Sum of all stiff on top alternate RMSE's squared

SSQ(2) - Sum of all soft on top alternate RMSE's squared

SSWS - Sums of squares within sets

SUM(1) - Sum of all stiff on top alternate RMSE's

SUM(2) - Sum of all soft on top alternate RMSE's

TSSQ - Total sum of alternate RMSE's squared

TSUM - Total sum of alternate RMSE's

SUBROUTINE SIGNIF

This is an F-distribution table for a 10% level of significance with the numerator at 1 since there will always be only two sets.

SUBROUTINE SIGNIF VARIABLES

F - Ratio of AMSBS over AMSWS (See VARI variables)

IDFWS - Degrees of freedom within sets (Denominator)

ISW - Pointer as to significance

ISW = 0 - Not significant at 10%.

ISW = 1 - Is significant at 10%.

SUBROUTINE FIBO

This subroutine is a Fibonacci search which is used to determine the minimal value of a unimodal function. A subroutine **FUNC** (X,Y) is called to obtain the Y value of the unimodal function, Y = F(X).

SUBROUTINE FIBO VARIABLES

N - Number of search desired, Max = 20

X1 - Lower limit of X value

X2 - Upper limit of X value

X - Location of optimal Y

Y - Optimal Y value

```
C     TWO LAYER ELASTIC MODULI FOR FIVE DEFLECTIONS
      DIMENSION STA(200),W(200,5),D(10),AW(5),AWV(5),RATIO(200),
     *  AP2(200),LA1(5),LA2(5),LA3(5),LA4(5),LA5(5),LA6(5),
     *RATIO1(200),AS2(200),A(20),SCI(200),
     *E11(200), E21(200),RMSE1(200),
     *  IXDATE(3),COMM(7),REM(4),RMSE(200),BLRMS(200),ALRMS(200)
      INTEGER CNT
      REAL * 8 STA,DAS,DAP,DBLE,E11,E21,RMSE1,RMSE,BLRMS,ALRMS
C
CCC   STATEMENT FUNCTION TO ROUND 'X' TO NEAREST 'EVEN'
C
      ROUND( X, EVEN )  =  AINT( ( X + EVEN * .5 ) / EVEN  )
     * *  EVEN
C
   10 CONTINUE
      READ(5,1,END=1000)  NCARD, ( A(I), I = 1 , 20 )
    1 FORMAT( I3, 19A4, A1 )
      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) ICONT,ISECT,M,IDAY,IYEAR,STA(I),(D(K),K=1,10),
     *(REM(J),J=1,4),ICK
    6 FORMAT(    I4,4I2,A7,3X, 5(F2.1,F3.2),8X,4A4,I2)
C     PRINT OUTPUT COLUMN HEADINGS
C
C     CALCULATE DEFLECTIONS & SCI ( DEFLECTIONS IN MILS )
      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
      DO 5 J=1,5
      IF(W(I,J) .EQ. 0.0) GO TO 21
    5 CONTINUE
      DO 7 J=1,4
      IF(W(I,J) .LT. W(I,J+1)) GO TO 22
    7 CONTINUE
      DO 8 J=1,5
      W(I,J) = W(I,J) / 1000.
    8 CONTINUE
C
C     PASS THE W'S & TOTAL PAVEMENT THICKNESS TO EMPI,
C     EMPI RETURNS UNROUNDED VALUES OF PAVEMENT & SUBGRADE AND RMSE
C     MODULI  AS DAP & DAS & RMSE(I) AND E11(I),E21(I),& RMSE1(I)
```

-4

```
C
      CALL EMPI(DBLE(W(I,1)),DBLE(W(I,2)),DBLE(W(I,3)),DBLE(W(I,4)),
     *DBLE(W(I,5)),DBLE(DP),DAP,DAS,RMSE(I),E11(I),E21(I),RMSE1(I))
C     CONVERT THE W'S TO MILS
      DO 9 J=1,5
      W(I,J) = W(I,J) * 1000.
    9 CONTINUE
      RMSE(I) = RMSE(I) * 1000.
      RMSE1(I) = RMSE1(I) * 1000.
      DAS  =  ROUND( DAS, 100. )
      DAP  =  ROUND( DAP, 100. )
      AS2(I) = DAS
      AP2(I) = DAP
      IF(E11(I) .EQ. 99999) GO TO 23
      E11(I) = ROUND(E11(I),100.)
      E21(I) = ROUND(E21(I),100.)
   23 CONTINUE
      N = N + 1
      IF(ICK .EQ. 0) GO TO 10
      GO TO 80
   11 READ(5,2) IDIST,C01,C02,C03,C04,ICONT,ISECT,IJOB,HWY1,
     * HWY2, XLANE, DP,M,IDAY,IYEAR,IDYNA,(COMM(I),I=1,7)
    2 FORMAT(    I2,3A4,A2,I4,2I2,A4,A3,A3,F5.2,4I2,7A4)
      PRINT 51
   51 FORMAT( '1' )
      PRINT 52
   52 FORMAT(35X,'TEXAS HIGHWAY DEPARTMENT' /)
      PRINT 53,IDIST
   53 FORMAT(33X,'DISTRICT ',I2,' - DESIGN SECTION' /)
      PRINT 54
   54 FORMAT(21X,'DYNAFLECT DEFLECTIONS AND CALCULATED ',
     * 'ELASTIC MODULI ' / )
      CALL DATE ( IXDATE(1), IXDATE(2), IXDATE(3)   )
      PRINT 55,IXDATE
   55 FORMAT(32X,'THIS PROGRAM WAS RUN - ', 2A3,A2 /   )
      PRINT 56, IDIST, C01, C02, C03, C04
      PRINT 57, ICONT, ISECT,IJOB,HWY1,HWY2,M,IDAY,IYEAR,IDYNA
      PRINT 58,(COMM(I),I=1,7),DP
   58 FORMAT(10X,7A4,2X,'PAV. THICK. = ',F5.2,' INCHES' /)
       N=0
      DO 15 J=1,5
      AW(J) = 0.0
   15 CONTINUE
      ASCI=0.
      AAS2=0.
      AAP2=0.
      BAS2 = 0.
      BAP2 = 0.
      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,                    TTI 1000
     * (LA3(I),I=1,5), T3                                               TTI 1010
    3 FORMAT(     5A4,F4.2,5A4,F4.2,5A4,F4.2)                           TTI 1020
      PRINT 59,(LA1(I),I=1,5),T1,(LA2(I),I=1,5),T2                      TTI 1030
      PRINT 59, ( LA3(I), I=1,5), T3                                    TTI 1040
   59 FORMAT(16X, 5A4, 1X, F5.2, 5X, 5A4, 1X, F5.2/)                    TTI 1050
      GO TO 10                                                          TTI 1060
C     READ & PRINT INFORMATION ON DATA CARD 3, IF PRESENT               TTI 1070
   13 READ(5,3)  (LA4(I),I=1,5),T4,(LA5(I),I=1,5),T5,                   TTI 1080
     * (LA6(I),I=1,5), T6                                               TTI 1090
      PRINT 59,(LA4(I),I=1,5),T4,(LA5(I),I=1,5),T5                      TTI 1100
      PRINT 59, ( LA6(I), I=1,5), T6                                    TTI 1110
      GO TO 10                                                          TTI 1120
   22 CONTINUE                                                          TTI 1130
      AS2(I) = 7777777                                                  TTI 1140
      AP2(I) = 7777777                                                  TTI 1150
      IF(ICK .EQ. 0) GO TO 10                                           TTI 1160
      GO TO 80                                                          TTI 1170
   21 CONTINUE                                                          TTI 1180
      AS2(I) = 888888                                                   TTI 1190
      AP2(I) = 888888                                                   TTI 1200
      IF(ICK .EQ. 0) GO TO 10                                           TTI 1210
      GO TO 80                                                          TTI 1220
   80 CONTINUE                                                          TTI 1230
      PRINT 61                                                          TTI 1240
   61 FORMAT(/ 7X,'STATION   W1    W2    W3    W4     W5',              TTI 1250
     = '     SCI  ** ES   ** ** EP   **   * RMSE *'/)                   TTI 1260
      CNT = 0                                                           TTI 1270
      KNT = 0                                                           TTI 1280
      MNT = 0                                                           TTI 1290
      JNT = 0                                                           TTI 1300
      LNT = 0                                                           TTI 1310
      LO = 0                                                            TTI 1320
      DO 50 I=1,N                                                       TTI 1330
      IF(AS2(I) .EQ. 7777777) GO TO 24                                  TTI 1340
      IF(AS2(I) .EQ. 888888) GO TO 25                                   TTI 1350
      RATIO(I) = AP2(I)/AS2(I)                                          TTI 1360
      IF(E11(I) .EQ. 99999) GO TO 26                                    TTI 1370
      RATIO1(I) = E11(I)/E21(I)                                         TTI 1380
      IF(RATIO(I) .LT. 1.0) GO TO 27                                    TTI 1390
      IF(RATIO1(I) .LT. 1.0) GO TO 28                                   TTI 1400
C     BOTH ALTERNATES HARD ON TOP                                       TTI 1410
      PRINT 62,STA(I),(W(I,J),J=1,5),SCI(I)                             TTI 1420
   62 FORMAT(7X,A7,1X,6(F6.3),10X,'NO SOLUTION')                        TTI 1430
      MNT = MNT + 1                                                     TTI 1440
      LO = LO + 1                                                       TTI 1450
      GO TO 50                                                          TTI 1460
   27 IF(RATIO1(I) .GT. 1.0) GO TO 29                                   TTI 1470
C     BOTH ALTERNATES ARE SOFT ON TOP                                   TTI 1480
      PRINT 62,STA(I),(W(I,J),J=1,6),SCI(I)                             TTI 1490
```

```
   MNT = MNT + 1                                                    TTI 1500
   LO = LO + 1                                                      TTI 1510
   GO TO 50                                                         TTI 1520
28 PRINT 63,STA(I),(W(I,J),J=1,5),SCI(I),AS2(I),AP2(I),RMSE(I)      TTI 1530
63 FORMAT(7X,A7,1X,6(F6.3),2F10.0,2X,F8.4)                          TTI 1540
   PRINT 64,E21(I),E11(I),RMSE1(I)                                  TTI 1550
64 FORMAT(T17,'ALTERNATE SOLUTION',T52,2F10.0,2X,F8.4)              TTI 1560
   BAS2 = BAS2 + E21(I)                                             TTI 1570
   BAP2 = BAP2 + E11(I)                                             TTI 1580
   AAS2 = AAS2 + AS2(I)                                             TTI 1590
   AAP2 = AAP2 + AP2(I)                                             TTI 1600
   JNT = JNT + 1                                                    TTI 1610
   BLRMS(JNT) = RMSE1(I)                                            TTI 1620
   LNT = LNT + 1                                                    TTI 1630
   ALRMS(LNT) = RMSE(I)                                             TTI 1640
   CNT = CNT + 1                                                    TTI 1650
   KNT = KNT + 1                                                    TTI 1660
   MNT = MNT + 2                                                    TTI 1670
   GO TO 40                                                         TTI 1680
29 PRINT 63,STA(I),(W(I,J),J=1,5),SCI(I),E21(I),E11(I),RMSE1(I)     TTI 1690
   PRINT 64,AS2(I),AP2(I),RMSE(I)                                   TTI 1700
   BAS2 = BAS2 + AS2(I)                                             TTI 1710
   BAP2= BAP2 + AP2(I)                                              TTI 1720
   AAS2 = AAS2 + E21(I)                                             TTI 1730
   AAP2 = AAP2 + E11(I)                                             TTI 1740
   JNT = JNT + 1                                                    TTI 1750
   BLRMS(JNT) = RMSE(I)                                             TTI 1760
   LNT = LNT + 1                                                    TTI 1770
   ALRMS(LNT) = RMSE1(I)                                            TTI 1780
   CNT = CNT + 1                                                    TTI 1790
   KNT = KNT + 1                                                    TTI 1800
   MNT = MNT + 2                                                    TTI 1810
   GO TO 40                                                         TTI 1820
26 CONTINUE                                                         TTI 1830
   IF(RATIO(I) .LT. 1.0) GO TO 30                                   TTI 1840
   PRINT 63 ,STA(I),(W(I,J),J=1,5),SCI(I),AS2(I),AP2(I),RMSE(I)     TTI 1850
   AAS2 = AAS2 + AS2(I)                                             TTI 1860
   AAP2 = AAP2 + AP2(I)                                             TTI 1870
   KNT = KNT + 1                                                    TTI 1880
   MNT = MNT + 1                                                    TTI 1890
   GO TO 40                                                         TTI 1900
30 PRINT 63,STA(I),(W(I,J),J=1,5),SCI(I),AS2(I),AP2(I),RMSE(I)      TTI 1910
   BAS2 = BAS2 + AS2(I)                                             TTI 1920
   BAP2 = BAP2 + AP2(I)                                             TTI 1930
   CNT = CNT + 1                                                    TTI 1940
   MNT = MNT + 1                                                    TTI 1950
40 CONTINUE                                                         TTI 1960
   DO 16 M=1,5                                                      TTI 1970
16 AW(M) = AW(M) + W(I,M)                                           TTI 1980
   ASCI = ASCI + SCI(I)                                             TTI 1990
```

```
      IF(MNT .EQ. 20) GO TO 31
      GO TO 50
   31 PRINT 51
      PRINT 56, IDIST, CO1, CO2, CO3, CO4
   56 FORMAT( T35,'DIST.        COUNTY'/ T36, I2,9X, 3A4,A2 /)
      PRINT 57, ICONT, ISECT,IJOB,HWY1,HWY2,M,IDAY,IYEAR,IDYNA
   57 FORMAT( T19, 'CONT.   SECT.   JOB   HIGHWAY    DATE',
     " '        DYNAFLECT' / T19,I4,2I7,4X,A4,A3,I4,2('-',I2),I9 /)
      PRINT 61
      MNT = 0
      GO TO 50
   24 PRINT 65,STA(I)
   65 FORMAT(7X,A7,3X,'NEGATIVE SCI OTHER CALCULATIONS OMMITTED')
      MNT = MNT + 1
      GO TO 50
   25 PRINT 66,STA(I)
   66 FORMAT(7X,A7,3X,'ERROR IN DATA')
      MNT = MNT + 1
   50 CONTINUE
C     CALCULATE AVERAGES
      N = N - LO
      DO 17 M=1,5
   17 AWV(M) = AW(M)/N
      ASCIV = ASCI/N
      IF(KNT .EQ. 0) GO TO 32
      AAS2V = AAS2/KNT
      AAP2V = AAP2/KNT
   32 CONTINUE
      IF(CNT .EQ. 0) GO TO 33
      BAS2V = BAS2/CNT
      BAP2V = BAP2/CNT
      IF(KNT .EQ. 0) GO TO 33
      IF(JNT .LT. 3 .AND. LNT .LT. 3) GO TO 33
      CALL VARI(ALRMS,BLRMS,JNT,LNT,ISW)
      IF(ISW .EQ. 0) ISW = 2
      GO TO 34
   33 CONTINUE
      ISW = 3
   34 CONTINUE
      PRINT 81,(AWV(J),J=1,5),ASCIV
   81 FORMAT(/7X,'AVERAGES',/,8X,7HW'S,SCI,6(F6.3))
      PRINT 82,N,N,N,N,N,N
   82 FORMAT(8X,'POINTS',T19,I3,3X,I3,3X,I3,3X,I3,3X,I3,3X,I3)
      IF(KNT .EQ. 0) GO TO 35
      IF(CNT .NE. 0) GO TO 36
      PRINT 83,AAS2V,AAP2V
   83 FORMAT(8X,'STIFF ON TOP SOLUTIONS',T52,2F10.0)
      PRINT 84,KNT,KNT
   84 FORMAT(8X,'POINTS',T58,I3,T68,I3)
      PRINT 85
```

```
   85 FORMAT(8X,'NO SOFT ON TOP SOLUTIONS')
      GO TO 90
   36 CONTINUE
      PRINT 83,AAS2V,AAP2V
      PRINT 84,KNT,KNT
      PRINT 86,BAS2V,BAP2V
   86 FORMAT(8X,'SOFT ON TOP SOLUTIONS',T52,2F10.0)
      PRINT 87,CNT,CNT
   87 FORMAT(8X,'POINTS',T58,I3,T68,I3)
      GO TO 90
   35 CONTINUE
      PRINT 88
   88 FORMAT(8X,'NO STIFF ON TOP SOLUTIONS')
      PRINT 86,BAS2V,BAP2V
      PRINT 87,CNT,CNT
   90 CONTINUE
      PRINT 91
   91 FORMAT(/10X,'W1    DEFLECTION AT GEOPHONE 1')
      PRINT 92
   92 FORMAT( 10X,'W2    DEFLECTION AT GEOPHONE 2')
      PRINT 93
   93 FORMAT( 10X,'W3    DEFLECTION AT GEOPHONE 3')
      PRINT 94
   94 FORMAT( 10X,'W4    DEFLECTION AT GEOPHONE 4')
      PRINT 95
   95 FORMAT( 10X,'W5    DEFLECTION AT GEOPHONE 5')
      PRINT 96
   96 FORMAT( 10X,'SCI   SURFACE CURVATURE INDEX ( W1 MIN',
     * 'US W2)'    )
      PRINT 97
   97 FORMAT( 10X,'ES    ELASTIC MODULUS OF THE SUBGRADE FRO',
     * 'M W1,W2,W3,W4,& W5')
      PRINT 98
   98 FORMAT( 10X,'EP    ELASTIC MODULUS OF THE PAVEMENT FRO',
     * 'M W1,W2,W3,W4,& W5')
      GO TO (100,200,300) , ISW
  100 PRINT 99
   99 FORMAT(10X,'***** IN CASES WITH ALTERNATES, RMSES OF THE SOFT AND
     *STIFF ON TOP',/,16X,'SOLUTIONS ARE DIFFERENT AT A 10 PERCENT LEVEL
     * OF SIGNIFICANCE')
      GO TO 300
  200 PRINT 101
  101 FORMAT(10X,'***** IN CASES WITH ALTERNATES,RMSES ARE NOT SIGNIFICA
     *NTLY DIFFERENT')
  300 CONTINUE
      GO TO 10
 1000 CONTINUE
      END
```

```
      SUBROUTINE EMPI(W1,W2,W3,W4,W5,H,E1,E2,TEMP,E11,E21,TEMPO)
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION RLOG(30),RATIO(30),X(20),RMSE(30),E(20)
      DIMENSION RAT1(30),RAT2(30),RAT3(30)
      DIMENSION R(5),W(5)
      COMMON /A/ R,W
      REAL*8 MSE,LRMSE
      N=5
      R(1) = 10.0
      R(2) = 15.620499
      R(3) = 26.0
      R(4) = 37.363083
      R(5) = 49.030603
      W(1)=W1
      W(2)=W2
      W(3)=W3
      W(4)=W4
      W(5)=W5
      DLTA = .5
      RLOG(1) = -2.5
      DO 1 K=2,21
    1 RLOG(K) = RLOG(K-1) + DLTA
      DO 2 J=1,21
      RATIO(J) = 10**(RLOG(J))
      RATIO1 = RATIO(J)
      DO 3 I=1,N
      EX=2.*H*(((2.+RATIO1)/3.)**0.33333333)
      EXSQ=EX*EX
      XL=DSQRT(R(I)*R(I)+EXSQ)
      XL3=XL*XL*XL
      XL5=XL*XL*XL*XL*XL
      XTWO=(1./XL)+(EXSQ/(2.*XL3))+((3.*EXSQ*EXSQ)/(2.*XL5))
    3 X(I)=(1./R(I))+(RATIO1-1.)*XTWO
      SMXW=0.0
      SMXSQ=0.0
      SMESQ=0.0
      DO 4 I=1,N
      SMXW=SMXW+X(I)*W(I)
    4 SMXSQ=SMXSQ+X(I)*X(I)
      B=SMXW/SMXSQ
      DO 5 I=1,N
      E(I)=W(I)-(B*X(I))
    5 SMESQ=SMESQ+E(I)*E(I)
      MSE=SMESQ/N
      RMSE(J)=DSQRT(MSE)
      LRMSE = DLOG10(RMSE(J))
    2 CONTINUE
      K=20
      TEMP1 = RMSE(1)
      TEMP2 = RMSE(1)
```

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```
      TEMP3 = RMSE(1)
      ISUB1 = 1
      ISUB2 = 1
      ISUB3 = 1
      DO 8 L=2,K
      IF(RMSE(L) .GT. TEMP1) GO TO 6
      TEMP3 = TEMP2
      ISUB3 = ISUB2
      TEMP2 = TEMP1
      ISUB2 = ISUB1
      TEMP1 = RMSE(L)
      ISUB1 = L
      GO TO 8
    6 CONTINUE
      IF(RMSE(L) .GT. TEMP2) GO TO 7
      TEMP3 = TEMP2
      ISUB3 = ISUB2
      TEMP2 = RMSE(L)
      ISUB2 = L
      GO TO 8
    7 CONTINUE
      IF (RMSE(L) .GT. TEMP3) GO TO 8
      TEMP3 = RMSE(L)
      ISUB3 = L
    8 CONTINUE
      TX1 = RLOG(ISUB1 - 1)
      TX2 = RLOG(ISUB2 - 1)
      TX3=RLOG(ISUB3-1)
      TX11 = TX1 + 1.0
      TX21 = TX2 + 1.0
      TX31 = TX3 + 1.0
C     TEST FOR MINIMUN AT TX2
      JR1 = ISUB2 - ISUB1
      JR = IABS(JR1)
      IF(JR .EQ. 1) GO TO 99
C     FIND MINIMUNS FOR TX1 & TX2
      NOI = 11
      CALL FIBO(NOI,TX1,TX11,RLOG1,RMLOG,H)
      NOI = 11
      CALL FIBO(NOI,TX2,TX21,RLOGO,RMLOGO,H)
      TEMP = 10**RMLOG
      TEMPO = 10**RMLOGO
      CALL ANS(RLOG1,E1,E2,H)
      CALL ANS(RLOGO,E11,E21,H)
      GO TO 70
   99 CONTINUE
C     NO MINIMUN AT ISUB2
C     TEST FOR MINIMUN AT ISUB3
      JW1 = ISUB3 - ISUB1
      JW = IABS(JW1)
```

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```
      JWT1 = ISUB3 - ISUB2                                              EMPI1010
      JWT = IABS(JWT1)                                                  EMPI1020
      IF(JW .EQ. 1) GO TO 98                                            EMPI1030
      IF(JWT .EQ. 1) GO TO 98                                           EMPI1040
C     MINIMUN AT ISUB1 AND ISUB3                                        EMPI1050
      NOI = 11                                                          EMPI1060
      CALL FIBO(NOI,TX1,TX11,RLOG1,RMLOG,H)                             EMPI1070
      NOI = 11                                                          EMPI1080
      CALL FIBO(NOI,TX3,TX31,RLOGO,RMLOGO,H)                            EMPI1090
      TEMP = 10**RMLOG                                                  EMPI1100
      TEMPO = 10**RMLOGO                                                EMPI1110
      CALL ANS(RLOG1,E1,E2,H)                                           EMPI1120
      CALL ANS(RLOGO,E11,E21,H)                                         EMPI1130
      GO TO 70                                                          EMPI1140
   98 CONTINUE                                                          EMPI1150
C     O LY ONE DISTINCT MINIMUN                                         EMPI1160
      NOI = 11                                                          EMPI1170
      CALL FIBO(NOI,TX1,TX11,RLOG1,RMLOG,H)                             EMPI1180
      TEMP = 10**RMLOG                                                  EMPI1190
      CALL ANS(RLOG1,E1,E2,H)                                           EMPI1200
      E11 = 99999                                                       EMPI1210
      E21 = 99999                                                       EMPI1220
      TEMPO = 99999                                                     EMPI1230
   70 CONTINUE                                                          EMPI1240
      RETURN                                                            EMPI1250
      END                                                               EMPI1260
```

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```
      SUBROUTINE FIBO(N,X1,X2,X,Y,H)
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION FIB(20)
      DATA FIB/1.0D0,2.0D0,3.0D0,5.0D0,8.0D0,13.0D0,21.0D0,34.0D0,
     *55.0D0,89.0D0,144.0D0,233.0D0,377.0D0,610.0D0,987.0D0,1597.0D0,
     *2584.0D0,4181.0D0,6765.0D0,10946.0D0/
      DX=(X2-X1)/FIB(N)
      XL=X1
      XR=X2
      N=N-1
      X=XL+FIB(N)*DX
      CALL FUNC(X,VR,H)
    1 N=N-1
      X=XL+FIB(N)*DX
      CALL FUNC(X,VL,H)
    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,H)
      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,H)
      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,H)
      IF(V.GT.VR) GO TO 8
      X=X2
      Y=V
      RETURN
      END
```

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```
      SUBROUTINE FUNC(RLOG1,RMLOG,H)
      IMPLICIT REAL*8(A-H,O-Z)
      REAL*8 MSE
      DIMENSION WHAT(20),E(20),X(20),R(5),W(5)
      COMMON /A/ R,W
      N = 5
      RATIO1 = 10**(RLOG1)
      DO 3 I=1,N
      EX=2.*H*(((2.+RATIO1)/3.)**0.33333333)
      EXSQ=EX*EX
      XL=DSQRT(R(I)*R(I)+EXSQ)
      XL3=XL*XL*XL
      XL5=XL*XL*XL*XL*XL
      XTWO=(1./XL)+(EXSQ/(2.*XL3))+((3.*EXSQ*EXSQ)/(2.*XL5))
    3 X(I)=(1./R(I))+(RATIO1-1.)*XTWO
      SMXW=0.0
      SMXSQ=0.0
      SMESQ=0.0
      DO 4 I=1,N
      SMXW=SMXW+X(I)*W(I)
    4 SMXSQ=SMXSQ+X(I)*X(I)
      B=SMXW/SMXSQ
      DO 5 I=1,N
      E(I)=W(I)-(B*X(I))
    5 SMESQ=SMESQ+E(I)*E(I)
      MSE=SMESQ/N
      RMSE = DSQRT(MSE)
      RMLOG = DLOG10(RMSE)
      RETURN
      END
```

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```
      SUBROUTINE ANS(RLOG1,E1,E2,H)                                     ANS(  10
      IMPLICIT REAL*8(A-H,O-Z)                                          ANS(  20
      DIMENSION RAT1(30),WHAT(20),E(20),X(20)                           ANS(  30
      DIMENSION R(5),W(5)                                               ANS(  40
      COMMON /A/ R,W                                                    ANS(  50
      N = 5                                                             ANS(  60
      DO 27 I=1,N                                                       ANS(  70
      RATIO1 = 10**RLOG1                                                ANS(  80
      EX=2.*H*(((2.+RATIO1)/3.)**0.3333333)                             ANS(  90
      EXSQ = EX*EX                                                      ANS( 100
      XL = DSQRT(R(I)*R(I)+EXSQ)                                        ANS( 110
      XL3=XL*XL*XL                                                      ANS( 120
      XL5=XL*XL*XL*XL*XL                                                ANS( 130
      XTWO=(1./XL)+(EXSQ/(2.*XL3))+((3.*EXSQ*EXSQ)/(2.*XL5))            ANS( 140
   27 X(I)=(1./R(I))+(RATIO1 -1.)*XTWO                                  ANS( 150
      SMXW=0.0                                                          ANS( 160
      SMXSQ=0.0                                                         ANS( 170
      SMESQ=0.0                                                         ANS( 180
      DO 28 I=1,N                                                       ANS( 190
      SMXW=SMXW+X(I)*W(I)                                               ANS( 200
   28 SMXSQ=SMXSQ+X(I)*X(I)                                             ANS( 210
      B=SMXW/SMXSQ                                                      ANS( 220
      DO 29 I=1,N                                                       ANS( 230
      WHAT(I)= B*X(I)                                                   ANS( 240
   29 E(I)=W(I)-WHAT(I)                                                 ANS( 250
      E1=238.73241 *(1./B)                                              ANS( 260
      E2 = E1/RATIO1                                                    ANS( 270
      RETURN                                                            ANS( 280
      END                                                               ANS( 290
```

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```
      SUBROUTINE VARI(RMSE,RMSE1,CNT,KNT,ISW)                           VARI  10
      IMPLICIT REAL*8(A-H,O-Z)                                          VARI  20
      DIMENSION SUM(50),SSQ(50),RMSE(200),RMSE1(200)                    VARI  30
      INTEGER CNT                                                       VARI  40
      DO 1 L=1,50                                                       VARI  50
      SSQ(L) = 0.0                                                      VARI  60
    1 SUM(L) = 0.0                                                      VARI  70
      KSET = 1                                                          VARI  80
      DO 11 I=1,KNT                                                     VARI  90
      SUM(KSET) = SUM(KSET) + RMSE(I)                                   VARI 100
      SSQ(KSET) = SSQ(KSET) + (RMSE(I)**2)                              VARI 110
   11 CONTINUE                                                          VARI 120
      KSET = KSET + 1                                                   VARI 130
      DO 2 I=1,CNT                                                      VARI 140
      SUM(KSET) = SUM(KSET) + RMSE1(I)                                  VARI 150
      SSQ(KSET) = SSQ(KSET) + (RMSE1(I)**2)                             VARI 160
    2 CONTINUE                                                          VARI 170
      TSUM = SUM(1) + SUM(2)                                            VARI 180
      TSSQ = SSQ(1) + SSQ(2)                                            VARI 190
      N = KNT + CNT                                                     VARI 200
      TSS = TSSQ - ((TSUM**2.)/N)                                       VARI 210
      SSQSET =((SUM(1)**2.)/KNT)+((SUM(2)**2.)/CNT)                     VARI 220
      SSBS = SSQSET - ((TSUM**2.)/N)                                    VARI 230
      SSWS = TSS - SSBS                                                 VARI 240
      IDFWS = N - KSET                                                  VARI 250
      IDFBS = KSET - 1                                                  VARI 260
      AMSBS = SSBS/IDFBS                                                VARI 270
      AMSWS = SSWS/IDFWS                                                VARI 280
      F = AMSBS/AMSWS                                                   VARI 290
      CALL SIGNIF(F,IDFWS,ISW)                                          VARI 300
      RETURN                                                            VARI 310
      END                                                               VARI 320
```

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```
      SUBROUTINE SIGNIF(F,IDFWS,ISW)
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION FDIST(30)
      DATA FDIST/39.864D0,8.5263D0,5.5383D0,4.5448D0,4.0604D0,
     *3.7760D0,3.5894D0,3.4579D0,3.3603D0,3.2850D0,3.2252D0,3.1765D0,
     *3.1362D0,3.1022D0,3.0732D0,3.0481D0,3.0262D0,3.007D0,2.9899D0,
     *2.9747D0,2.9609D0,2.9486D0,2.9374D0,2.9271D0,2.9177D0,2.9091D0,
     *2.9012D0,2.8939D0,2.8871D0,2.8807D0/
      ISW = 0
      IF(IDFWS .GE.31) GO TO 2
      IF(F .GE. FDIST(IDFWS)) ISW = 1
      RETURN
    2 IF(IDFWS .GE. 40) GO TO 3
      IF(F .GE. 2.8807) ISW = 1
      RETURN
    3 IF(IDFWS .GE. 60) GO TO 4
      IF(F .GE. 2.8354) ISW = 1
      RETURN
    4 IF(IDFWS .GE. 120) GO TO 5
      IF(F .GE. 2.7914) ISW = 1
      RETURN
    5 IF(F .GE. 2.7478) ISW = 1
      RETURN
      END
```