BOUSDEF: A Backcalculation Program for Determining Moduli of a Pavement Structure

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Highway and transportation agencies have an increasing responsibility for the maintenance, rehabilitation, and management of highways, particularly with regard to asphaltic concrete pavements. Efficient and economical methods are required for determining the structural properties of existing flexible pavements. Nondestructive testing (NDT) of pavements is one of the most useful and cost-effective methods for evaluating the structural adequacy of pavements. With the wide use of NDT, in particular the deflection test, a large amount of test data can be obtained. One common use of deflection data is to determine the pavement layer moduli through backcalculation. The microcomputer program BOUSDEF for backcalculating the moduli of a pavement structure using deflection basin data is presented. The solution techniques for use in developing the program are described, including the use of the method of equivalent thicknesses, Boussinesq theory, consideration of nonlinearity of pavement materials, and consideration of overburden pressure on stress calculation. Evaluation of the program was performed by two approaches: (a) comparing the backcalculated moduli with theoretical moduli, and (b) comparing the backcalculated moduli with results from other developed backcalculation programs. The evaluation shows that the moduli backcalculated using the BOUSDEF program compare well with the theoretical moduli and also are compatible with those from other developed programs. The BOUSDEF program runs fast compared with other backcalculation programs; therefore, the program can be effectively used as a tool to make initial evaluations of deflection testing data for determining pavement layer moduli.

Highway and transportation agencies have increasing responsibility for maintenance, rehabilitation, and management of highways, particularly with regard to asphaltic concrete (AC) pavements. Efficient and economical methods are required for determining structural properties of existing flexible pavements.

Pavement structural properties may be generally stated in terms of the resilient modulus, which is a key element in mechanistic pavement analysis and evaluation procedures. For a multilayer pavement structure, the resilient modulus of each pavement layer may be determined by two possible methods—destructive testing and nondestructive testing (NDT). Destructive testing is generally done by obtaining cores from an existing pavement and testing them using laboratory equipment. NDT, on the other hand, uses deflection basin data generated from an NDT device to quantify the response of a pavement structure due to a known load. The known response is then used in a backcalculation procedure, which generally means using the deflection basin data to determine the pavement layer moduli. The NDT method has certain advantages over the destructive method, such as no physical damage to the pavement structure, and requiring no laboratory tests.

NDT of AC pavements is one of the most useful and cost-effective methods developed by engineers to assist in the management of pavements. With the increased responsibility that highway agencies have for effectively apportioning funds and efficiently designing major rehabilitation projects, the use of NDT methods has become, or in some cases, can become, an invaluable aid in determining the actual condition of pavement sections in a highway network (*1*). The emphasis in the *1986 AASHTO Guide for Design of Pavement Structures* (*2*) on use of the resilient moduli of pavement materials in pavement design and on use of NDT in overlay design also suggests that these methods will have increased usage in the future.

The analysis of NDT data to determine pavement layer properties requires use of mechanistic methods. The principal objective of mechanistic analysis of NDT data is to produce moduli of pavement layers for in-service temperatures at various load levels. These mechanistic methods assume that stresses, strains, and deformations in pavements can be modeled as multilayered linear or nonlinear elastic structures, resting on linear or nonlinear elastic foundations, as shown in Figure 1. This capability makes it possible to use a trial-and-error procedure to assume the layer properties, calculate the surface deflections, compare these with the measured deflections, and repeat the procedure until the calculated and measured deflections are acceptably close. Several such backcalculation methods of analysis have been developed using different assumptions or algorithms concerning the layer material properties, all of which have the trial-and-error procedure as their basis. One drawback of all the available programs is computing efficiency, which seriously impacts their use in routine design work.

BOUSDEF is a much faster backcalculation program. The program is based on the method of equivalent thicknesses and modified Boussinesq equations. The solution technique, development of the program, and comparison with other backcalculation programs are described in the following sections.

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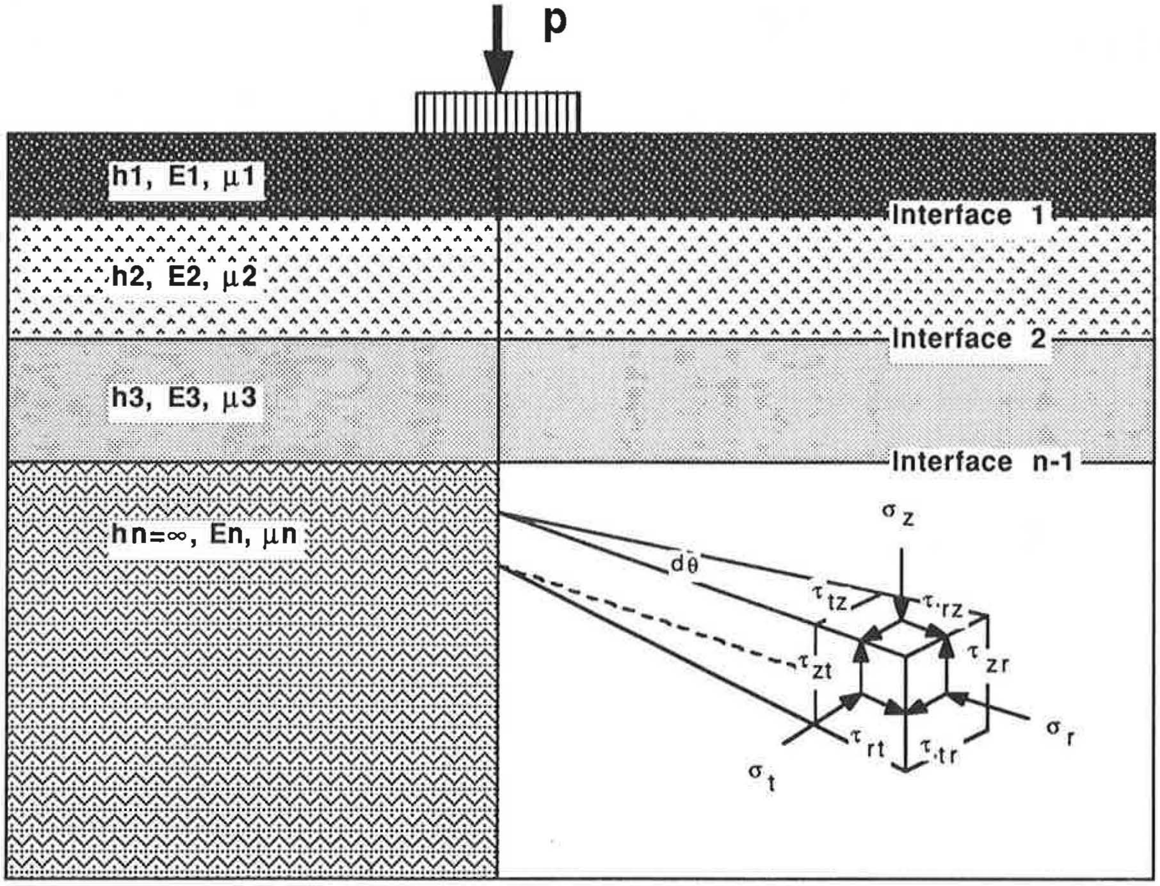


FIGURE 1 Generalized multilayered elastic system.

SOLUTION TECHNIQUE

The BOUSDEF program includes the following techniques:

1. Use of the method of equivalent thicknesses,
2. Use of Boussinesq theory,
3. Consideration of nonlinearity of pavement materials, and
4. Consideration of overburden pressure.

The following paragraphs briefly describe these techniques.

Method of Equivalent Thicknesses

The method of equivalent thicknesses (*3*) assumes that any two layers with similar structural stiffness will distribute loading in the same way. According to this assumption, all layers in a multilayered structure can be converted to one layer with equivalent stiffness by using the following relationship:

$$D = \frac{Eh^3}{12(1 - \mu^2)} \tag{1}$$

where

D = stiffness,
h = layer thickness,
E = modulus of elasticity, and
μ = Poisson's ratio.

For a two-layer system, the equivalent thickness of a layer with modulus E_2 and Poisson's ratio μ_2 relative to a layer of thickness h_1, modulus E_1, and Poisson's ratio μ_1, may be expressed by equating the stiffness of both layers, that is,

$$D_1 = D_2,$$

or,

$$\frac{E_1 h_1^3}{12(1 - \mu_1^2)} = \frac{E_2 h_2^3}{12(1 - \mu_2^2)} \tag{2}$$

Rearranging the equation,

$$h_2 = h_1 \left[\frac{E_1}{E_2}\frac{(1 - \mu_2^2)}{(1 - \mu_1^2)}\right]^{1/3}$$

By expanding this concept for a multilayer system as shown in Figure 2, a general form of the equation may be written

$$h_{ei} = \sum_{i=1}^{n-1} h_i \left[\frac{E_i}{E_n}\frac{(1 - \mu_n^2)}{(1 - \mu_i^2)}\right]^{1/3} \tag{3}$$

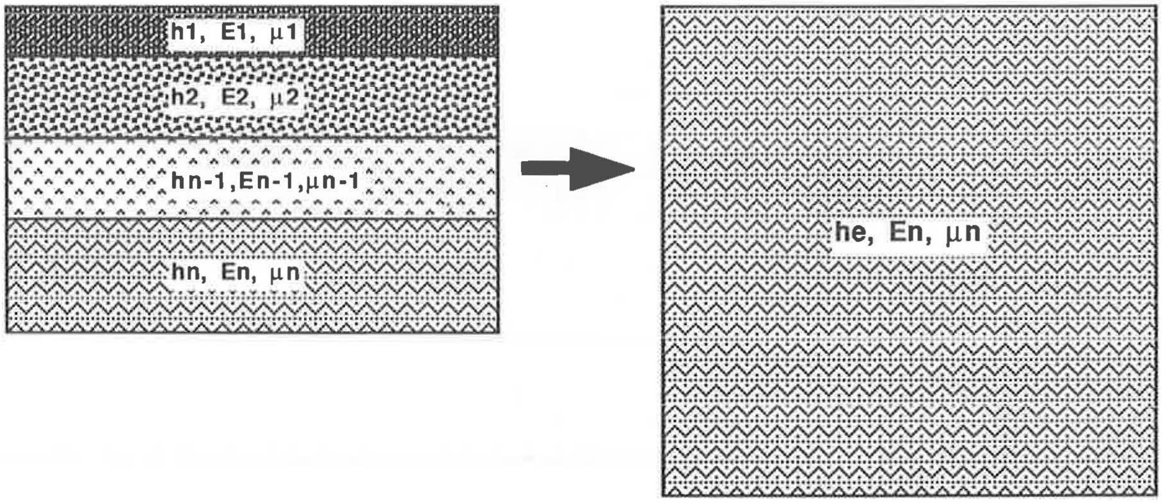


FIGURE 2 **Conceptual representation of method of equivalent thicknesses.**

where

h_{ei} = equivalent thickness for ith layer,
h_i = thickness of ith layer,
E_i = modulus of ith layer,
E_n = modulus of nth layer,
μ_i = Poisson's ratio for ith layer, and
μ_n = Poisson's ratio for nth layer.

Limitations of the Method of Equivalent Thicknesses

There are a number of limitations with regard to the use of the method of equivalent thicknesses. One is that the pavement layer moduli should decrease with depth, preferably by a factor of at least two between consecutive layers. Another is that the equivalent thickness of a layer should preferably be larger than the radius of the loaded area (*4*).

Boussinesq Equations for Deflections

With the use of the equivalent thicknesses method, the Boussinesq equation for calculating deflection at a depth z and radius r in an elastic half-space can be applied to a multilayer elastic system (*3*). The general equation for deflection due to a point load, as shown in Figure 3a, is,

$$d_{z,r} = \frac{(1 + \mu)P}{2\pi RE} [2(1 - \mu) + \cos^2\Theta] \tag{4}$$

where

$d_{z,r}$ = deflection at depth z and radius r,
P = point load,
R = distance from point load to the location where deformation occurs,
E = modulus of elasticity, and
Θ = angle between centerline of load and location of analysis (see Figure 3a).

For a uniformly distributed load (Figure 3b), integration of Equation 4 yields

$$d_z = \frac{(1 + \mu)\sigma_0 a}{E} \cdot \left[\frac{1}{[1 + (a/z)]^{1/2}} + (1 - 2\mu)\left\{ [1 + (z/a)^2]^{1/2} - \frac{z}{a} \right\} \right] \tag{5}$$

where

d_z = deflection on the load axis,
σ_0 = stress under the loading plate,
a = radius of the loading plate, and
z = depth where deformation occurs.

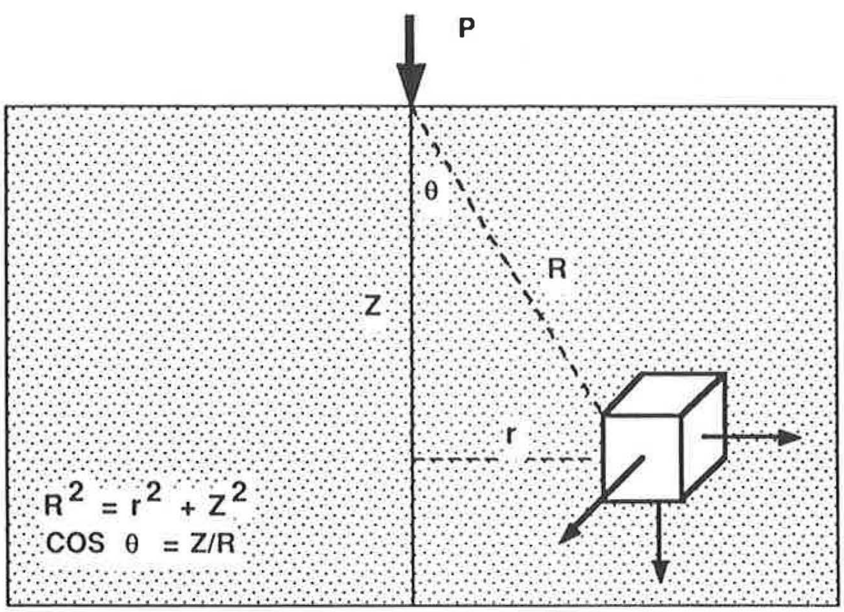
Equation 5 for the uniformly distributed load is valid only for calculation of deflections on the load axis. For points off the axis of the load, the integration cannot be carried out analytically, but for layered systems with a stiff top layer, Boussinesq's equation for a point load, Equation 4, will usually give satisfactory results (*3*).

Boussinesq Equations for Stresses

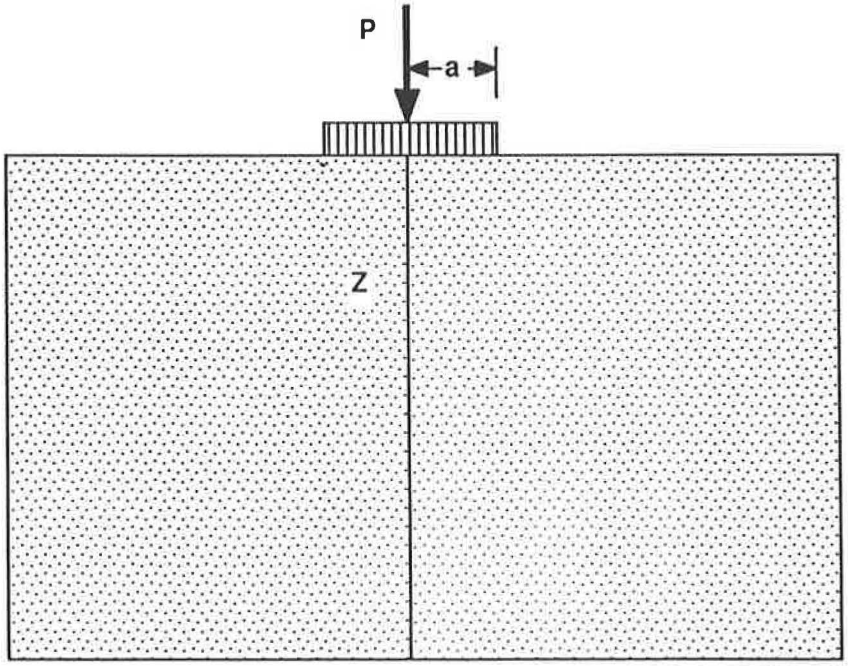
Boussinesq also formulated equations for calculating stresses for a homogeneous, isotropic, linear, elastic semi-infinite space. The use of the method of equivalent thicknesses allows these equations to be used for a multilayer pavement system. For a load uniformly distributed over a certain area as shown in Figure 3b, the normal stresses can be determined using the following equations:

$$\sigma_z = \sigma_0 \left\{ 1 - \frac{1}{[1 + (a/z)^2]^{3/2}} \right\} \tag{6}$$

$$\sigma_r = \sigma_t = \sigma_0 \left\{ \frac{1 + 2\mu}{2} - \frac{1 + \mu}{[1 + (a/z)^2]^{1/2}} + \frac{1}{2[1 + (a/z)^2]^{3/2}} \right\} \tag{7}$$



a) Point Load



b) Distributed Load

FIGURE 3 Conceptual representation of Boussinesq's half-space loading condition.

where

σ_z = vertical stress, and
$\sigma_r = \sigma_t$ = horizontal stresses.

These equations will be used to calculate stresses induced by loadings.

Correction Factors for Boussinesq Method

The use of the method of equivalent thicknesses allows the Boussinesq theory to be applied in a multilayer system. Stresses, strains, and deformation at any point in an elastic half-space can be determined by using corresponding Boussinesq equations. In order to obtain good agreement between the stresses, strains, and deflection calculated by the Boussinesq approach and by exact elastic theory, Ullidtz and Peattie (*3*) suggest that correction factors should be applied to the equivalent thicknesses. For the simple case of calculations on the axis of a uniformly distributed load, Equation 3 is modified as follows:

$$h'_{ei} = f \sum_{i=1}^{n-1} h_i \left[\frac{E_i\,(1 - \mu_n^2)}{E_n\,(1 - \mu_i^2)} \right]^{1/3} \qquad (8)$$

where f is a correction factor; for a two-layer system, $f = 0.9$; for a multilayer system (>2 layers), $f = 1.0$ for the first layer, 0.8 for the rest of the layers.

Additional correction factors are required when using Equation 4 for the point load for more general analysis of deflection, because the assumption that the uniformly distributed load can be approximated by a point load produces inaccuracies near the surface of the pavement. These corrections are as follows (*5*):

$$Z'_i = \frac{1.5a}{2(1 - \mu_i) - [2(1 - \mu_i) - 0.7](Z_i/2a)} \qquad Z_i < a \qquad (9a)$$

$$Z'_i = Z_i + 0.6\,\frac{a^2}{Z_i} \qquad Z_i \geq a \qquad (9b)$$

where

Z'_i = corrected equivalent thickness for ith layer,
Z_i = h'_{ei}, modified equivalent thickness for ith layer, and
a = load radius.

Consideration of Nonlinearity of Lower Layer Materials

The resilient properties of pavement materials, specially those coarse grained and fine grained, are generally stress dependent. The resilient moduli of the these materials vary according to the stress state within the layers. The moduli of these materials are usually approximated by the following relationships:

$$M_R = k_1\theta^{k_2} \quad \text{for coarse-grained materials, or} \qquad (10a)$$

$$M_R = k_1\sigma_d^{k2} \quad \text{for fine-grained materials.} \qquad (10b)$$

where

M_R = resilient modulus (psi),
θ = bulk stresses (psi),
σ_d = deviator stress (psi), and
k_1, k_2 = regression coefficients that depend on materials properties.

Most often, these coefficients are determined through laboratory tests.

Consideration of Overburden Stresses

Actual stresses in a pavement structure consist of two parts—load-induced and overburden stresses. For vertical stresses, the overburden pressure is calculated by multiplying the layer thicknesses by their respective densities and summing these to the desired depth. The total vertical stress σ_{vt} is the sum of the load-induced stress σ_{vl} and overburden pressure,

$$\sigma_{vt} = \sigma_{vl} + \sum_{i=1}^{n} h_i\gamma_i \qquad (11)$$

where

h_i = thickness of ith layer, and
γ_i = density of ith layer.

The total horizontal stress σ_{ht} is a function of the load-induced horizontal stress σ_{hl} plus horizontal stress due to overburden pressure,

$$\sigma_{ht} = \sigma_{hl} + K_0 \sum_{i=1}^{n} h_i\gamma_i \qquad (12)$$

where K_0 is the coefficient of at-rest earth pressure.
These expressions do not include a term for pore water pressure, because pore water pressure is a function of ground water table depth. The assumption is made that the ground water table is at depth below the top of the subgrade and therefore does not affect the results.

The coefficient of at-rest earth pressure K_0 is a function of the angle of friction ϕ for a given soil as determined by a triaxial compression test. For granular soils,

$$K_0 = 1 - \sin\phi \qquad (13a)$$

and for fine-grained soils (*6*),

$$K_0 = 0.95 - \sin\phi \qquad (13b)$$

Das (*7*) reported an approximate range of ϕ from 25 to 38 degrees for normally consolidated clays and from 26 to 46 degrees for sands. Overall, this represents a range of K_0 from 0.28 to 0.56. For most geotechnical work, when triaxial compression test data are not available, a value of 0.5 is assumed for K_0 (*8*).

DEVELOPMENT OF THE BOUSDEF COMPUTER PROGRAM

Program Flowchart

The BOUSDEF program is developed for determining in situ moduli of a pavement structure using deflection data through a backcalculation technique. Figure 4 shows a flow diagram of the program.

To start with, the program first reads input data sets that include NDT load force and load radius, pavement layer thicknesses, Poisson's ratio, minimum, maximum, and initial modulus, density of pavement materials, deflection data (up to seven sensor readings), percent tolerance to stop the deflection matching process, and number of iterations. By calling the subroutine DEFLECTION, which uses the solution techniques described earlier, the initial modulus and layer thickness information are used to determine the equivalent thick-

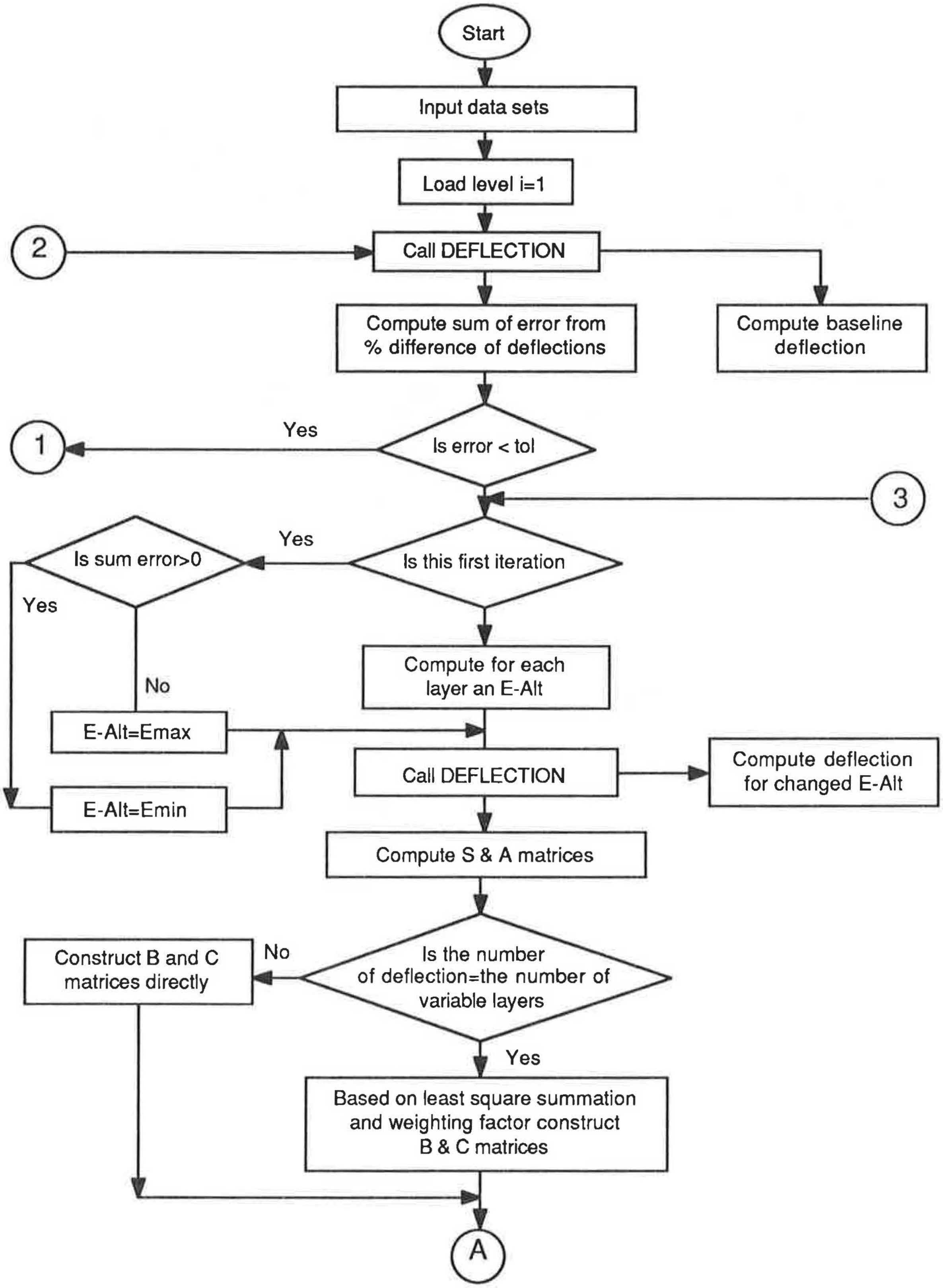


FIGURE 4 **Flowchart of BOUSDEF program (*continued on next page*).**

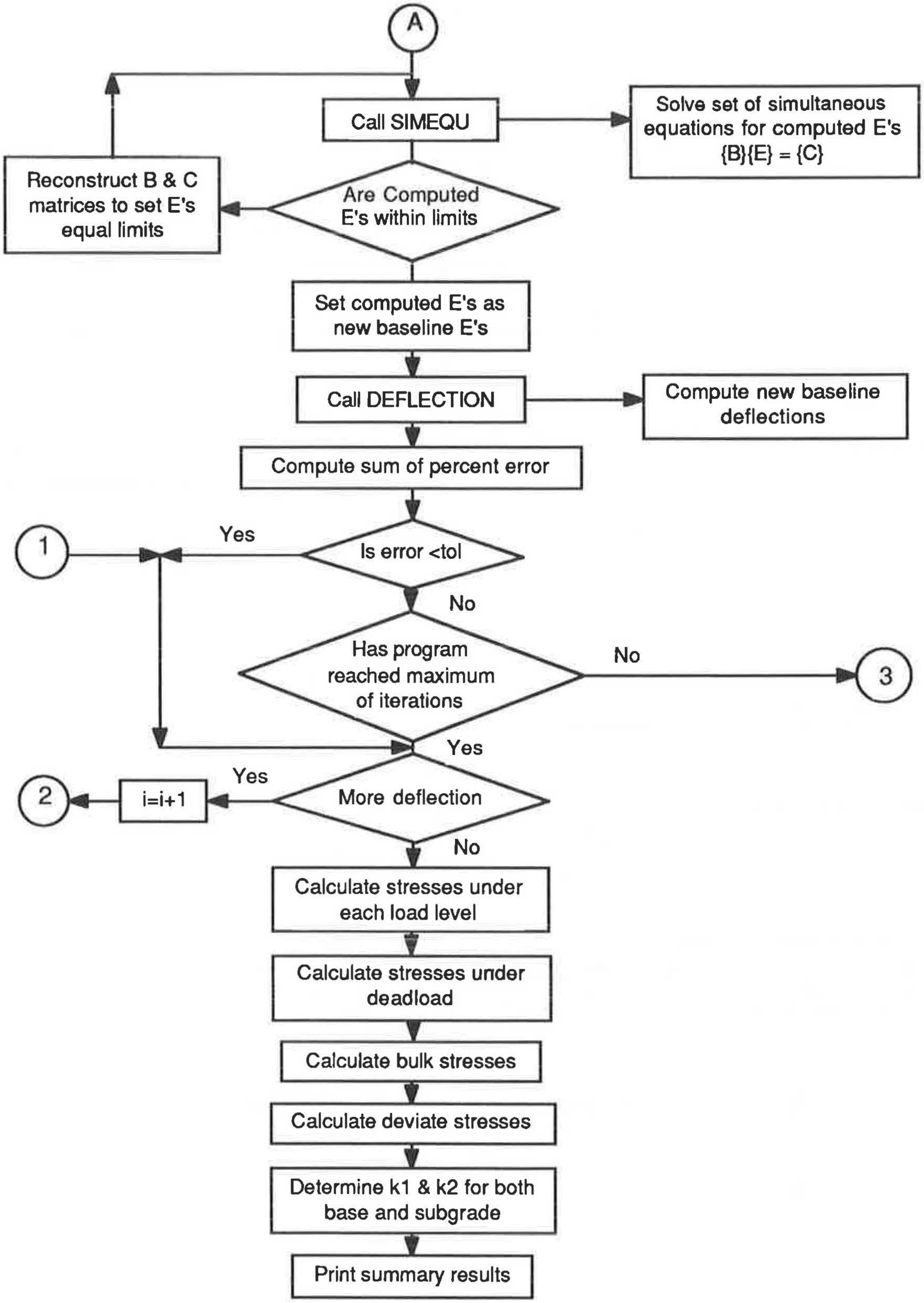


FIGURE 4 *(continued)*

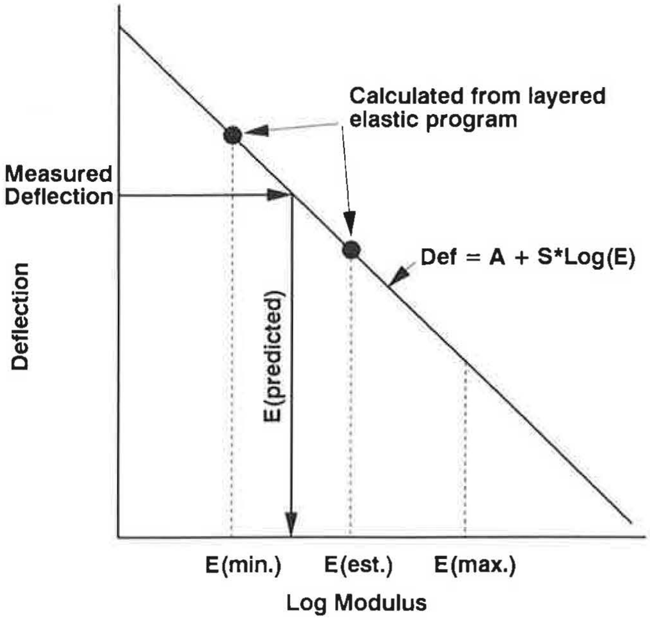


FIGURE 5 Simplified description of deflection matching procedure.

nesses. Deflections for the given NDT load and load radius are then calculated. The calculated deflections are compared to measured deflections. If the sum of the differences is greater than the tolerance specified by the user, the program will start iterations by changing the moduli to compute a new set of deflections.

A simplified description of the deflection matching procedure is shown in Figure 5. This process repeats until the sum of the differences is less than the tolerance or the maximum number of iterations has been reached. This procedure is repeated for each load level until all deflection data are used.

The moduli determined from each set of deflection basin data are used to calculate normal stresses induced by load. Stresses under the deadload of the upper pavement materials are also determined. For the base layer, bulk stresses in the middle of the layer are calculated. For the subgrade, deviator stresses on the top of subgrade are determined. These stress values and moduli are then regressed to find coefficients k_1 and k_2 for both base layer and subgrade.

The backcalculated modulus corresponds to an average condition in the pavement material, whereas the bulk and deviator stresses are calculated under the load at the middle of the base layer and the top of the subgrade rather than through the entire body of the base and subgrade. Therefore, the nonlinear analysis is limited to the stress condition at a specific location rather than at different depths of base and subgrade. Also, the method of equivalent thicknesses or Boussinesq approach is least reliable in predicting horizontal stresses (*3*).

Program Output

The program has the capability of determining the following:

1. Resilient modulus for each pavement layer.
2. Bulk stresses and deviator stresses induced by both load and deadload of upper-layer pavement materials.
3. Coefficients k_1 and k_2 for base and subgrade layers, appearing in Equations 10a and 10b.

Example

An example is provided to illustrate the use of the program. Table 1 presents the pavement and deflection test data for the example. The pavement is a conventional flexible structure with 8-in. asphalt concrete surface, 12-in. aggregate base, and infinite depth of subgrade. Deflection testing was performed using a falling weight deflectometer (FWD) on one short section of a road.

By using the BOUSDEF program, resilient modulus for each pavement layer was determined and presented in Table 2. Bulk stresses in the middle of the base layer and deviator stresses on the top of subgrade are calculated. Regression coefficients k_1 and k_2 for both base and subgrade are also determined. As can be seen in Table 2, both base and subgrade materials appear to have a nonlinear property with $k_2 = 0.58$ for base and -0.13 for subgrade. The results are plotted in Figure 6.

Sensitivity to the User Input

The initial moduli specified by the user seem to have minor effect on the final backcalculated moduli. This feature

TABLE 1 PAVEMENT AND DEFLECTION DATA FOR THE EXAMPLE

Pavement Data

Layer	Thickness	Poisson's ratio	Density (pcf)
AC	8"	0.35	144
Agg. Base	12"	0.40	120
Subgrade	∞	0.40	100

Deflection Data

Load (lbs)	Sensor 0"	8"	18"	36"	58"
	Deflection Readings (mils)				
2789	6.07	4.04	2.41	1.25	0.91
3035	6.59	4.02	2.41	1.37	0.94
3055	6.55	3.89	2.28	1.50	0.94
6521	12.92	8.26	6.47	3.19	1.82
6644	13.18	8.81	7.23	3.53	1.82
6562	13.82	9.57	6.47	3.88	1.72
6521	13.31	8.26	7.10	3.53	1.94
6480	13.05	8.48	5.58	3.65	1.93
6480	13.44	12.72	7.48	5.59	3.50
11442	22.09	14.35	11.92	5.81	3.76
11770	22.48	15.44	13.19	6.38	3.96
11606	23.77	16.74	11.79	6.84	3.83
11442	22.99	14.78	12.68	6.84	3.97
11770	22.35	14.78	10.65	6.84	3.91

Note: Load radius is 5.9 inches

TABLE 2 SUMMARY OF BACKCALCULATION RESULTS FOR THE EXAMPLE

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   Summary of Non-linear Characteristics of Lower Layers

              For base layer: kl=    8069  k2=  0.58
              For subgrade:   kl=   18687  k2= -0.13

             Summary of Moduli and Stresses *

Load (lb)    E(1)      E(2)      E(3)        BSTRS      DSTRS
 2,789     106,432   26,911    16,377        7.29       5.59
 3,035      83,362   38,107    16,870        8.99       5.76
 3,055      74,978   49,985    16,606        9.88       5.59
 6,480     104,087   48,343    14,961       16.81       7.75
 6,480     399,359   17,074     9,462        7.74       5.96
 6,521     117,982   39,666    15,393       15.41       8.01
 6,521      99,314   54,258    13,863       17,67       7.44
 6,562     142,581   24,546    15,015       12.58       8.40
 6,644     158,740   29,287    14,770       13.00       7.96
11,442     117,180   53,092    14,045       27.83      10.55
11,442     100,939   69,773    12,518       31.35       9.65
11,606     136,673   35,135    13,533       23.61      11.16
11,770     156,599   41,680    13,376       24.18      10.46
11,770     105,657   69,787    13,774       31.79      10.18

Average    135,994     42,689      14,326
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* Moduli and stresses are in psi.
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minimizes the variation in the final moduli caused by the user's input and gives a more reliable solution. An initial evaluation was performed using data presented in Table 3.

Measured deflections for a load of 14,696 lb at loading radius 9.0 in. using the WES Vibrator device were as follows (*1*):

Distance from Load (in.)	*Deflection (mils)*
0.0	6.47
18.0	4.27
36.0	2.34
60.0	1.47

Calculated moduli are presented in Table 4. Apparently, the program provides similar results regardless of what the initial modulus values are.

EVALUATION OF THE BOUSDEF PROGRAM

To evaluate the BOUSDEF program, two approaches were used, (a) comparing backcalculated moduli with theoretical values, and (b) comparing backcalculated moduli with results from other developed programs. The process is described in the following paragraphs.

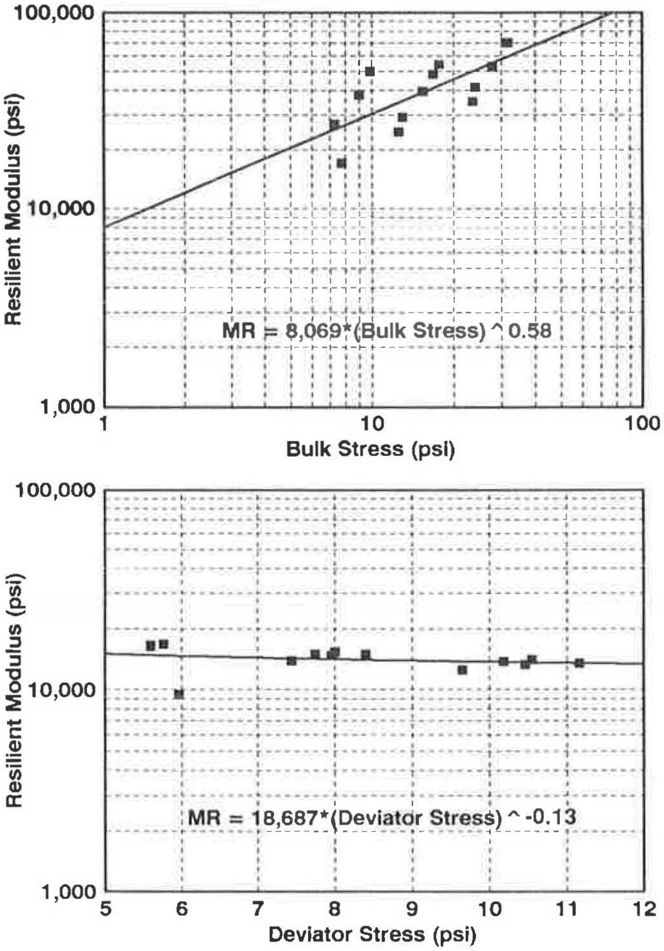


FIGURE 6 Plot of example output.

TABLE 3 DATA USED FOR EVALUATING SENSITIVITY ON INITIAL MODULUS (*1*)

Layer	Thickness	Poisson's Ratio
1	11.0''	0.30
2	15.0''	0.35
3	∞	0.45

Comparison with Theoretical Values

The BOUSDEF program was evaluated by comparing the backcalculated results with hypothesized theoretical values. This comparison is done by assuming a set of pavement structures with different combination of layer thicknesses and different resilient modulus. Among the evaluated pavement structures, as shown in Figure 7, five are conventional pavement systems, with three 3-layer structures and two 4-layer structures. Two pavement systems have a cement-treated base (CTB). Three are portland cement concrete (PCC) pavement structures. To represent typical field conditions, resilient modulus for flexible pavement ranges from 100 to 1,500 ksi. For PCC pavements, typical design values are also used. Poisson's ratio was 0.35 for the AC, 0.4 for the base and subgrade, and 0.15 for the CTB and PCC. Surface deflections for the

TABLE 4 EFFECT OF INITIAL MODULI ON CALCULATED MODULI

Initial Moduli (psi)			Calculated Moduli (psi)		
Surface	Base	Subgrade	Surface	Base	Subgrade
Variation of surface modulus					
200,000	50,000	25,000	768,422	57,228	46,810
300,000	50,000	25,000	768,455	57,248	46,803
400,000	50,000	25,000	768,485	57,248	46,803
500,000	50,000	25,000	764,142	57,702	46,766
600,000	50,000	25,000	764,203	57,693	46,768
700,000	50,000	25,000	764,250	57,689	46,769
800,000	50,000	25,000	772,642	56,432	46,914
900,000	50,000	25,000	769,176	56,987	46,835
1,000,000	50,000	25,000	764,989	57,592	46,791
Variation of base modulus					
500,000	10,000	10,000	728,648	56,086	46,783
500,000	20,000	10,000	739,009	54,808	46,863
500,000	30,000	10,000	738,916	54,843	46,837
500,000	40,000	10,000	738,827	54,860	46,830
500,000	50,000	10,000	738,859	54,845	46,842
500,000	60,000	10,000	738,985	54,813	46,861
500,000	70,000	10,000	728,289	56,131	46,770
500,000	80,000	10,000	735,888	54,997	47,021
500,000	90,000	10,000	740,119	54,560	47,021
500,000	100,000	10,000	739,447	54,540	46,980
Variation of subgrade modulus					
500,000	30,000	10,000	738,916	54,843	46,837
500,000	30,000	20,000	735,079	55,446	46,847
500,000	30,000	30,000	728,013	56,166	46,759
500,000	30,000	40,000	743,267	54,092	46,998
500,000	30,000	50,000	733,450	55,287	47,091
500,000	30,000	60,000	736,109	53,809	48,243
500,000	30,000	70,000	735,286	54,468	47,642
500,000	30,000	80,000	735,390	54,333	47,767
500,000	30,000	90,000	735,356	54,292	47,814
500,000	30,000	100,000	739,984	53,871	47,754

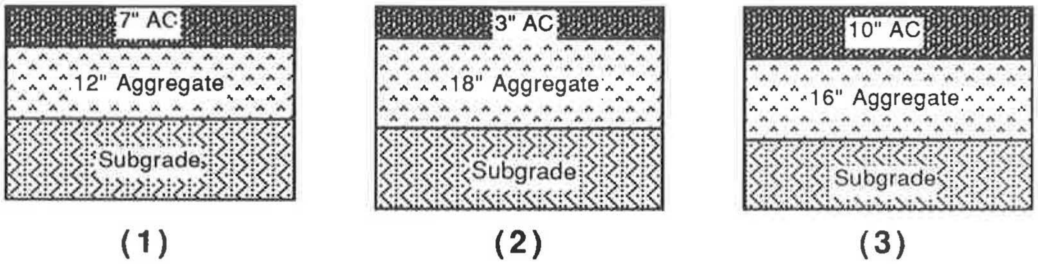
assumed pavement structures were calculated using the method of equivalent thicknesses together with Boussinesq equations. Initial comparison on surface deflections calculated using Boussinesq equations, ELSYM5, and BISAR was made beforehand. The comparison showed that deflections calculated from Boussinesq equations, ELSMY5, and BISAR were similar for conventional and PCC pavements, but not as good for pavements with a stiff base. Thus, Boussinesq equations are valid for computing the surface deflections for the conventional and PCC pavements. Deflections at six radial distances (0, 8, 12, 24, 36, and 58 in.) were calculated for the flexible pavements. For PCC pavements, deflections at seven locations (0, 12, 24, 36, 48, 60, and 84 in.) were computed. The calculated deflection basins were then used as inputs to backcalculate the layer moduli.

Table 5 presents the calculation results. The backcalculated moduli for all structures are close to the theoretical values, indicating the BOUSDEF program has the capability of backcalculating the layer moduli from known deflections, layer thicknesses, and load data. However, the method of equivalent thicknesses is not recommended for pavements with base layers that are stiff compared to the surface (*4*), as mentioned earlier. Pavements with CTB layers were included here to illustrate that BOUSDEF is capable of providing an initial evaluation for such pavements. Alternative means of backcalculation should also be carried out to improve this evaluation.

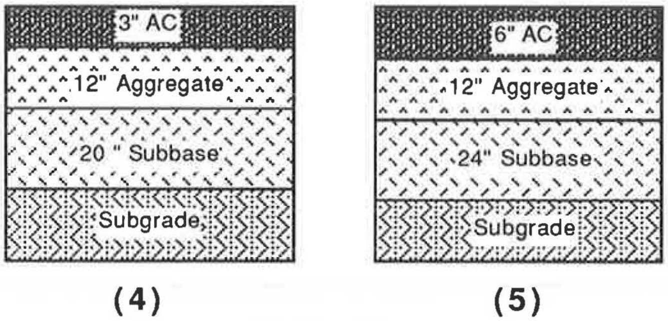
Comparison with Other Developed Programs

The BOUSDEF program was also compared with four developed programs, BISDEF (*9*), CHEVDEF (*10*), ELSDEF (*1*), and MODCOMP2 (*11*). Pavement data and deflection test data used for the comparison were obtained from a real pavement. Deflections were measured using a KUAB falling weight deflectometer. These data are presented in Tables 6 and 7, respectively. The computed layer moduli for the various programs are presented in Table 8. Results from BOUSDEF are close to those from the other developed programs.

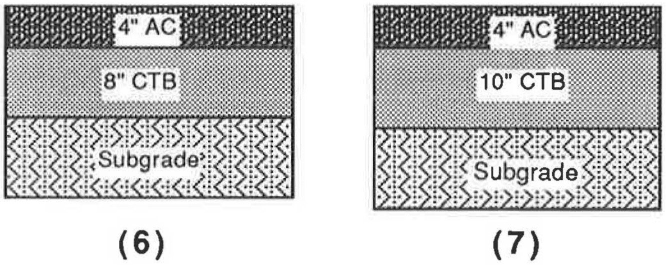
One major advantage of the BOUSDEF program over the other programs is its computational speed. In using a deflection data set presented in Table 3, the BOUSDEF program takes only 3 sec to find the solution, using an IBM AT microcomputer with a math coprocessor. The same data would take significantly longer time using the other programs, as can be seen in Table 9. This feature renders easy the use of the program for evaluating a large amount of deflection data. Furthermore, BOUSDEF is a user-friendly program. The program has a built-in data file creating and editing routine;



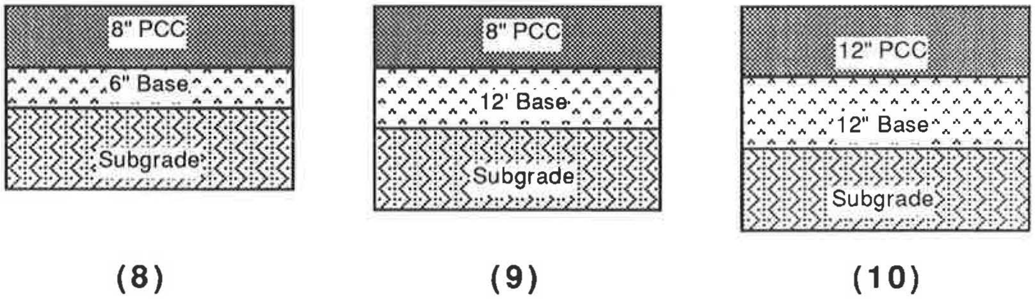
a) Flexible 3-layer systems



b) Flexible 4-layer systems



c) Stabilized base systems



d) PCC systems

FIGURE 7 Pavement structures used for deflection calculation.

this significantly eases the data input and edit process and avoids possible calculation errors due to improper data entry.

SUMMARY

This paper has presented a microcomputer program for backcalculating the moduli of a pavement structure using deflection basin data. The solution techniques for use in developing the program are described, including use of the method of equivalent thicknesses, Boussinesq theory, consideration of nonlinearity of pavement materials, and consideration of overburden pressure on stress calculation. Evaluation of the program was performed using two approaches: (a) comparing backcalculated moduli with hypothesized theoretical moduli, and (b) comparing backcalculated moduli with those from other developed backcalculation programs. The evaluation shows that the moduli backcalculated using the BOUSDEF program compare well with the theoretical moduli and also are compatible with other developed programs used for comparison.

TABLE 5 COMPARISON BETWEEN THEORETICAL AND BACKCALCULATED VALUES

Pavement	Theoretical Values *					Backcalculated				
Structure	1	2	3	4	5	1	2	3	4	5
Three-Layer Conventional										
7" AC	100.0	300.0	600.0	1000.0	1500.0	101.9	289.9	602.7	1022.1	1551.1
12" Agg.	25.0	25.0	25.0	25.0	25.0	24.7	25.0	25.1	24.6	24.4
Subgrade	10.0	10.0	10.0	10.0	10.0	10.0	10.1	9.9	9.9	9.9
3" AC	100.0	300.0	600.0	1000.0	1500.0	100.7	310.1	594.3	1017.2	1538.2
18" Agg.	20.0	20.0	20.0	20.0	20.0	20.0	19.8	20.1	19.9	19.8
Subgrade	10.0	10.0	10.0	10.0	10.0	10.0	9.9	9.9	9.9	9.9
10" AC	200.0	600.0	1000.0	1500.0		202.6	615.5	1017.5	1566.5	
16" Agg.	25.0	25.0	25.0	25.0		31.1	31.9	31.6	30.8	
Subgrade	10.0	10.0	10.0	10.0		10.0	9.9	10.1	9.9	
Four-Layer Conventional										
3" AC	300.0	600.0	1000.0	1500.0		357.3	638.8	1024.9	1493.5	
12" Base	25.0	25.0	25.0	25.0		23.6	24.3	24.6	25.0	
20" Subbs	10.0	10.0	10.0	10.0		9.7	10.0	10.0	10.0	
Subgrade	7.0	7.0	7.0	7.0		7.2	7.0	7.0	7.0	
6" AC	100.0	300.0	600.0	1000.0		101.3	298.5	615.6	1027.3	
12" Base	25.0	25.0	25.0	25.0		24.9	25.1	24.0	23.9	
24" Subbs	12.0	12.0	12.0	12.0		12.0	12.0	12.1	12.1	
Subgrade	8.0	8.0	8.0	8.0		8.0	8.0	8.0	8.0	
Cement Treated Base										
4" AC	300.0	600.0	1000.0			294.8	588.3	1158.5		
8" CTB	1200.0	1200.0	1200.0			1216.1	1205.4	1107.7		
Subgrade	10.0	10.0	10.0			10.0	10.0	10.0		
4" AC	300.0	600.0	1000.0			292.7	584.0	1081.8		
10" CTB	1200.0	1200.0	1200.0			1215.0	1225.8	1081.8		
Subgrade	10.0	10.0	10.0			10.0	10.0	10.0		
PCC										
8" PCC	4000.0					4172.8				
6" Base	20.0					21.2				
Subgrade	10.0					9.9				
8" PCC	4000.0					4028.6				
12" Base	20.0					19.8				
Subgrade	10.0					9.9				
12" PCC	4000.0					4015.5				
12" Base	20.0					20.0				
Subgrade	10.0					10.0				

* Moduli are in ksi.

TABLE 6 PAVEMENT DATA USED FOR BACKCALCULATION

Pavement Layer	Material	Thickness (inch)	Poisson's Ratio
1	Asphalt Concrete	9.0	0.35
2	Aggregate Base	16.0	0.40
3	Soil Subgrade	∞	0.40

TABLE 7 DEFLECTION DATA USED FOR BACKCALCULATION

Test Site	FWD Load (lb)	Deflection @ Sensor Location 0"	8"	18"	30"	60"
1	11,729	22.99	16.74	12.81	9.81	4.57
2	11,647	27.39	21.68	14.96	11.06	5.33
3	11,442	20.54	17.28	12.30	9.69	4.90
4	11,073	24.16	20.33	14.08	10.83	5.77
5	11,688	16.28	13.70	8.88	6.95	3.92

Note: FWD Load Radius is 5.9 inches.

TABLE 8 SUMMARY OF BACKCALCULATION RESULTS*

Test Site	Program	AC Surface	Aggregate Base	Subgrade
1	BISDEF	194.0	25.1	11.5
	BOUSDEF	163.0	25.7	11.2
	CHEVDEF	175.8	24.7	12.1
	ELSDEF	200.0	23.6	11.7
	MODCOMP2	162.8	33.4	10.5
2	BISDEF	173.7	15.4	10.5
	BOUSDEF	157.7	15.2	9.9
	CHEVDEF	150.7	16.6	10.5
	ELSDEF	174.0	15.2	10.4
	MODCOMP2	131.5	27.1	9.3
3	BISDEF	288.3	20.1	11.2
	BOUSDEF	262.2	19.3	10.9
	CHEVDEF	257.8	23.3	11.3
	ELSDEF	286.9	20.0	11.3
	MODCOMP2	184.0	50.6	9.3
4	BISDEF	206.4	19.0	9.4
	BOUSDEF	196.5	17.0	9.2
	CHEVDEF	182.3	21.7	9.2
	ELSDEF	205.7	18.9	9.4
	MODCOMP2	431.8	1.0	N/S**
5	BISDEF	259.1	37.7	14.8
	BOUSDEF	266.0	30.5	14.8
	CHEVDEF	260.9	36.4	15.0
	ELSDEF	258.2	37.2	14.8
	MODCOMP2	165.8	89.7	12.9

* Moduli are in ksi.
** N/S = No Solution.

TABLE 9 COMPARISON ON COMPUTING TIME AND BACKCALCULATED RESULTS

PROGRAM	COMPUTED LAYER MODULI (KSI)			COMPUTING TIME (SECONDS)
	LAYER 1	LAYER 2	LAYER 3	
BISDEF*	685.7	55.4	48.8	285
BOUSDEF	764.1	57.7	46.8	3
CHEVDEF	527.8	28.6	29.9	327
ELSDEF	632.1	84.7	34.2	485
MODCOMP2	772.5	35.9	53.0	495

*Contains proprietary BISAR program

The BOUSDEF program runs fast in comparison with other backcalculation programs. Therefore, the program can be effectively used as a tool to make initial evaluation of deflection testing data for determining pavement layer moduli that may further be used for mechanistic analysis of pavement structure and overlay design.

REFERENCES

1. R. L. Lytton, F. L. Roberts, and S. Stoffels. *Determination of Asphaltic Concrete Pavement Structural Properties by Nondestructive Testing*. Final Report, Texas Transportation Institute, College Station, April 1986.
2. *Guide for the Design of Pavement Structures*. AASHTO, Washington, D.C., 1986.
3. P. Ullidtz and K. R. Peattie. Pavement Analysis by Programmable Calculators. *Journal of Transportation Engineering*, ASCE, Sept. 1980.
4. P. Ullidtz. *Pavement Analysis*. Elsevier, 1987.
5. P. Ullidtz. *A Fundamental Method for Prediction of Roughness, Rutting and Cracking of Pavements*. Association of Asphalt Paving Technologists, Vol. 48, 1979, pp. 557–586.
6. E. W. Brooker and H. O. Ireland. Earth Pressure at Rest Related to Stress History. *Canadian Geotechnical Journal*, Vol. 2, No. 1, 1965, pp. 1–15.
7. B. M. Das. *Principles of Foundation Engineering*. Brooks/Cole Engineering Division, Wadsworth, Inc., Monterey, Calif., 1984.
8. D. E. Newcomb. *Development and Evaluation of A Regression Method to Interpret Dynamic Pavement Deflections*. Ph.D. dissertation, University of Washington, Seattle, 1986.
9. A. J. Bush. *Computer Program BISDEF*. U.S. Army, Corps of Engineers, Waterways Experiment Station, Vicksburg, Miss., Nov. 1985.
10. A. J. Bush. *Nondestructive Testing of Light Aircraft Pavements, Phase II, Development of the Nondestructive Evaluation Methodology*. Final Report FAA-RD-80-9-II, FAA, U.S. Department of Transportation, Washington, D.C., Nov. 1980.
11. L. H. Irwin. *User's Guide to MODCOMP2*. Report 83-8, Cornell University Local Roads Program, Ithaca, N.Y., Nov. 1983.

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