MODULUS: A Microcomputer-Based Backcalculation System

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MODULUS is a microcomputer-based backcalculation system that can be used on 2-, 3-, or 4-layer pavement systems with or without rigid bedrock layers. It uses a linear elastic program to generate a data base of deflection bowls. Once generated, a pattern search routine is used to fit measured and calculated bowls; error minimization is rapid, less than 5 sec per bowl on a 386 type microcomputer. The system is general purpose and can process data from any nondestructive testing device. The user has several options when performing backcalculations, including specifying the depth to bedrock or using existing default data bases for common pavement structures. Outputs include a summary listing showing the mean and variances of moduli values and also a graphical output that plots moduli values along a project and automatically performs subsectioning according to the recommended AASHTO procedure. The MODULUS system is described together with discussion on continuing efforts to validate the moduli values. These validations include (a) comparison of laboratory and field moduli values, and (b) the use of multidepth deflectometers to monitor deflections within the pavement system. The results of monthly deflection measurements on experimental pavements around the state of Texas are also described. Finally, current efforts to improve the MODULUS system are described. These attempts include automatically estimating the depth to bedrock using either the error minimization or zero deflection approach.

In order to assist the engineer in the pavement analysis process, an efficient procedure must be developed that permits modulus backcalculation from surface deflection data and allows review of the data to determine if subsectioning is required. One such microcomputer-based procedure is called "MODULUS" (*1*,*2*). MODULUS uses a linear elastic program to generate a data base of computed deflection bowls, before fitting the measured bowls. Once the data base is generated for a particular pavement, the linear elastic program is not called again, no matter how many bowls are to be analyzed. Therefore, the data base can be generated before testing, and the measured bowls can be processed in real time. The procedure as described in later sections makes use of the properties of the linear elastic solution by working in terms of modular ratios. It can handle a 2-, 3-, or 4-layer problem; in the case of a 4-layer problem, the elastic layer program is automatically run at least 27 times (3 surface × 3 base × 3 subbase modular ratios) to generate the required data base. A pattern search routine is used to fit the measured and calculated bowls.

The data base concept has an advantage over existing programs such as CHEVDEF (*3*), which calls the linear elastic deflection program (NLAYER + 1) * ITER + 1 times for each bowl, where NLAYER is the total number of layers and ITER is the user-specified number of convergence iterations. In the case of a 4-layer system, the CHEVDEF program with ITER = 3 would require 16 runs of the linear elastic program per bowl, whereas the MODULUS program would require only 27 runs independent of the number of bowls to be analyzed. MODULUS has been designed for the highway environment for which many deflection bowls are measured at regular intervals along a project.

A review of the theoretical background to the MODULUS backcalculation procedure is contained in the following section; the next section contains an overview of the system itself, including options available to the user in inputting data, performing backcalculations, and displaying results; the next section contains some case studies conducted in Texas with comparison of field and laboratory *E* values; the last section describes attempts to validate backcalculated values using instruments buried in pavements. (Multidepth deflectometers were used for this purpose and this approach looks extremely promising. Current activities to automatically locate bedrock are also presented in this section.)

THEORETICAL BACKGROUND

The theoretical background includes the following formulation of the objective function and convexity test. [More details may be found in the literature (*1*,*2*).]

Formulation of the Objective Function

The procedure is to find the set of parameters that corresponds to the best fit of the measured deflection bowl. The best fit is achieved by minimizing the error between the measured and calculated deflection bowl. The objective function to be minimized is therefore written as

$$\varepsilon^2 = \sum_{i=1}^{s} \left(\frac{W_i^m - W_i^c}{W_i^m} \right)^2 \mathrm{We}_i \qquad (1)$$

where

ε^2 = squared error,
W_i^m = measured deflection at sensor i,
W_i^c = computed deflection at sensor i,
s = number of sensors, and
We_i = user-supplied weighing factor for sensor i.

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Equation 1 can also be written as

$$\varepsilon^2 = \sum_{i=1}^{s} \left(1 - \frac{W_i^c}{W_i^m}\right)^2 \mathrm{We}_i \tag{2}$$

The unknown variables are those required to compute the surface deflections W_i^c, i.e.,

$$W_i^c = F_i(X_j) \qquad j = 1, 2, 3, \ldots n \tag{3}$$

where X_j are n unknown variables.

Any solution to Equation 2 calls for a solution of Equation 3, which is obtained numerically in most cases by running a separate program (such as BISAR and CHEVRON in the case of linear elasticity and ILLI-PAVE in the case of nonlinear elasticity). The number of calls depends on the minimization algorithm used. In the case of linear elasticity, the computed deflection W_i^c at sensor i (or radial distance r_i) can be expressed as follows:

$$W_i^c = f_i(E_k, \nu_k, h_k, r_i, O)$$

$$i = 1, 2, \ldots s; \qquad k = 1, 2, \ldots n. \tag{4}$$

where

E_k = modulus of elasticity for layer k,
n = number of layers,
ν_k = Poisson's ratio for layer k,
h_k = thickness of layer k, and
O = other variables, such as pressure, contact area, radius, interface conditions.

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

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

$$W_i^c = \frac{p}{E_{sg}} f^i\left(\frac{E^1}{E_{sg}}, \ldots, \frac{E^k}{E_{sg}}, \ldots, \frac{E^n}{E_{sg}}\right) \tag{5}$$

where

p = pressure (psi), and
E_{sg} = subgrade modulus of elasticity (ksi).

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

From Equations 2 and 5, it is possible to obtain a direct solution for the subgrade modulus E_{sg}, by taking derivatives of Equation 2 with respect to E_{sg} and equating them to zero to minimize the squared error. Details of the derivation are given in the literature (*1,2*), and the calculated solution for E_{sg} is shown in Equation 6.

$$E_{sg} = \frac{p f_1 \sum_{i=1}^{s} f_i^2 \mathrm{We}_i / f_1^2 (W_i^m)^2}{\sum_{i=1}^{s} f_i \mathrm{We}_i / f_1 W_i^m} \tag{6}$$

Although Equation 6 can be simplified, this normalized form is preferred for data processing. Equation 6 provides a direct method for estimating subgrade modulus E_{sg} from the data base of normalized f_i/f_1 deflection values. This data base is built from multiple runs of the linear elastic program. Each run corresponds to a set of modular ratios E_k/E_{sg}. Therefore, an E_{sg} can be calculated for each set of $f_i(E_k/E_{sg})$. In order to decide which solution minimizes the error, it is necessary to calculate the squared error associated with each set of modular ratios using an expanded version of Equation 2.

$$\varepsilon^2 = \sum_{i=1}^{s} \left(1 - \frac{p f_i}{E_{sg} W_i^m}\right)^2 \mathrm{We}_i \tag{7}$$

where E_{sg} is the particular solution of Equation 6 corresponding to the given modular ratio, and p is the actual pressure under which the W_i^c values were calculated. By locating the minimum squared error from Equation 7, a seed value of E_{sg} is selected, and the corresponding seed values of E_{BASE} and E_{SURFACE} are calculated. These seed values are used as input to the pattern search routine.

In the MODULUS system, the Hookes-Jeeves pattern search algorithm is used to find the set of moduli values that minimize error (*4*). This algorithm is known always to converge (sometimes to a local minimum), unlike other algorithms, which may not converge. The possibility of a local minimum is evaluated by a convexity test as described in the next subsection.

Convexity Test

This test involves evaluating the shape of the error surface through the minimum error solution. This test is illustrated with the aid of an example. Table 1 shows the calculated E_{sg} and ε^2 values from Equations 6 and 7, for a range of modular ratios for a particular pavement and input deflection bowl. Figure 1 shows a three-dimensional representation of the error surface. The minimum error occurs at modular ratios $E_1/E_{sg} = 30$, $E_2/E_{sg} = 3$, $E_{sg} = 35.7$ ksi. (These values are used as input seed values for the pattern search routine.) The two-dimensional plot of the error surfaces through the minima are shown in Figure 2. In both cases, the surface is convex and the solution passes the convexity test.

Figure 3 shows an error surface that fails the convexity test. If the slope of the error surface changes, then the error surface

TABLE 1 CALCULATED E_{sg} AND ε^2 FOR EACH MODULAR RATIO FOR A PARTICULAR PAVEMENT TYPE AND INPUT FWD DEFLECTION BOWL

E_1/E_{sg}	E_2/E_{sg}	$^aE_{sg}$ (ksi)	$^b\varepsilon^2$
10	1	43.2	0.4496
30	1	39.7	0.1902
100	1	36.9	0.0367
10	3	36.8	0.0230
30	3	35.7	0.0213
100	3	34.7	0.0269
10	10	34.9	0.0866
30	10	34.4	0.153
100	10	33.9	0.231

[a] From Equation 6.
[b] From Equation 7.

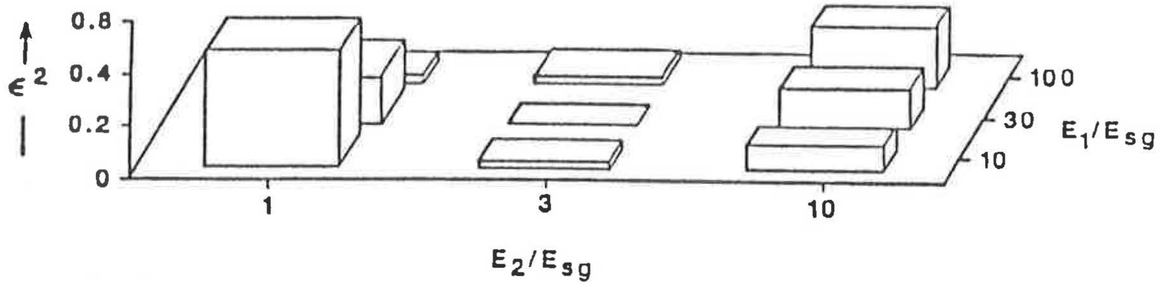


FIGURE 1 Three-dimensional representation of the error surface from Table 1.

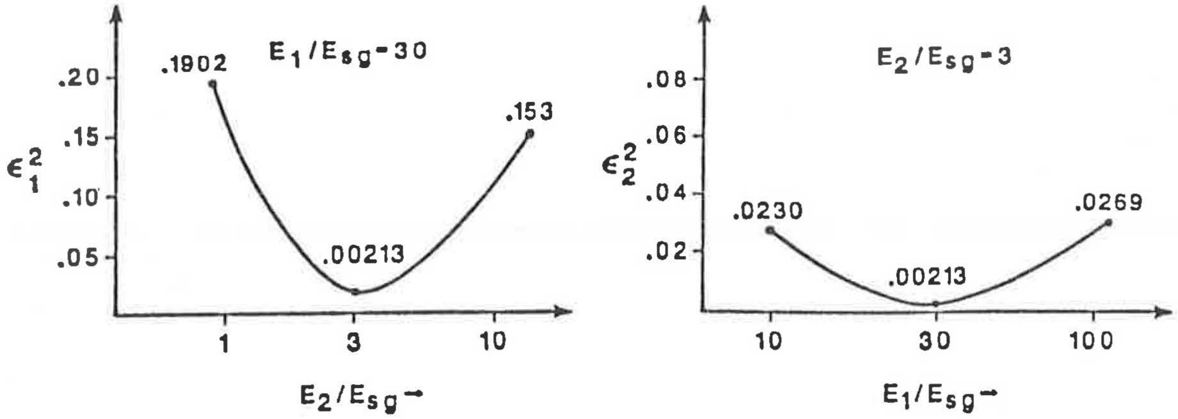


FIGURE 2 Two-dimensional representation of error surface through minimum.

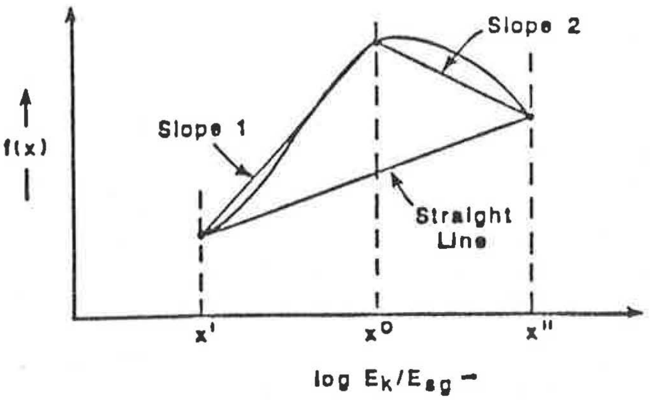


FIGURE 3 Error surface that fails convexity test.

is not convex and MODULUS prints the warning message "failed convexity test." This message implies that increasing the range of acceptable moduli values will possibly result in a lower minimum error.

DESCRIPTION OF THE MODULUS SYSTEM

The MODULUS system is shown schematically in Figure 4. The system has three major subsystems, which are described in the following paragraphs. When running MODULUS, the Main Menu shown in Figure 5 prompts the user to select one of them.

Subsystems

Subsystem 1: Convert FWD Data to Input Data. This subsystem inputs the field diskette from a Dynatest FWD and converts it into a format compatible with the backcalculation subsystem (the .OUT file). Typically during testing, between 1 and 4 drops are made at regular intervals along the highway. The drops may be at a fixed load or at increasing loads. This subsystem requires the user to specify which of these drops are to be included in the analysis. For example, all drop number 2s may be extracted for analysis. For any other NDT device, the .OUT file must be input manually into the required file format.

Subsystem 2: Run MODULUS Backcalculation. The user has the following three options for doing the backcalculation:

- *Option 1—Use an Existing Fixed Design.* The system has built into it 24 default data bases of commonly found pavement types (12 types × 2 depths to a rigid layer), as shown in Figure 6. The users have the option of replacing these default data bases with their own (created using Option 3). In Option 1, the linear elastic program is not run. Only the search routine is used to match the calculated deflections in the data base with the input field deflections.
- *Option 2—Input Material Types.* This option was developed for the inexperienced user who is unfamiliar with backcalculation procedures. The user simply inputs material types, thicknesses, and test temperature, as shown in Figure 7, for example. The system then selects ranges of acceptable moduli values and reasonable Poisson's ratios. In Option 2, the linear

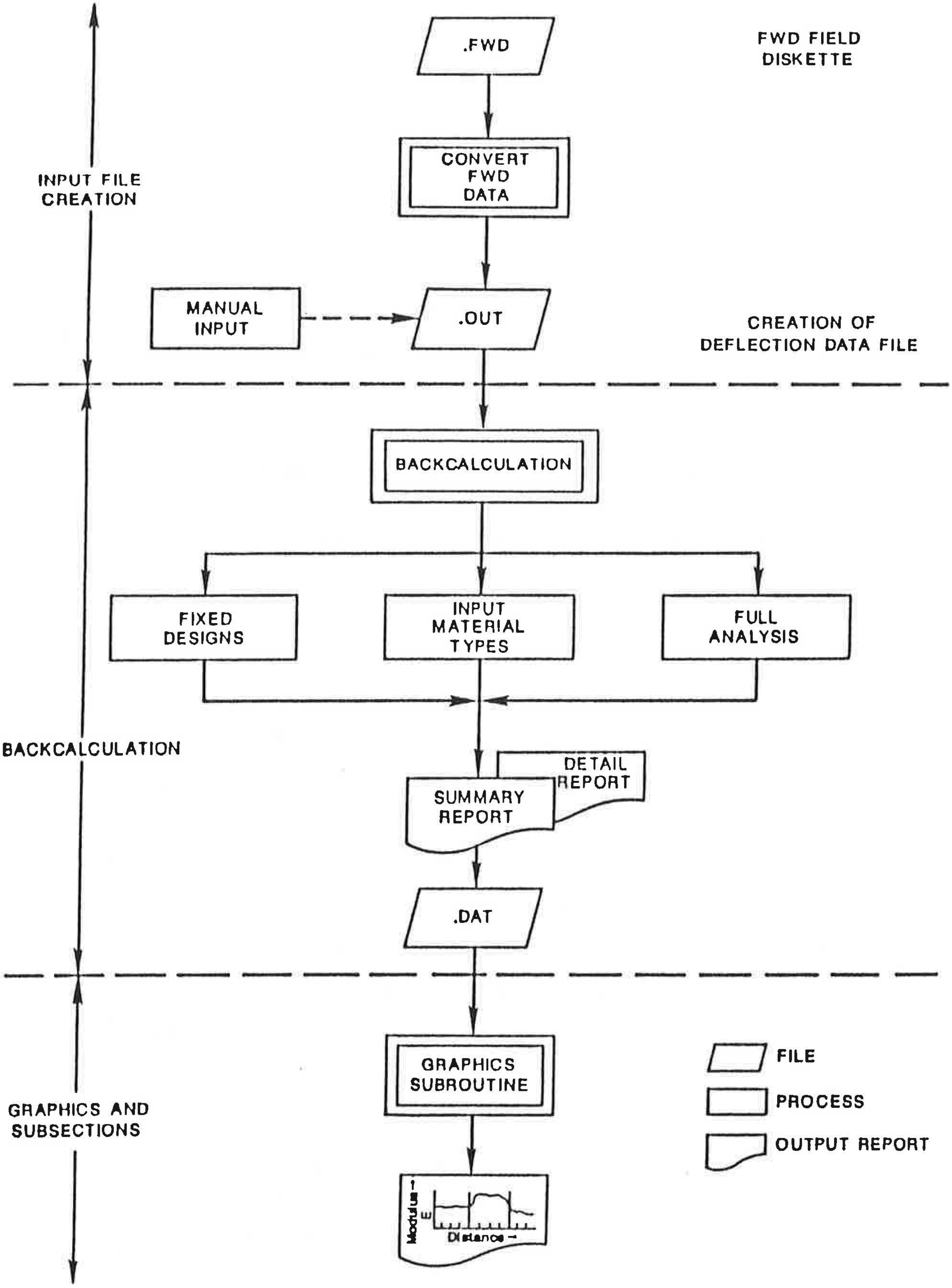
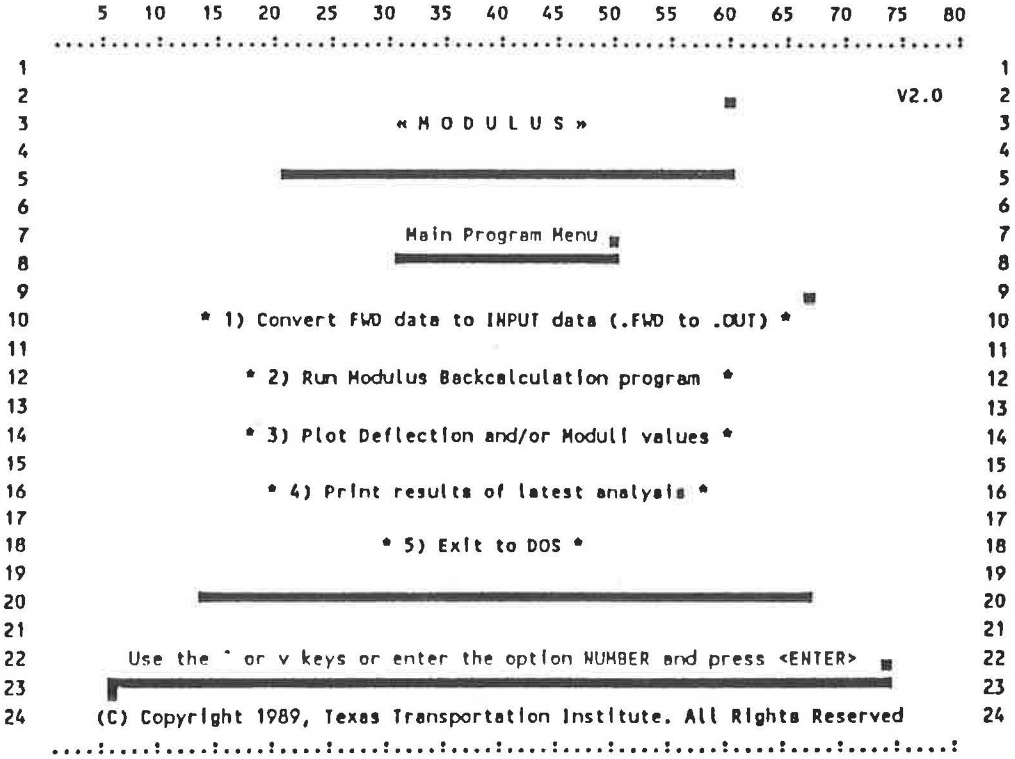


FIGURE 4 MODULUS system flowchart.



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                                                                       V2.0
                             « M O D U L U S »



                             Main Program Menu


              * 1) Convert FWD data to INPUT data (.FWD to .OUT) *

                 * 2) Run Modulus Backcalculation program  *

                 * 3) Plot Deflection and/or Moduli values *

                   * 4) Print results of latest analysis *

                            * 5) Exit to DOS *



        Use the ^ or v keys or enter the option NUMBER and press <ENTER>

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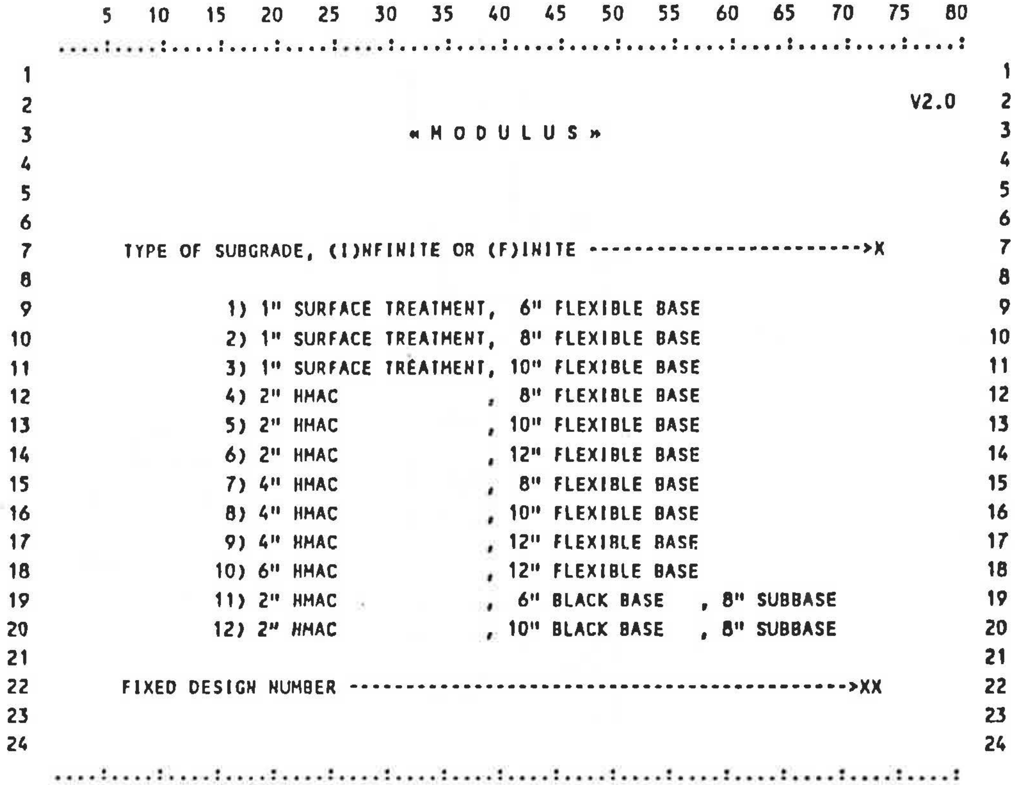
FIGURE 5 Main menu screen from MODULUS.



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                                                                        V2.0
                              « M O D U L U S »

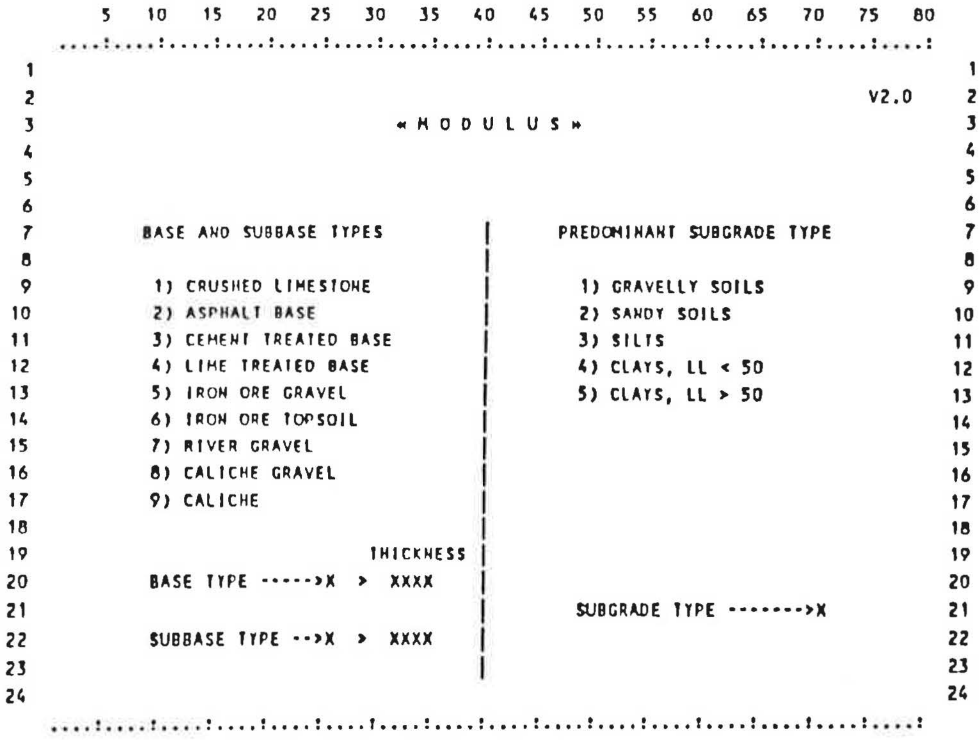


      TYPE OF SUBGRADE, (I)NFINITE OR (F)INITE ------------------------>X

                   1) 1" SURFACE TREATMENT,  6" FLEXIBLE BASE
                   2) 1" SURFACE TREATMENT,  8" FLEXIBLE BASE
                   3) 1" SURFACE TREATMENT, 10" FLEXIBLE BASE
                   4) 2" HMAC              ,  8" FLEXIBLE BASE
                   5) 2" HMAC              , 10" FLEXIBLE BASE
                   6) 2" HMAC              , 12" FLEXIBLE BASE
                   7) 4" HMAC              ,  8" FLEXIBLE BASE
                   8) 4" HMAC              , 10" FLEXIBLE BASE
                   9) 4" HMAC              , 12" FLEXIBLE BASE
                  10) 6" HMAC              , 12" FLEXIBLE BASE
                  11) 2" HMAC              ,  6" BLACK BASE   , 8" SUBBASE
                  12) 2" HMAC              , 10" BLACK BASE   , 8" SUBBASE

      FIXED DESIGN NUMBER ------------------------------------------->XX
```

FIGURE 6 Existing data bases within MODULUS backcalculation Option 1.



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                                                                     V2.0
                               «M O D U L U S»



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

FIGURE 7 A MODULUS input screen for backcalculation Option 2.

elastic program is run to generate a deflection data base before the pattern search routine.

- *Option 3—Run a Full Analysis.* This option is for the experienced user. As shown in Figure 8, the user supplies all the layer thicknesses including depth to bedrock (H4), sensor spacing, and the acceptable ranges of layer moduli.

Once the analysis is complete, a summary or detailed listing of the backcalculated *E* values is produced. A typical summary listing is presented in Table 2. This table presents the results of the analysis of multiple drops taken at the same spot. The last column in this table is the average error between measured and computed deflection bowls. The percentage error calculation, convexity test results, and other items are available on request in a detail output.

Subsystem 3. Plot Deflection and Moduli Values. The results of the backcalculation process are displayed graphically in this subsystem. An example is shown in Figure 9. MODULUS also uses the cumulative difference method of the *AASHTO Design Guide* (*5*) to perform subsectioning. Mean and standard deviation of moduli values are produced for each subsection identified.

System Requirements

MODULUS occupies approximately 300 kB and minimum system requirements are as follows:

- IBM AT or compatible microcomputer
- 640 kB RAM
- DOS 3.0 or later
- Math co-processor chip 80287 (or equivalent)
- A hard disk
- EGA graphics card with 256 kB of screen memory and a compatible RGB monitor

It is recommended that an advanced microcomputer (286 or 386) be used to minimize execution time. Time estimates for running a simple 3-layer system (surface, base, and semi-infinite subgrade) are shown below:

Machine	*Generate Deflection Data Base (sec)*	*Search Routine (sec/bowl)*
286/12 MHz	258	6.5
386/20 MHz	57	1.8

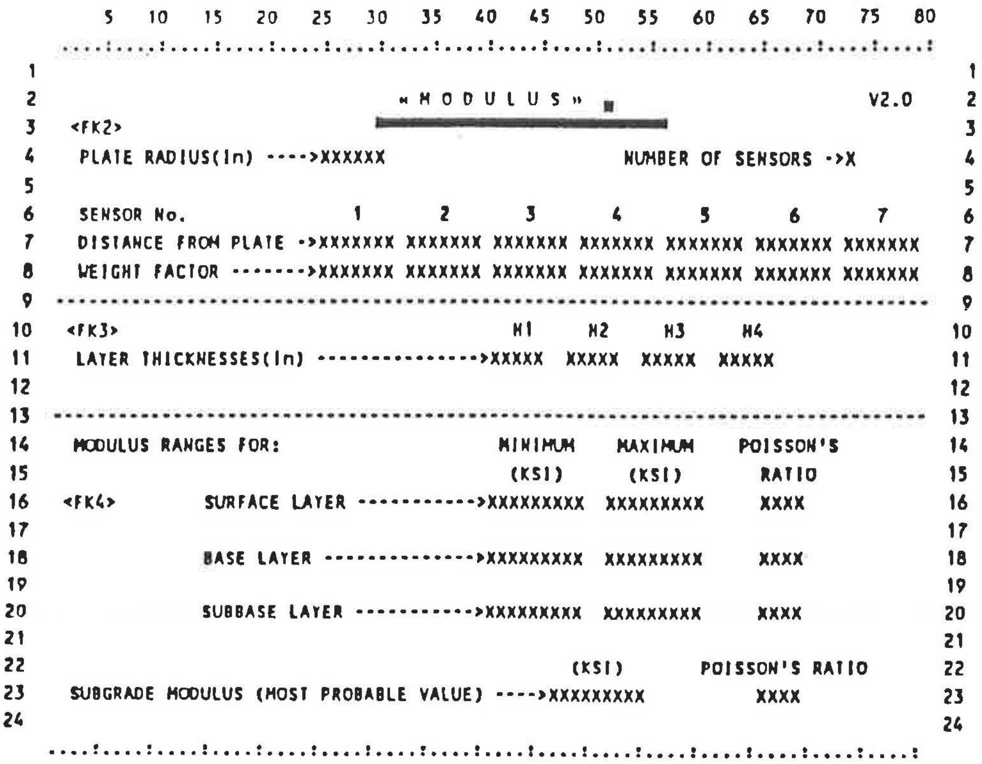
The time to generate the data base increases as the number of layers and range of acceptable moduli values increase.

CASE STUDIES USING MODULUS

In this section, the following four applications of the MODULUS backcalculation system are presented:

1. Comparison with BISDEF.
2. Analysis of multiple drops at the same location.
3. Effects of depth to rigid layer.
4. Seasonal variations in backcalculated moduli.

All of the deflection data used were collected with a Dynatest FWD.



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                              « M O D U L U S »                           V2.0
<FK2>
 PLATE RADIUS(In) ---->XXXXXX                      NUMBER OF SENSORS ->X

 SENSOR No.                1        2        3        4        5        6        7
 DISTANCE FROM PLATE ->XXXXXXX XXXXXXX XXXXXXX XXXXXXX XXXXXXX XXXXXXX XXXXXXX
 WEIGHT FACTOR ------->XXXXXXX XXXXXXX XXXXXXX XXXXXXX XXXXXXX XXXXXXX XXXXXXX
...........................................................................
<FK3>                                      H1      H2      H3      H4
 LAYER THICKNESSES(In) --------------->XXXXX  XXXXX  XXXXX  XXXXX

...........................................................................
 MODULUS RANGES FOR:                      MINIMUM     MAXIMUM     POISSON'S
                                           (KSI)       (KSI)        RATIO
<FK4>        SURFACE LAYER ----------->XXXXXXXXX  XXXXXXXXX      XXXX

             BASE LAYER -------------->XXXXXXXXX  XXXXXXXXX      XXXX

             SUBBASE LAYER ----------->XXXXXXXXX  XXXXXXXXX      XXXX

                                                  (KSI)      POISSON'S RATIO
SUBGRADE MODULUS (MOST PROBABLE VALUE) ---->XXXXXXXXX          XXXX
```

FIGURE 8 A MODULUS input screen for the full analysis option.

TABLE 2 MODULUS OUTPUT FROM MULTIPLE DROPS AT THE SAME LOCATION

TTI DEFLECTION ANALYSIS SYSTEM

District: 17
County: 21
Highway/Road: TTIAMI

	Thickness(In)	MODULI RANGE(psi) Minimum	MODULI RANGE(psi) Maximum
Pavement:	5.00	200,000	800,000
Base:	8.00	30,000	200,000
Subbase:	0.00	0	0
Subgrade:	INFINITY	30,000	

Station	Load (lbs)	Measured Deflection (mils): R1	R2	R3	R4	R5	R6	R7	Calculated Moduli values (psi): SURFACE(E1)	BASE(E2)	SUBBASE(E3)	SUBGRADE(E4)	Absolute % ERROR/Sensor
9.010	9,167	9.34	5.49	3.08	2.08	1.71	1.26	0.83	484,287	71,425	0	35,045	4.31
9.020	8,815	8.85	5.40	3.08	2.12	1.63	1.30	1.05	461,041	89,276	0	32,408	1.93
9.030	8,791	8.73	5.36	3.08	2.12	1.63	1.26	1.01	511,722	83,816	0	32,739	1.66
9.040	8,775	8.69	5.40	3.08	2.08	1.63	1.26	1.01	547,717	79,214	0	32,772	2.00
9.050	8,751	8.73	5.40	3.08	2.12	1.63	1.26	1.01	529,906	80,526	0	32,566	1.74
9.060	8,679	8.61	5.36	3.04	2.08	1.63	1.26	1.01	528,668	82,394	0	32,503	2.16
9.070	8,695	8.61	5.40	3.08	2.08	1.59	1.26	1.05	558,059	79,195	0	32,380	1.84
9.080	8,719	8.61	5.36	3.08	2.08	1.63	1.26	1.01	548,575	81,009	0	32,576	1.96
9.090	8,871	8.90	5.45	3.12	2.12	1.63	1.30	1.05	491,264	84,334	0	32,507	1.76
9.100	8,735	8.73	5.40	3.08	2.12	1.67	1.22	0.93	604,100	69,802	0	33,149	2.97
9.110	8,719	8.73	5.40	3.08	2.12	1.67	1.26	0.97	534,908	78,841	0	32,584	2.63
9.120	8,663	8.65	5.40	3.08	2.12	1.63	1.26	0.97	576,865	75,029	0	32,485	2.27
Mean:		8.77	5.40	3.08	2.10	1.64	1.26	1.00	531,426	79,572	0	32,810	2.27
Std. Dev:		0.20	0.04	0.02	0.02	0.03	0.02	0.05	40,243	5,469	0	734	0.75
Var Coeff(%):		2.31	0.69	0.55	0.98	1.84	1.63	4.94	7.57	6.87	0.00	2.24	33.08

TABLE 5 TYPICAL DEFLECTION DATA FROM ONE SITE IN TTI STUDY 1123

DISTRICT: 21 SITE: 5 HIGHWAY: FM 1425 SOUTH MP 3

MONTH	TIME		LOAD	W1	W2	W3	W4	W5	W6	W7	M1	M2	TS	T1	T2
OCT	AM	LOW	9664	21.33	13.98	7.96	5.20	3.93	3.12	2.57	0.000	-0.131	0.0	87.0	87.0
		HIGH	9552	24.52	16.71	9.57	5.92	4.25	3.28	2.69					
		NORM	9000	22.10	14.87	8.61	5.44	4.03	3.12	2.56					
OCT	PM	LOW	9344	26.80	15.13	8.12	5.36	4.13	3.28	2.69	0.000	-0.131	0.0	98.0	89.0
		HIGH	9336	30.89	18.46	9.77	5.96	4.33	3.40	2.69					
		NORM	9000	27.15	16.60	8.95	5.67	4.16	3.25	2.62					
NOV	AM	LOW	9672	20.66	14.57	8.80	5.56	4.29	3.16	2.77	-0.136	-0.195	98.0	83.0	83.0
		HIGH	9608	24.12	16.83	9.97	6.24	4.41	3.40	2.69					
		NORM	9000	21.56	15.19	9.08	5.72	4.09	3.17	2.56					
NOV	PM	LOW	9472	23.93	14.61	8.20	5.36	4.09	3.20	2.65	0.000	-0.195	104.0	94.0	85.0
		HIGH	9352	27.43	17.23	9.57	5.96	4.37	3.40	2.77					
		NORM	9000	25.47	16.28	9.14	5.71	4.17	3.23	2.61					
DEC	AM	LOW	9808	20.34	15.09	9.77	6.32	4.41	3.40	2.65	0.000	-0.109	92.0	77.0	76.0
		HIGH	9776	23.41	17.03	10.53	6.55	4.53	3.48	2.77					
		NORM	9000	19.67	14.34	9.04	5.80	4.12	3.16	2.50					
DEC	PM	LOW	9600	20.23	13.47	8.04	5.36	4.05	3.20	2.61	-0.111	-0.109	89.0	92.0	90.0
		HIGH	9576	24.00	16.32	9.69	6.12	4.41	3.44	2.73					
		NORM	9000	20.90	14.57	8.99	5.80	4.19	3.22	2.57					
JAN	AM	LOW	7728	9.29	7.53	5.59	4.01	3.02	2.32	1.82	-0.847	-0.045	55.0	55.0	60.0
		HIGH	7728	10.15	8.32	6.15	4.49	3.22	2.48	1.94					
		NORM	9000	11.56	9.57	7.13	5.10	3.77	2.86	2.25					
JAN	PM	LOW	10288	13.42	10.89	8.00	5.68	4.21	3.24	2.57	-1.584	-0.066	58.0	57.0	60.0
		HIGH	10392	14.84	12.32	9.25	6.59	4.85	3.64	2.81					
		NORM	9000	12.47	10.29	7.65	5.48	3.97	3.00	2.32					
FEB	PM	LOW	10096	16.53	12.63	8.64	5.88	4.29	3.28	2.65	-1.355	-0.023	75.0	63.0	63.0
		HIGH	10056	18.61	14.73	10.33	6.95	4.93	3.60	2.89					
		NORM	9000	15.85	12.57	8.81	5.97	4.24	3.15	2.51					
MAR	AM	LOW	9656	24.75	17.66	10.61	6.63	4.65	3.52	2.85	-0.822	0.000	109.0	82.0	78.0
		HIGH	9464	26.99	18.81	10.97	6.71	4.73	3.60	2.89					
		NORM	9000	24.91	17.36	10.28	6.36	4.51	3.44	2.78					
MAR	PM	LOW	9488	25.58	16.36	9.41	5.96	4.41	3.40	2.73	0.000	0.000	108.0	92.0	80.0
		HIGH	9376	29.28	18.93	10.85	6.79	4.93	3.76	3.04					
		NORM	9000	27.05	17.90	10.22	6.33	4.50	3.43	2.73					

NOTE: M=moisture sensors (in bars), TS=surface temperature, T=thermocouples (°F) at bottom of asphalt and base.

tests on the asphalt and triaxial tests on the base and subgrade. The base samples were remolded to approximately the same moisture content and density as found in the field.

A summary of the first 6 months' deflection data collected on this site is presented in Table 5. On average, eight drops at four different load levels were made per site per visit. This table shows the high, low, and normalized average deflection bowls for the drop closest to 9,000 lb. These normalized deflections for this site were processed through the MODULUS system with results as shown in Figures 11 and 12.

Figure 11 shows the backcalculated *E* value of the asphalt layer plotted against the temperature at the bottom of the asphalt at the time of testing. Also included on this figure are the laboratory determined stiffness values from Figure 10. The laboratory data were collected with the diametrical resilient modulus device, at loading times of 50 and 100 ms. The FWD loading time is approximately 28 ms. There appears to be good agreement between measured and calculated surface moduli for this site.

The variation in calculated subgrade modulus throughout the year is shown in Figure 12. The peak value corresponds to the January data when the pavement was at its coldest.

CURRENT ACTIVITIES TO IMPROVE SYSTEM

The current activities are focused on (a) using pavement instrumentation to validate backcalculated moduli values, and

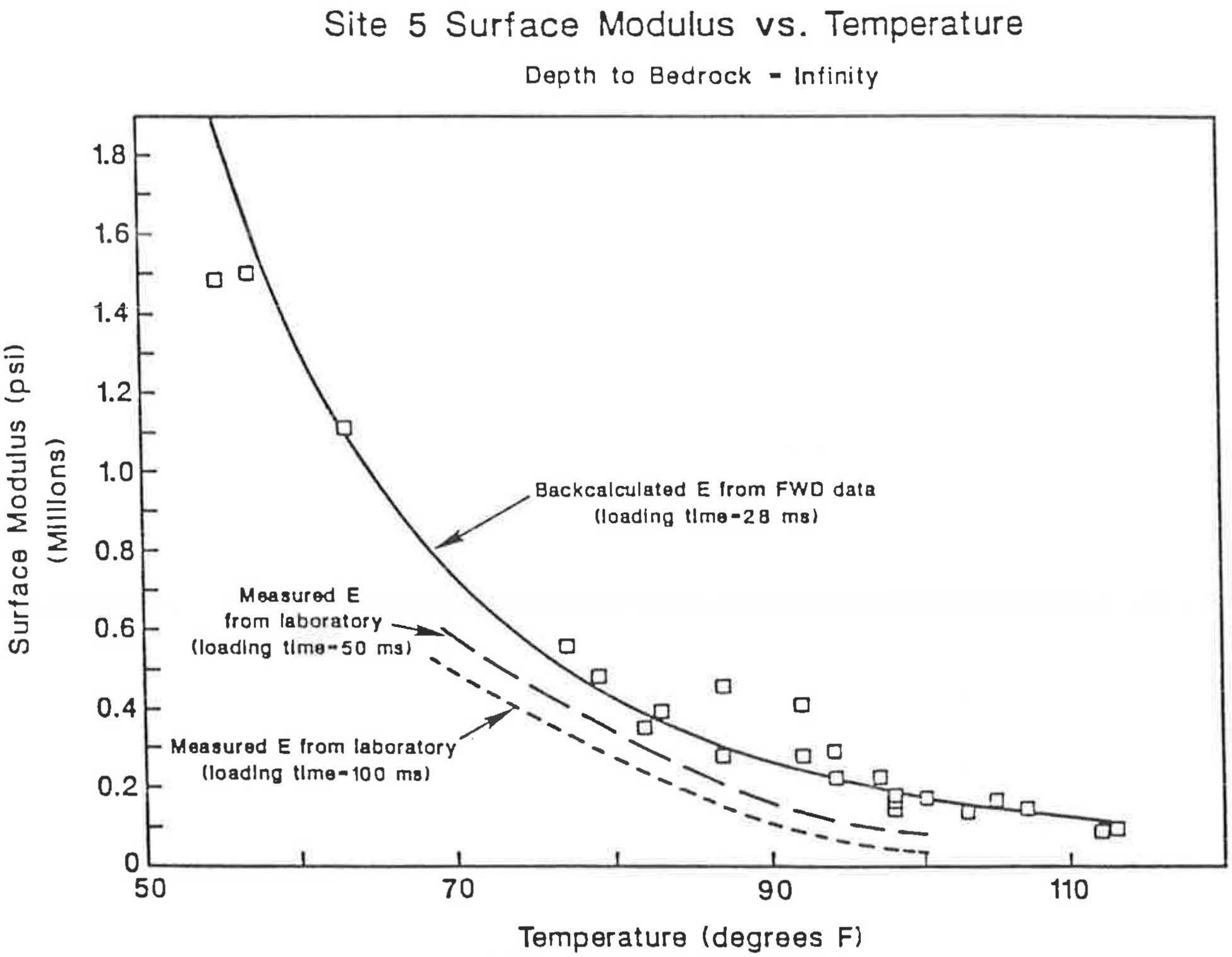


FIGURE 11 Comparison of backcalculated and measured moduli for asphalt surfacing on Site 5.

(b) efforts to automatically locate depth to bedrock. Both of these are discussed in the following paragraphs.

Instrumentation

The best procedure for validating backcalculation results is by using pavement instrumentation. Because it is impossible to replicate field conditions in the laboratory, it is unlikely that any correspondence exists between laboratory- and field-derived *E* values. The Texas Transportation Institute has been evaluating a multidepth deflectometer (*6,7*). By simultaneously taking surface and depth deflections, it is possible to validate backcalculated *E* values. On thick pavements (5 in. of asphalt over 24 in. of granular base), good agreement was found (*7*) on moduli values calculated independently from surface and depth deflections. Work in this area is continuing.

Depth to Bedrock

Table 4 highlighted the significant influence bedrock has on the backcalculated *E* values. Two approaches are being evaluated to automatically detect bedrock from the deflection data:

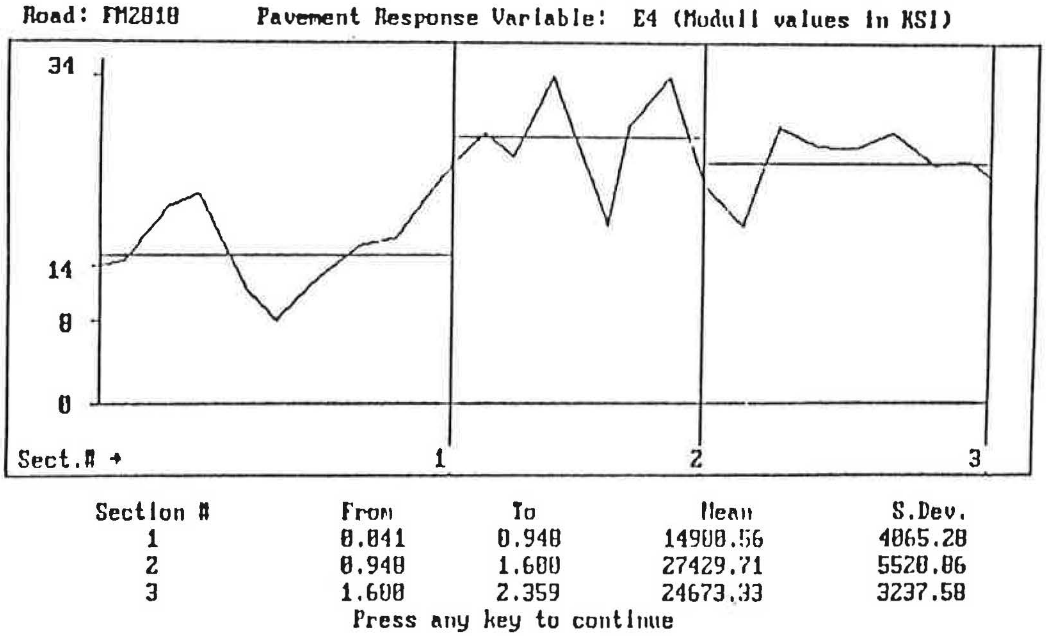
1. Plotting outer sensor deflections (Sensors 5, 6, 7) against the inverse of the radial distance and extrapolating the line to the zero deflection point. Assuming the outer sensors are only affected by the subgrade, then a point of zero surface deflection could indicate the depth of a rigid layer.
2. By rerunning MODULUS using different depths to bedrock and searching for the minimum error condition.

Field tests are under way to evaluate if either of these improve the estimation of layered elastic properties.

CONCLUSIONS

MODULUS is a user-friendly backcalculation system that should assist engineers in their pavement analysis studies. The system has already been prereleased to several state departments of transportation and some consultants. Their recommendations were included in the final system that is ready for release by NCHRP. The system produces results similar to those of existing programs, such as CHEVDEF, but has several additional features that should benefit, such as graphic outputs and subsectioning.

More work is required in the area of correlating laboratory results and field backcalculations. The preliminary subgrade correlations are poor. It is thought that the current triaxial test is only a limited simulation of the stress conditions that



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

```
     Section #            From        To            Mean           S.Dev.
         1                0.041       0.940         14900.56       4065.28
         2                0.940       1.600         27429.71       5520.06
         3                1.600       2.359         24673.33       3237.58
                              Press any key to continue
```

FIGURE 9 Graphical output of backcalculated *E* values, including subsectioning.

Comparison with BISDEF

The output of MODULUS was compared with that of BISDEF, which is the BISAR version of the backcalculation program developed by the Corps of Engineers (*3,8*). In this analysis, FWD data were collected on an experimental pavement (at the Texas A&M Research Annex) consisting of 5 in. of asphalt over an 8-in. granular base over a sandy gravel subgrade. The backcalculated moduli values are presented in Table 3. Both procedures give similar *E* values, particularly for the subgrade layer.

Multiple Drops at the Same Location

In order to evaluate the repeatability of MODULUS, 12 drops of the FWD were made at the same location on Section 9 at the TTI Research Annex. The deflection bowls and backcalculated *E* values are presented in Table 2. The purpose of this and other tests (*2*) was to determine the number of readings to be taken at an individual site to characterize the pavement to a specified level of confidence. However, the first deflections taken were significantly higher than the following readings. In Table 3, the maximum deflection of the first drop is 2.85 standard deviations greater than the mean; all subsequent drops are within one standard deviation.

For FWD testing, at a minimum an agency should take two drops at each location and the second should be used for data analysis.

Effects of Rigid Layer

The placement of a rigid layer within the subgrade has considerable effect on the backcalculated moduli values. The Corps of Engineers recommends a layer placed at 20 ft (*3*). The existing MODULUS program allows the placement of a rigid layer at any depth in the subgrade. To illustrate, the same data set was rerun using several depths to a rigid layer. The resulting effect on the backcalculated subgrade modulus and fitting error between measured and calculated deflections is presented in Table 4.

TABLE 3 COMPARISON OF *E* VALUES BACKCALCULATED USING BISDEF AND MODULUS ON SECTION 9 AT THE TTI RESEARCH ANNEX

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

NOTE: Error is the absolute percent error per sensor.

TABLE 4 EFFECT OF PLACING A RIGID LAYER AT VARYING DEPTHS

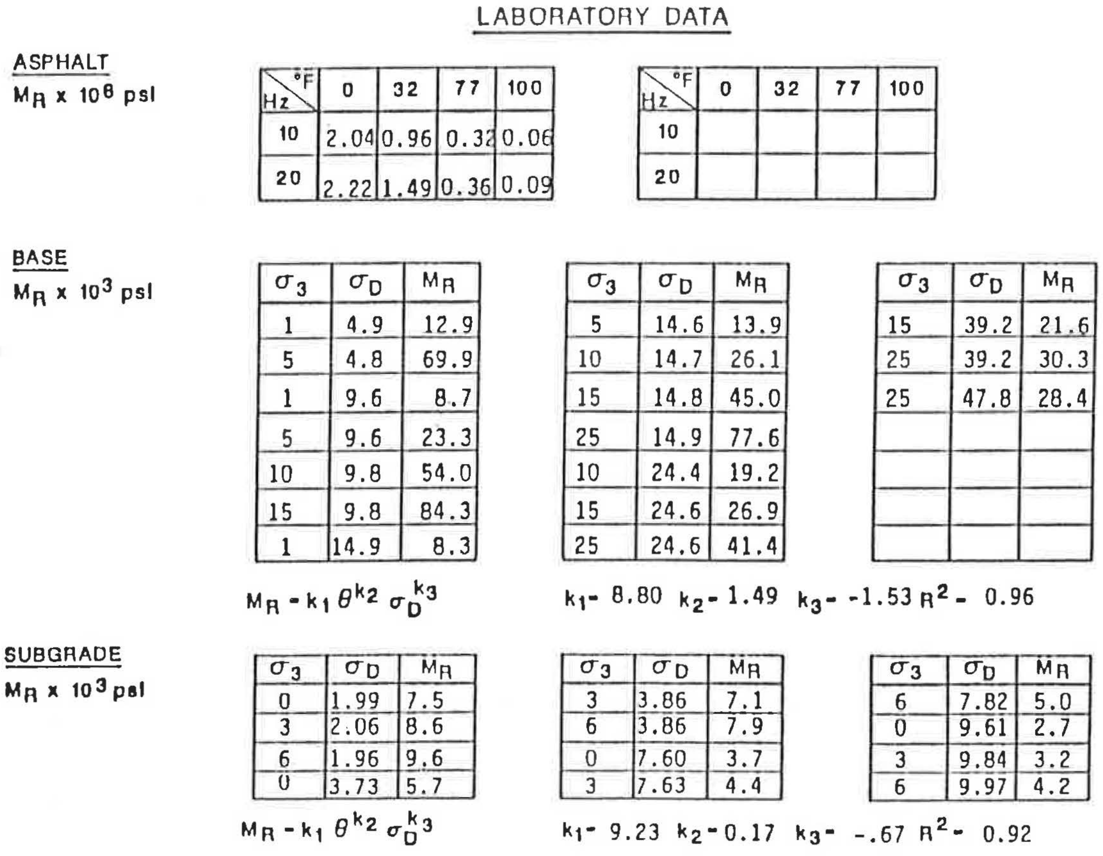
Depth to Rigid Layer (inches)	Backcalculated Subgrade Modulus (ksi)	Absolute % Error/Sensor
-	21.9	5.72
360	17.6	3.76
300	16.8	3.65
240	15.8	3.96
180	14.3	5.61
120	11.8	10.53
60	7.3	25.12

The best fit between measured and calculated bowls occurred with a rigid layer placed at approximately 300 in. below the surface. Clearly, the subgrade *E* value obtained is a function of the specified depth to a rigid layer. The implication is that if the depth of the bedrock layer is unknown then the MODULUS system should be rerun with different depth to rigid layers to minimize absolute error.

Seasonal Variations in Backcalculated Moduli

TTI is currently completing a major study of deflection patterns of highway pavements around the state of Texas. Twenty-two experimental pavements have been instrumented with temperature and moisture sensors. These sites are all on in-service pavements and each site is 100 ft in length. Deflections have been measured both in the morning and afternoon, on 1 day per month over a 12-month period. Samples of surfacing, base, and subgrade were taken and returned to the laboratory for stiffness testing. Triaxial tests were performed on base and subgrade samples using the AASHTO T274–82 procedure, and diametrical resilient moduli tests were conducted on the asphalt surfacings.

The laboratory test data for a particular site are shown in Figure 10. This site consists of a 6-in. asphalt layer over a 6-in. granular base over a sandy clay subgrade. The water table was encountered at a depth of 8.5 ft. Thermocouples were installed at the bottom of the surfacing and base, and moisture sensors were placed in the middle of the base and 6 in. into the subgrade. The laboratory test results included diametrical



LABORATORY DATA

ASPHALT

$M_R \times 10^6$ psi

Hz \ °F	0	32	77	100
10	2.04	0.96	0.32	0.06
20	2.22	1.49	0.36	0.09

Hz \ °F	0	32	77	100
10				
20				

BASE

$M_R \times 10^3$ psi

σ_3	σ_D	M_R
1	4.9	12.9
5	4.8	69.9
1	9.6	8.7
5	9.6	23.3
10	9.8	54.0
15	9.8	84.3
1	14.9	8.3

σ_3	σ_D	M_R
5	14.6	13.9
10	14.7	26.1
15	14.8	45.0
25	14.9	77.6
10	24.4	19.2
15	24.6	26.9
25	24.6	41.4

σ_3	σ_D	M_R
15	39.2	21.6
25	39.2	30.3
25	47.8	28.4

$M_R = k_1 \theta^{k_2} \sigma_D^{k_3}$ $k_1 = 8.80$ $k_2 = 1.49$ $k_3 = -1.53$ $R^2 = 0.96$

SUBGRADE

$M_R \times 10^3$ psi

σ_3	σ_D	M_R
0	1.99	7.5
3	2.06	8.6
6	1.96	9.6
0	3.73	5.7

σ_3	σ_D	M_R
3	3.86	7.1
6	3.86	7.9
0	7.60	3.7
3	7.63	4.4

σ_3	σ_D	M_R
6	7.82	5.0
0	9.61	2.7
3	9.84	3.2
6	9.97	4.2

$M_R = k_1 \theta^{k_2} \sigma_D^{k_3}$ $k_1 = 9.23$ $k_2 = 0.17$ $k_3 = -.67$ $R^2 = 0.92$

FIGURE 10 Material test results for Site 5.

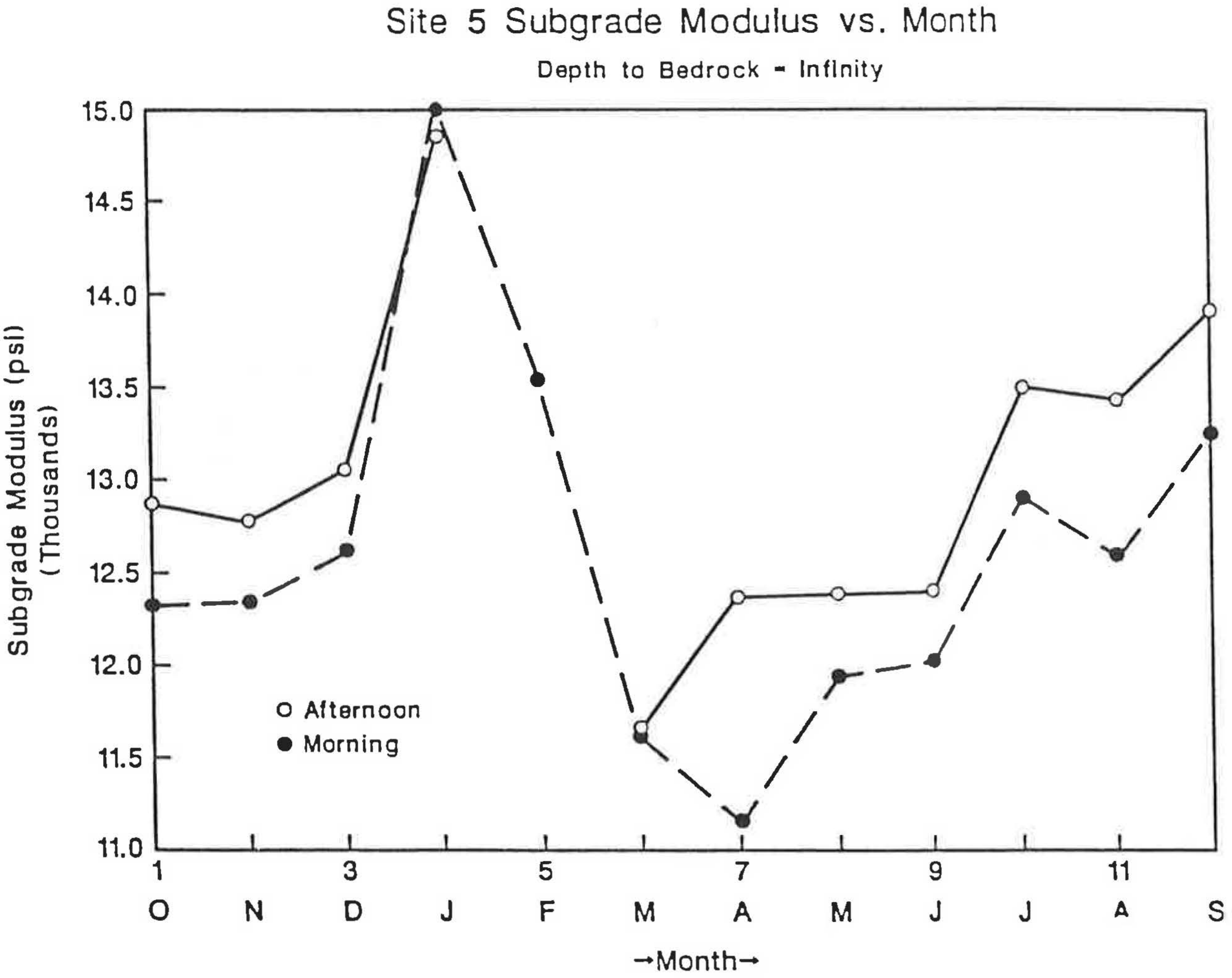


FIGURE 12 Monthly variations in backcalculated subgrade MODULUS.

exist under the FWD. Other factors such as soil suction and disturbances during sampling are major concerns.

ACKNOWLEDGMENTS

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