Sensitivity Analysis of Selected Backcalculation Procedures

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One major problem facing highway engineers today is the evaluation of existing pavement systems. This evaluation is necessary to meet today's demands for higher magnitudes of traffic loads and intensity. In particular, there exists a need for a reliable, quick, and nondestructive tool that permits the evaluation of pavements to obtain accurate information about existing structural conditions. In response to this need, several types of nondestructive testing equipment and analysis procedures have been developed and are currently available. Their use in predicting pavement layer moduli must be carefully evaluated, as this particular application is now an integral part of the new AASHTO overlay design procedure. BISDEF, MODCOMP2, and SEARCH analysis procedures were evaluated and the sensitivity of the backcalculated moduli to variations in input parameters was investigated. Results obtained for typical asphalt concrete and aggregate-surfaced pavements showed that the backcalculated moduli were sensitive to several of the user-supplied inputs. The backcalculated moduli from BISDEF were sensitive to layer thickness, depth of stiff layer, and assumed range of layer modulus used. For the MODCOMP2 and SEARCH programs, the backcalculated moduli were sensitive to layer thickness. Backcalculated moduli from all three programs were sensitive to variations in surface deflection measurements. Although identical values were input, the backcalculated moduli from the three procedures differed.

One major problem facing highway engineers today is the evaluation of existing pavement systems. This evaluation is necessary to meet today's demands for higher magnitudes of traffic loads and intensity. In particular, there exists a need for a reliable, quick, and nondestructive tool that permits the evaluation of pavements to obtain accurate information about existing structural conditions. In response to this need, several types of nondestructive testing (NDT) equipment and backcalculation procedures have been developed and are currently available *(1–4)*.

These backcalculation procedures are complex, relatively new, and still plagued by problems, including the following *(1)*.

1. The nonuniqueness of the resilient modulus backcalculated from the measured deflection basin,
2. Errors due to possible variation in thickness of pavement layers,
3. Errors involved in assuming a semi-infinite subgrade,
4. Time involved in the iterative process,
5. Errors in backcalculated moduli because of the nonlinear behavior of granular layers and subgrade, and
6. Errors involved in using input values out of the range for which the model was calibrated.

These problems must be dealt with to fully implement the 1986 AASHTO guides for design of pavement structures.

The objective of this paper is to present evaluations of selected procedures currently being used to determine the modulus of pavement layers. The sensitivity of the predicted moduli to various input parameters is also evaluated. The procedures evaluated were the following:

1. BISDEF,
2. MODCOMP2, and
3. SEARCH.

These procedures were selected because of their availability to the authors and the extent of their documentation. They also have been adapted for use on microcomputers and can be run on IBM and IBM-compatible microcomputers.

STUDY APPROACH

Data Collection

The surface deflection measurements used in the analysis were collected from sites located in the Willamette National Forest in Oregon. Typical data from asphalt concrete (AC) and aggregate-surfaced pavements were used. The KUAB falling weight deflectometer (FWD) was used in the collection of surface deflection data. Figure 1 shows the load and deflection sensor layout of the KUAB FWD. Figure 2 shows typical pavement structures used in the analysis.

Procedures Considered

BISDEF

This computer program, developed by the U.S. Army Corps of Engineers, Waterways Experiment Station *(2, 5)*, uses a deflection basin from NDT results to predict the elastic moduli of up to four pavement layers. These determinations are accomplished by matching the calculated deflection basin to the measured deflection basin.

The basic assumption of this method is that dynamic deflections correspond to those predicted from the layered elastic theory. This method uses the BISAR *(6)* layered elastic pro-

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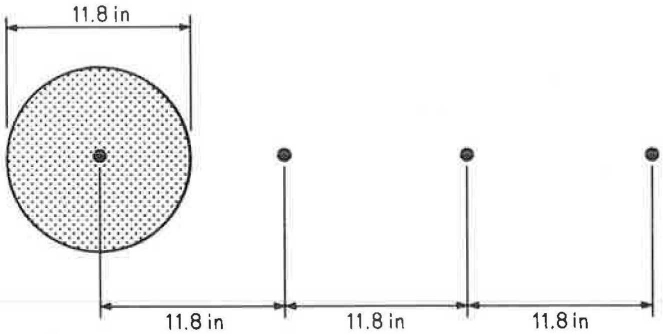

FIGURE 1 Layout of FWD sensor placement.

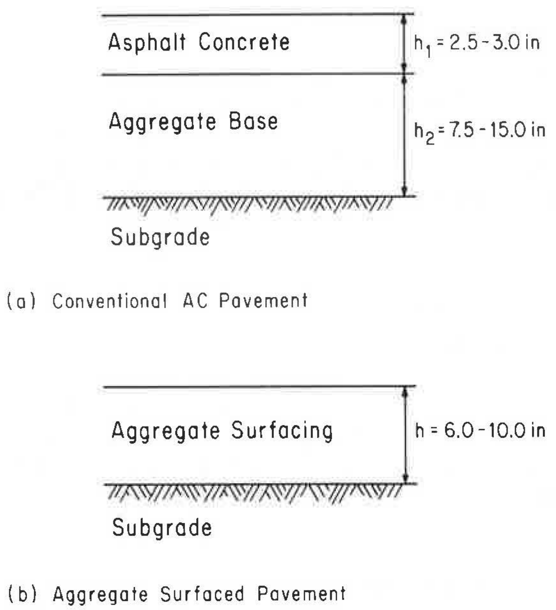

FIGURE 2 Typical pavement structures used in the analysis.

gram to compute the deflections, stresses, and strains of the structures under investigation. The procedure was initially calibrated using data from the Model 2008 Road Rater. There was good agreement between computed and measured deflections when a rigid layer of 240-in. thickness below the surface of the pavement was assumed. The effect of the static load applied to the pavement as a preload was also investigated; for computer modeling this effect was practically negligible for most comparisons.

To determine the layer moduli, the basic inputs include initial estimates of the elastic layer pavement characteristics, as well as deflection basin values. Inputs for each layer include

1. Thickness of each layer,
2. Range of allowable modulus,
3. Initial estimate of modulus, and
4. Poisson ratio.

For the deflection basin, the required inputs are

1. Deflections at a number of sensor locations, and
2. A maximum acceptable error in deflection matching.

The modulus of any layer may be assigned or computed. If assigned, the value is based on the type of material or properties of the material at the time of testing. The number of layers with unknown modulus values cannot exceed the number of measured deflections. The best results are obtained when the moduli of not more than three layers are to be calculated *(5)*.

The program is solved using an iterative process that provides the best fit between measured deflection and computed deflection basins. In this procedure, the set of moduli that minimizes the error sum between the computed deflection and measured deflections is determined. BISDEF, which uses the BISAR *(6)* subroutine for stress and deflection computations, is capable of handling multiple wheel loads and variable interface friction. CHEVDEF, which uses the Chevron elastic layer program, can only handle single-wheel loads *(7)*. The two procedures produce identical results for single-loading cases (e.g., FWD data).

MODCOMP2

MODCOMP2 program specifications, developed by Irwin *(3)*, include the following:

1. Up to eight layers can be included in the pavement system.
2. The layer combinations may be linear elastic or nonlinear stress dependent.
3. The program is capable of accepting data from several typical NDT devices (e.g., FWD, Road Rater, and Dynaflect).
4. It is capable of accepting up to six load levels.

MODCOMP2 uses the Chevron elastic layer computer program for determining the stresses, strains, and deflections in the pavement system. As in BISDEF/CHEVDEF, there is no closed-form solution for determining layer moduli from surface deflection data. Thus, an iterative approach is used that requires an input of initial or estimated moduli for each layer. The basic iterative process is repeated for each layer until the agreement between the calculated and measured deflection is within the specified tolerance or until the maximum number of iterations has been reached.

Because untreated base course and subgrade materials behave as nonlinear materials, the resilient modulus of such materials can be expressed by the equation $M_r = K_1 \theta^{K_2}$, where θ is bulk stress and K_1 and K_2 are constants. The program has the added capability to derive K_1 and K_2 parameters for a given layer when they are unknown. In such cases, the user must provide deflection basin data for at least three load levels. The program can accept data for up to six load levels.

SEARCH

This computer program, developed at the Texas Transportation Institute *(4)*, uses a pattern-search technique to fit deflection basins with curves shaped like elliptic integral functions. These curves are solutions to the differential equations used in elastic layer theory. The theoretical development of the deflection equation used in the program is discussed in detail by Lytton and Michalak *(4)*. The equation is based on the behavior of an elastic layer resting on a rigid incompressible layer, as first postulated by Vlasov and Leont'ev *(8)*. To account for multiple layers, a generalized form of Odemark's assumption *(9)* is used. This assumption transform the thickness of all layers to an equivalent thickness of a material having a single modulus. The input data include

1. Thickness of AC and granular base layers,
2. Force applied and radius of loading plate, and
3. Measured deflection values, and their radial distances, from center of loading plate.

The program searches for the elastic moduli that fit the measured basin to the calculated basin with the least average error. The output includes calculated moduli, computed and measured deflections, force applied, and squared error of the fitted basin.

Type of Deflection Data

The surface deflection values used in this study were obtained from pavements in the Willamette National Forest near Eugene, Oregon. The data were obtained using the KUAB FWD (Figure 1), owned and operated by Pavetech, Inc., of Redmond, Washington. The KUAB FWD *(10, 11)* is a trailer-mounted device towed by a standard-sized automobile. The impulse force is created by dropping a set of two weights from different heights. By varying the drop height, the force is varied from 4,900 to 11,300 lb. The two-mass system is used to create a smooth load pulse similar to that created by a moving wheel load *(10, 11)*. Surface deflections are measured with four seismic transducers (seismometers) that are lowered automatically with the loading plate. Because it can apply a load of a magnitude equal to that produced by a loaded truck, there is no need to correct the determined in situ moduli for stress sensitivity.

Evaluated Input Parameters

The evaluated input parameters included all the user-supplied inputs that could affect the predicted value of the moduli, such as

1. Range of modulus for each unknown layer modulus,
2. Depth of the stiff layer,
3. Seed modulus for each layer,
4. Layer thicknesses for all pavement layers,
5. Magnitude of surface deflection, and
6. Number of iterations and allowable deflection match tolerances.

If applicable, these factors were evaluated for each computer program and for AC and aggregate-surfaced pavements. The evaluation consisted of predicting the unknown modulus of the various pavement layers using different values of each input parameter under consideration. Table 1 summarizes the standard input values.

TABLE 1 STANDARD INPUT VALUES

Variable Name	AC SURFACED PAVEMENTS		AGGREGATE SURFACED PAVEMENTS	
Seed Moduli (psi)	Surfacing - 375,000 Base - 30,000 Subgrade - 14,500 Stiff Layer - 1,000,000(1)	Used in Tables: 1,2,4,6,8,10 13,15,16	Pavement - 30,000 Subgrade - 14,000 Stiff Layer - 1,000,000(1)	Tables: 1,3,7
Layer Thickness (in.)	Surfacing h_1 = 2.5 Base h_2 = 14.5 Subgrade h_3 = 240.0(1)	Used for BISDEF in Tables: 1,2, 4,6,8,12,13,16	Pavement h_1 = 8.95 Subgrade h_2 = 240	Tables: 1,3,7 9,14
	Surfacing h_1 = 3.0 Base h_2 = 7.0 Subgrade h_3 =	Used for MODCOMP2 in Tables: 4,10,13,15	Pavement h_1 = 9.86 Subgrade h = infinity	Tables: 5,11
Modulus Range (psi)	Surfacing - 250,000-850,000 Base - 10,000-50,000 Subgrade - 3,000-23,000	Used for BISDEF in Tables: 1,2, 4,6,8,10,13, 15,16	Pavement - 1,000-100,000 Subgrade - 1,000-100,000	All BISDEF Tables
	Not required for MODCOMP2 and SEARCH			
Deflection Values (mils)	Sensor No.: 1 2 3 4 43.10 26.40 17.80 9.60	Tables: 1,2,6,8, 13,16	Sensor No.: 1 2 3 4 36.70 12.70 4.30 2.40	Tables: 1,3, 7,9,14
	34.60 19.80 10.10 4.50	Tables: 4,10,13,15		
	51.72 31.68 21.36 11.52	Table: 12		

(1) Stiff layer not used in MODCOMP2 and SEARCH

RESULTS

Results of the sensitivity analysis are summarized in Tables 2–17. Table 2 presents the effect of modulus range on the predicted moduli for BISDEF for both conventional AC and aggregate-surfaced pavements. The table presents the effect of range class (*A–E*) on the backcalculated moduli and the deflection match difference. Tables 3 and 4 present the effect of the stiff layer position on the predicted moduli and deflection match difference for the BISDEF program for both AC and aggregate-surfaced pavements. The effect of initial moduli values on the backcalculated moduli is presented in Tables 5–8. Both MODCOMP2 and BISDEF were used. In these tables, the initial moduli of the pavement layers and the subgrade are varied. The backcalculated moduli are compared to moduli obtained from the standard input values and their percentage change noted.

Tables 9–13 present the effect of layer thickness on predicted moduli. The values for layer thickness in the tables are varied one at a time, and the backcalculated moduli obtained are compared to moduli obtained from standard input. For this study, all three procedures were used.

Tables 14 and 15 present the effect of variations in deflection measurement on the backcalculated moduli for all three programs. In these tables, the deflection measurements were arbitrarily increased or reduced by 5 and 10 percent from assumed correct values. The backcalculated moduli from these values were compared to the ones obtained from the assumed correct values and the percentage change in moduli was noted. This variation in deflection measurement corresponds to a situation in which the deflection sensors systematically underrecord or overrecord the deflection values.

Tables 16 and 17 present the effect of tolerances and number of iterations on the backcalculated moduli from MODCOMP2 and BISDEF procedures.

DISCUSSION OF RESULTS

The following discussion applies to the results in Tables 2–17. For the values of each variable, the results are compared to a standard. Table 1 presents the standard input values used in the analysis. Variations of input values from those shown in Table 1 are noted on the appropriate table where applicable. The choices of the values in Table 1 were based on the need to get a good match between the measured and calculated deflection basins. This matching produced some different standard structures for different procedures, although most structures were common to all procedures.

Effect of Modulus Range on Predicted Moduli

For a given pavement system, there is a combination of modulus range, initial modulus, and deflection basin that produces the best fit between the measured and calculated deflection basin (see Table 2). The best deflection match occurred at modulus ranges that were the same order of magnitude as typical moduli values of layer materials. When larger modulus ranges were input, the deflection match was not so good. However, very narrow modulus ranges appeared to result in a prediction of the upper or lower boundary deflection values because the predicted value exceeded the given range.

As shown in Figure 3, the deflection match difference for the AC pavements was below the BISDEF-specified value of 10 percent for most of the range values. This difference implies

TABLE 2 EFFECT OF RANGE ON PREDICTED MODULI AND DEFLECTION MATCHING (BISDEF)

	AGGREGATE SURFACED PAVEMENT				CONVENTIONAL AC PAVEMENT			
Range Class	Pavement Layer	Modulus Range (psi)	Predicted Moduli, (psi)	Deflection Match Difference,%	Pavement Layer	Modulus Range (psi)	Predicted Moduli, (psi)	Deflection Match Difference,%
A	Pavement	1-1,000,000	30,008	23.4	Surfacing	1-1,000,000	740,474	7.3
	Subgrade	1-1,000,000	13,966		Base	1-1,000,000	17,312	
					Subgrade	1-1,000,000	4,542	
B	Pavement	1-500,000	30,008	23.4	Surfacing	1-500,000	500,000	8.2
	Subgrade	1-500,000	13,966		Base	1-50,000	20,779	
					Subgrade	1-25,000	4,401	
C	Pavement	1,000-100,000	14,200	7.0	Surfacing	250,000-750,000	750,000	5.5
	Subgrade	1,000-100,000	2,232		Base	10,000-50,000	16,428	
					Subgrade	5,000-25,000	5,000	
D	Pavement	5,000-50,000	5,000	11.8	Surfacing	1-1,000,000	693,008	7.5
	Subgrade	5,000-50,000	9,877		Base	1-100,000	18,974	
					Subgrade	1-30,000	4,445	
E	Pavement	7,500-40,000	9,500	13.0	Surfacing	300,000-1,000,000	300,000	10.3
		7,500-40,000	10,000		Base	25,000-75,000	25,000	
					Subgrade	1-30,000	5,263	

Initial Moduli (Aggregate Surfaced)
Pavement - 30,000 psi and subgrade - 14,500 psi

Initial Moduli (AC Surfaced)
Surfacing - 375,000 psi, Base - 30,000 psi, and Subgrade - 14,500 psi

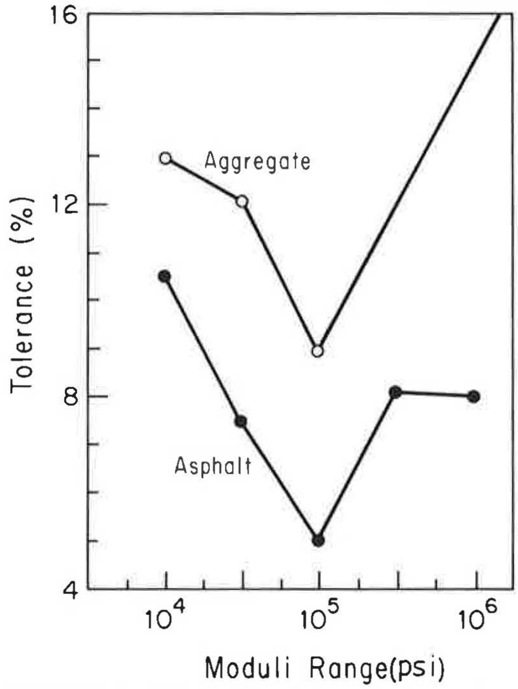

FIGURE 3 Effect of moduli range on deflection matching.

that for practical applications the modulus range does not significantly affect the values of the backcalculated moduli. For aggregate-surfaced pavements, the deflection match difference varied widely with the value of the range. Thus, the modulus range adopted can affect the predicted moduli. This range input parameter applies only for the BISDEF procedure. The range is supposed to improve the speed of convergence to a solution by limiting the range size in which the search for a modulus is to be conducted. Also, because the predicted moduli are not unique (i.e., several combinations of layer moduli can result from the same deflection basin), the range for each layer modulus serves to limit the moduli to their approximate practical values.

Effect of Depth of Stiff Layer

In the development of the BISDEF/CHEVDEF program *(2)*, use of an infinite subgrade layer tended to give larger deflections than measured values. To compensate for this effect, a rigid layer was placed in this system model at a depth of 240 in. (20 ft) below the surface. This placement resulted in a better match between computed deflections and those measured with the Road Rater 2008. In this paper, the position of the stiff layer was varied to determine its effect, if any, on the value of the predicted moduli.

Tables 3 and 4 present the results of the analysis of typical pavement structures using FWD deflection basins. For the conventional AC pavement (Table 3), the deflection match difference did not vary significantly with the depth of the stiff layer. However, the predicted moduli varied substantially from the one predicted at the standard 240-in. depth by as much as 30 percent at a depth of 90 in.

For aggregate-surfaced pavements (Table 4), this effect was more pronounced and variations in modulus of up to 69 percent were observed. Also, percent deflection match tolerances were high. The results point to the fact that there is an optimum depth for a given pavement system and deflection-measuring device stemming from the fact that the stiff layer is required to

TABLE 3 EFFECT OF STIFF LAYER DEPTH ON PREDICTED MODULI AND DEFLECTION MATCHING FOR CONVENTIONAL AC PAVEMENT (BISDEF)

	PREDICTED MODULI (psi)			DEFLECTION MATCH DIFFERENCE, %	% VARIATION IN MODULUS FROM STANDARD(2)		
Position of Stiff Layer,(in)(1)	Surfacing	Base	Subgrade		Surfacing	Base	Subgrade
5	850,000	10,000	3,000	68.8	+6.8	-38.5	-39.5
90	576,884	21,294	3,000	3.9	-27.5	+30.9	-39.5
140	661,549	19,079	4,003	5.0	-16.8	+17.3	-19.2
190	755,360	17,235	4,598	5.4	-5.0	+5.9	-7.2
240(2)	795,154	16,271	4,959	5.6	0.0	0.0	0.0
290	801,392	15,657	5,197	5.8	+0.8	-3.8	+4.8
340	850,000	15,262	5,365	5.9	+6.8	-6.6	+8.2
	850,000	13,969	6,309	6.3	+6.8	-14.1	+27

(1) Depth from the top of subgrade
(2) Standard depth

TABLE 4 EFFECT OF STIFF LAYER DEPTH ON PREDICTED MODULI AND DEFLECTION MATCHING FOR AGGREGATE-SURFACED PAVEMENT (BISDEF)

Position of (1) Stiff Layer	PREDICTED MODULI (psi) Pavement	Subgrade	% DEFLECTION MATCH DIFFERENCE	% VARIATION IN MODULUS FROM STANDARD (2) Surfacing	Base
24	100,000	7,282	38	150.0	-67.0
60	53,289	16,435	29.8	33.7	-25.6
120	44,703	19,793	13.7	12.2	-10.0
180	41,074	21,270	8.6	3.0	-3.8
200	40,372	21,584	7.6	1.3	-2.3
240 (2)	39,850	22,100	6.2	0.0	0.0
300	38,336	22,560	4.8	-3.8	2.1
400	37,116	23,355	3.6	-6.9	5.7
500	34,377	25,036	6.2	-13.7	13.2

(1) Depth from the top of subgrade
(2) Standard depth

limit the depth of summation of vertical strains. If the strains are summed to infinity, the resulting calculated deflections are usually higher than the measured values. Therefore, the position of the stiff layer will vary as a function of the deflection-measuring device and type of pavement structure.

Effect of Seed Moduli

Both BISDEF and MODCOMP2 require the use of initial or seed moduli to begin the iterative process. For the BISDEF/CHEVDEF program, the seed moduli for each layer must be within the range specified for that layer. In MODCOMP2, there is no restriction as to the value of this modulus. Tables 5–8 summarize the results of this evaluation.

Overall, the value of the initial modulus had very little effect on the backcalculated moduli for the paved surface (Tables 5 and 7). When the surfacing seed modulus was doubled, only a 4 percent change in the backcalculated surface modulus occurred. The seed moduli of the surface course had no effect on the backcalculated subgrade or base moduli. Also, changes in the seed moduli of the base and subgrade had a negligible effect on the backcalculated moduli.

These observations also apply to the aggregate-surfaced pavement consisting of granular surfacing over a prepared subgrade (Tables 6 and 8). For MODCOMP2, the backcalculated modulus is relatively more sensitive to the seed moduli of the base layer (Table 5). A maximum change of 9 percent occurred in the predicted base layer moduli when the base layer seed moduli changed by 35 percent.

TABLE 5 EFFECT OF INITIAL MODULUS ON PREDICTED MODULI FOR CONVENTIONAL AC PAVEMENT (MODCOMP2)

Seed Moduli	PREDICTED MODULI (psi) Surfacing	Base	Subgrade	% CHANGE FROM STANDARD (1) Surfacing	Base	Subgrade
Surfacing						
375,000 (1)	585,000	12,653	10,980	0.00	0.00	0.00
450,000	585,998	12,607	10,985	0.17	-0.36	0.05
550,000	587,358	12,544	10,993	0.40	-0.86	0.12
750,000	590,152	12,414	11,011	0.88	-1.89	0.28
850,000						
Base						
10,000	608,993	11,558	11,127	4.10	-8.60	1.34
20,000	594,712	12,205	11,038	1.66	-3.50	0.52
40,000	479,102	12,929	10,945	-1.00	2.18	-0.32
50,000	575,278	13,109	10,923	-1.66	3.60	-0.52
60,000	572,694	13,232	10,908	-2.10	4.58	-0.66
Subgrade						
5,000	577,898	13,028	10,933	-1.2	2.96	-0.43
10,000	589,587	12,441	11,007	0.78	-1.68	0.25
17,500	577,898	12,986	10,938	-1.21	2.60	-0.30
19,500	572,080	13,261	10,905	-2.21	4.80	-0.68

(1) Standard input was: Surfacing - 375,000 psi; Base - 30,000 psi; and Subgrade - 14,500 psi

TABLE 6 EFFECT OF INITIAL MODULUS ON PREDICTED MODULI FOR AGGREGATE-SURFACED PAVEMENT (MODCOMP2)

	PREDICTED MODULI (psi)		% CHANGE FROM STANDARD (1)	
Seed Moduli (psi)	Pavement	Base	Pavement	Base
Pavement				
10,000 (1)	73,894	17,478	0.00	0.00
20,000	73,909	17,475	0.02	0.02
30,000	73,902	17,476	0.01	-0.01
50,000	73,895	17,478	0.00	0.00
60,000	73,893	17,478	0.00	0.00
Base				
2,500	73,840	17,488	0.07	0.06
5,000	73,877	17,481	-0.06	0.02
7,500	73,807	17,494	-0.12	0.09
9,000	73,925	17,427	0.12	0.29

(1) Standard: Pavement - 10,000 psi and Base - 1,000 psi

TABLE 7 EFFECT OF INITIAL MODULUS ON PREDICTED MODULI FOR CONVENTIONAL AC PAVEMENT (BISDEF)

	PREDICTED MODULI (psi)			% CHANGE FROM STANDARD (1)		
Seed Moduli (psi)	Surfacing	Base	Subgrade	Surfacing	Base	Subgrade
Surfacing						
375,000 (1)	795,154	16,271	4,959	0.00	0.00	0.00
450,000	805,763	16,223	4,966	1.33	-0.29	0.14
550,000	818,504	16,145	4,974	2.94	-0.77	0.30
750,000	826,224	16,054	4,967	3.91	-1.33	0.16
850,000	813,661	16,164	4,963	2.33	-0.66	0.08
Base						
15,500	786,157	16,447	4,950	-1.13	1.08	-0.18
20,000	796,943	16,331	4,954	0.22	0.37	-0.10
40,000	795,622	16,261	4,962	0.06	0.06	0.06
50,000	793,051	16,349	4,953	-0.26	0.48	-0.12
Subgrade						
5,000	799,830	16,312	4,953	0.59	0.25	-0.12
10,000	792,302	16,269	4,962	-0.36	-0.01	0.06
17,500	811,143	16,194	4,960	2.00	-0.47	0.02
22,000	810,775	16,196	4,960	1.96	-0.46	0.02
25,000	809,386	16,211	4,959	1.78	-0.37	0.00

(1) Standard: Surfacing - 375,000 psi; Base - 30,000 psi; and Subgrade - 14,500 psi

TABLE 8 EFFECT OF INITIAL MODULUS VALUE ON PREDICTED MODULI FOR AGGREGATE-SURFACED PAVEMENT (BISDEF)

	PREDICTED MODULI (psi)		% CHANGE FROM STANDARD (1)	
Seed Moduli (psi)	Pavement	Subgrade	Pavement	Subgrade
Pavement				
10,000	14,390	12,217	0.64	0.30
20,000	14,455	12,198	1.09	0.14
30,000 (1)	14,299	12,180	0.00	0.00
40,000	14,462	12,194	1.14	0.14
50,000	14,469	12,190	1.19	0.08
Subgrade				
5,000	14,423	12,221	0.88	0.34
10,000	14,469	12,181	1.19	0.00
15,000	14,456	12,197	1.09	0.13
25,000	14,453	12,200	1.08	0.16

Standard: Pavement - 30,000 psi and Subgrade - 14,000 psi

TABLE 9 EFFECT OF LAYER THICKNESS ON PREDICTED MODULI FOR CONVENTIONAL AC PAVEMENT (BISDEF)

	PREDICTED MODULI (PSI)			% CHANGE FROM STANDARD (1)		
Layer Thickness, in.	Surfacing	Base	Subgrade	Surfacing	Base	Subgrade
Surfacing h_1						
1.5	850,000	25,541	4,627	6.9	56.9	-6.7
2.5 (1)	795,154	16,271	4,959	0.0	0.0	0.0
3.5	349,372	14,615	5,017	-56.0	-67.1	1.2
4.5	250,000	11,327	5,173	-68.5	-30.4	4.3
5.5	250,000	10,000	4,897	-68.6	-38.5	-1.2
Base h_2						
12.5	693,124	19,199	5,020	-12.8	17.9	1.2
13.5	753,543	17,542	4,988	-5.2	7.8	0.6
14.5 (1)	795,154	16,271	4,959	0.0	0.0	0.0
15.5	835,328	15,286	4,927	5.1	-6.1	0.6
16.5	850,000	14,662	4,880	6.9	-9.9	1.6

(1) Standard structure: Surfacing h_1 = 2.5 in. and Base h_2 = 14.5 in.

Effect of Layer Thickness

For all three procedures, pavement layer thickness has to be input, either from the construction data or from cores taken from the pavement. As shown in Tables 9–13, the predicted moduli are sensitive to the variation in thickness of both the surface and base layers. For a conventional AC pavement, the BISDEF-predicted surface and base moduli are very sensitive to the input thickness of the surface layer (Table 9). One inch of change in the surface layer thickness resulted in a change of over 60 percent in the value of the predicted surface modulus and a 60 percent change in the predicted base modulus. The base layer thickness does not have as much effect on the predicted modulus, as only an 18 percent change in predicted modulus occurred for a 2-in. change in the base thickness. The thickness of the layers had little effect on the predicted subgrade modulus. The observed change in predicted subgrade modulus was a maximum of about 7 percent for all the thickness changes considered. As presented in Table 10, the layer thicknesses have little effect on the predicted moduli of the aggregate-surfaced pavement.

For MODCOMP2, the predicted moduli are more sensitive to the input thickness than for BISDEF (Table 11). Both the surface and base moduli are very sensitive to the input surface and base layer thicknesses. The predicted subgrade modulus is also fairly sensitive when compared to the BISDEF-predicted value. For the aggregate-surfaced pavement, the same observations were noted (Table 12).

The predicted moduli from the SEARCH program are also sensitive to the surface and base thicknesses (Table 13). The moduli predicted by SEARCH for the base and subgrade are more sensitive to the surfacing than the base thickness.

Effect of Variations in Deflection Measurements

Tables 14 and 15 present the effect of the accuracy in deflection measurements. In these tables, variation magnitudes of +5 and

TABLE 10 EFFECT OF LAYER THICKNESS ON PREDICTED MODULI FOR AGGREGATE-SURFACED PAVEMENT (BISDEF)

	PREDICTED MODULI (psi)		% DIFFERENCE FROM STANDARD (1)	
Layer Thickness, in	Pavement	Subgrade	Pavement	Subgrade
Base (ho)				
6.95	15,425	11,908	7.92	-2.22
7.95	14,858	12,050	3.93	-1.13
8.00	14,838	12,050	3.74	-1.12
8.50	14,572	12,139	1.92	-0.33
8.95 (1)	14,299	12,180	0.00	0.00
9.00	14,441	12,203	0.90	0.20
9.50	14,287	12,276	-0.08	0.80
9.95	14,162	12,344	-0.96	1.30
10.95	13,934	12,493	-2.51	2.60

(1) Standard structure h_o = 8.95 in.

TABLE 11 EFFECT OF LAYER THICKNESS ON PREDICTED MODULI FOR CONVENTIONAL AC PAVEMENT (MODCOMP2)

	PREDICTED MODULI (psi)			% CHANGE FROM STANDARD (1)		
Layer Thickness, in	Surfacing	Base	Subgrade	Surfacing	Base	Subgrade
Surfacing h_1						
2.5	540,790	28,882	9,747	-7.56	128.26	-11.23
3.0 (1)	585,000	12,653	10,980	0.00	0.00	0.0
3.5	399,750	11,433	11,043	-31.66	-9.64	0.57
4.5	224,551	9,581	11,117	-61.62	-24.28	1.25
5.0	180,570	8,793	11,144	-69.13	-30.51	1.49
6.0	131,907	6,788	11,358	-77.45	-46.35	3.44
Base h_2						
6.0	469,616	20,176	10,383	-19.72	59.46	-5.44
6.5	470,979	19,525	10,325	-19.49	54.31	-5.96
7.0 (1)	585,000	12,653	10,980	0.00	0.00	0.00
7.5	580,544	12,799	10,932	-0.76	1.15	-0.44
8.0	571,670	13,129	10,852	-2.27	3.76	-1.16
14.0	539,842	13,596	10,273	-7.72	7.45	-6.44

(1) Standard structure: Surfacing h_1 = 3.0 in. and Base h_2 = 7.0 in.

TABLE 12 EFFECT OF LAYER THICKNESS ON PREDICTED MODULI FOR AGGREGATE-SURFACED PAVEMENT (MODCOMP2)

	PREDICTED MODULI (psi)		% DIFFERENCE FROM STANDARD (1)	
Layer Thickness, in	Pavement	Subgrade	Pavement	Subgrade
Pavement h_o				
7.86	88,521	18,566	19.79	6.22
8.86	79,668	18,033	7.81	3.18
9.86 (1)	73,894	17,478	0.00	0.00
6.86	103,091	19,062	39.51	9.06

(1) Standard Structure h_o = 9.86 in.

TABLE 13 EFFECT OF LAYER THICKNESS ON PREDICTED MODULI FOR CONVENTIONAL AC PAVEMENT (SEARCH)

	PREDICTED MODULI (psi)			% CHANGE FROM STANDARD (1)		
Layer Thickness, in	Surfacing	Base	Subgrade	Surfacing	Base	Subgrade
Surfacing h_1						
2.5 (1)	610,700	7,000	7,000	0.0	0.0	0.0
3.0	317,300	7,000	7,000	-48.0	0.0	0.0
3.5	425,300	5,400	6,100	-30.4	-22.8	-12.8
4.0	280,300	5,500	5,900	-54.1	-21.4	-15.7
4.5	508,500	2,100	9,400	-16.7	-70.0	34.4
5.0	371,700	1,900	9,900	-39.1	-72.8	41.4
6.0	290,900	700	18,700	-52.4	-90.0	167.1
Base h_2						
9.0	1,051,900	8,600	6,300	72.2	22.8	-10.0
12.0	612,700	7,000	7,000	0.3	0.0	0.0
14.5 (1)	610,700	7,000	7,000	0.0	0.0	0.0
16.0	827,300	6,400	6,400	35.5	-8.5	-8.5
18.0	923,300	6,200	6,200	51.2	-11.4	-11.4
20.0	1,030,900	6,000	6,100	68.8	-14.3	-12.8

(1) Standard structure: Surfacing h_1 = 2.5 in. and Base h_2 = 14.5 in.

TABLE 14 EFFECT OF FWD DEFLECTION MEASUREMENTS VARIATIONS ON PREDICTED MODULI FOR CONVENTIONAL AC PAVEMENT

Procedure Used	Average Variation in Deflection Measurement, %	Deflection Values ($x10^{-3}$) in.				PREDICTED MODULI (psi)			% CHANGE IN MODULI		
		1	2	3	4	Surfacing	Base	Subgrade	Surfacing	Base	Subgrade
	0	34.60	19.80	10.10	4.50	585,000	12,653	10,980	0.0	0.0	0.0
	+5	36.30	20.79	10.61	4.73	556,408	12,187	10,437	-4.8	-3.7	-4.9
MODCOMP2	+10	38.10	21.78	11.11	4.95	525,329	11,683	9,961	-10.2	-7.8	-9.2
	-5	32.87	18.81	9.60	4.28	521,401	14,922	11,895	-10.9	17.9	8.3
	-10	31.14	17.82	9.09	4.05	654,726	13,840	12.228	11.9	9.3	11.4
	0	43.10	26.40	17.80	9.60	795,235	16,271	4,959	0.0	0.0	0.0
	+5	45.25	27.72	18.69	10.08	772,506	15,362	4,731	-2.9	-5.6	-4.6
BISDEF	+10	47.41	29.04	19.58	10.56	747,693	14,631	4,513	-5.9	-10.1	-8.9
	-5	40.95	25.08	16.91	9.02	850,000	17,233	5,239	6.9	5.9	5.6
	-10	38.79	23.76	16.02	8.64	850,000	18,445	5,491	6.9	13.4	10.7
	0	43.10	26.40	17.80	9.60	1,313,300	6,900	7,300	0.0	0.0	0.0
	+5	45.25	27.72	18.69	10.08	1,120,200	7,000	7,000	-14.7	1.5	-4.1
SEARCH	+10	47.41	29.04	19.58	10.56	945,500	6,900	6,900	-28.0	0.0	-5.5
	-5	40.95	25.08	16.91	9.02	1,475,000	7,000	7,900	12.3	1.4	8.2
	-10	38.79	23.76	16.02	8.64	1,903,100	6,400	8,800	44.9	-7.3	20.5

TABLE 15 EFFECT OF FWD DEFLECTION MEASUREMENTS VARIATIONS ON PREDICTED MODULI FOR AGGREGATE-SURFACED PAVEMENTS

Procedure Used	Av. Variation in Deflection Measurement,%	DEFLECTION VALUES ($x10^{-3}$) in. 1	2	3	4	PREDICTED MODULI (psi) Pavement	Subgrade	% CHANGE IN MODULI Pavement	Subgrade
	0	36.70	12.70	4.30	2.40	25,243	15,757	0.0	0.0
	+5	38.54	13.34	4.52	2.52	24,090	14,992	-4.6	-4.9
BISDEF	+10	40.37	13.97	4.73	2.77	22,918	14,232	-9.2	-9.7
	-5	34.87	12.07	4.09	2.28	26,535	16,586	5.1	5.3
	-10	33.03	11.43	3.87	2.16	27,961	17,525	10.8	11.2
	0	36.70	12.70	4.30	2.40	27,291	15,681	0.0	0.0
	+5	38.54	13.34	4.52	2.52	26,051	14,928	-4.5	-4.8
MODCOMP2	+10	40.37	13.97	4.73	2.77	24,815	14,254	-9.0	-9.1
	-5	34.87	12.07	4.09	2.28	28,731	16,499	5.3	5.2
	-10	33.03	11.43	3.87	2.16	30,326	17,422	10.0	11.10

+10 percent have been applied to a set of known deflection measurements and the predicted moduli obtained from all three programs. All programs are sensitive to the variations in deflection measurements. The backcalculated surfacing layer moduli using MODCOMP2 and SEARCH show more sensitivity to these variations than the base or subgrade layer moduli, whereas for BISDEF all three backcalculated moduli are equally sensitive.

Effect of Tolerance and Number of Iterations

Table 16 presents the effect of tolerance and number of iterations on the backcalculated moduli. For MODCOMP2, the backcalculated modulus is insensitive to percentage deflection tolerance of less than 0.20 percent. For tolerance levels greater than 5 percent, the predicted modulus changes rapidly with higher values of tolerances. In the case of BISDEF (Table 17), the backcalculated modulus is insensitive to the tolerance level and number of iterations. The backcalculated modulus is insensitive to tolerance level above 5 percent, if the standard three iterations are used. Values of number of iterations greater than two do not have any effect on the backcalculated moduli.

IMPLICATIONS OF FINDINGS

The findings from this study show that the three backcalculation procedures have a number of limitations. The most important is that the predicted modulus is very sensitive to the user-supplied inputs. Some of these inputs cannot be physically measured (e.g., depth of stiff layer and initial moduli). To arrive at a reasonable solution from these procedures, one has to be aware of these limitations and develop methods for dealing with them.

Even with identical input values, the predicted moduli from the three programs are very different. Differences between BISDEF- and MODCOMP2-predicted values occur because BISDEF uses a standard depth to a rigid layer of 240 in. MODCOMP2 does not use such a layer and therefore the vertical strains are summed to infinity. Although not included in the standard input and not investigated in this paper, MOD-

TABLE 16 EFFECT OF TOLERANCES AND NUMBER OF ITERATIONS ON PREDICTED MODULI FOR CONVENTIONAL AC PAVEMENT (MODCOMP2)

Tolerance %	PREDICTED MODULI (psi) Surfacing	Base	Subgrade	% CHANGE FROM STANDARD (1) Surfacing	Base	Subgrade
0.05	585,000	12,653	10,980	0.00	0.00	0.00
0.15(1)	585,000	12,653	10,980	0.00	0.00	0.00
0.20	585,000	12,653	10,980	0.00	0.00	0.00
5	344,610	26,682	9,771	-41.00	110.00	-11.00
10	344,610	26,682	9,771	-41.00	110.00	-11.00
15	344,610	26,682	9,771	-41.00	110.00	-11.00
No. of Iterations						
5	518,589	15,905	10,622	-11.35	25.70	-3.26
10(1)	585,000	12,653	10,980	0.00	0.00	0.00
15	608,436	11,583	11,124	4.01	-8.46	1.31
20	608,436	11,583	11,124	4.01	-8.46	1.31

(1) Standard: Tolerance = 0.15% and No. of Iterations = 10

TABLE 17 EFFECT OF TOLERANCES AND NUMBER OF ITERATIONS ON PREDICTED MODULI FOR CONVENTIONAL AC PAVEMENT (BISDEF)

	PREDICTED MODULI (psi)			% CHANGE FROM STANDARD (1)		
Tolerance %	Surfacing	Base	Subgrade	Surfacing	Base	Subgrade
0.5	811,263	16,193	4,960	2.00	-0.48	0.02
2.5	811,263	16,193	4,960	2.00	-0.48	0.02
5.0	811,263	16,193	4,960	2.00	-0.48	0.02
10 (1)	795,235	16,271	4,959	0.00	0.00	0.00
12.5	795,235	16,271	4,959	0.00	0.00	0.00
15.0	795,235	16,271	4,959	0.00	0.00	0.00
20.0	795,235	16,271	4,959	0.00	0.00	0.00
No. of Iterations						
1	850,000	17,283	5,440	6.89	6.22	9.70
2	795,235	16,271	4,959	0.00	0.00	0.00
3 (1)	795,235	16,271	4,959	0.00	0.00	0.00
8	795,235	16,271	4,959	0.00	0.00	0.00
12	795,235	16,271	4,959	0.00	0.00	0.00
18	795,235	16,271	4,959	0.00	0.00	0.00
20	795,235	16,271	4,959	0.00	0.00	0.00

(1) Standard: Tolerance = 10% and No. of Iterations = 3

COMP2 can be used with a rigid layer at an appropriate depth in a manner similar to that of BISDEF. The difference between SEARCH and the other two programs is probably due to the differences in stress distribution between the Vlasov and Leont'ev *(8)* equation and the elastic layer programs used in BISDEF and MODCOMP2. The speed of computation using these programs depends on the hardware support available, but, on a relative scale, SEARCH is the fastest, followed by MODCOMP2 and BISDEF at about the same speed.

One major weakness of the programs used in this analysis is their inability to consider the stress sensitivity of the modulus in any given layer. Although MODCOMP2 has the capability to consider the stress sensitivity of the granular and subgrade layer, this option was not used because of the lack of sufficient data. If the variations in moduli and stress were taken into account, there would be no need to adopt a fictitious rigid layer.

Another major weakness is that the moduli determined with these procedures, indeed with most curve-fitting procedures, are never unique; there are several combinations of layer moduli that can result from the same deflection basin. This problem has been addressed by some researchers *(1)* by using regression equations to determine the seed moduli. However, such approaches are still based on locally developed relationships that cannot be used with confidence outside the area for which they were calibrated.

In general, the results clearly show the problems that might be encountered in attempting to use most of the backcalculation procedures available. A general guideline is that, before adopting any procedures for production or detailed analysis, a sensitivity study should be carried out. This study should look at all user-supplied input data, especially those that cannot be physically measured.

CONCLUSIONS AND RECOMMENDATIONS

The evaluations conducted in this study revealed the following:

1. The range of moduli used as input in BISDEF affects the accuracy of matching the measured and calculated deflection basins.
2. The predicted AC surface modulus by the BISDEF program is sensitive to the depth of the stiff layer and the surfacing and base thicknesses.
3. The predicted base modulus using BISDEF is sensitive to the depth of the stiff layer as well as the layer thicknesses of the surfacing and base layers.
4. The predicted subgrade modulus using BISDEF for the conventional AC pavement is only sensitive to the depth of the stiff layer. For the MODCOMP2 procedure, the predicted subgrade modulus is sensitive only to tolerance and number of iterations.
5. Using BISDEF, the predicted pavement and subgrade moduli for the aggregate-surfaced pavement are highly sensitive only to the depth of the stiff layer. For the same pavement type, the MODCOMP2-predicted modulus is sensitive only to the pavement layer thicknesses.
6. For the two programs requiring them as input, the seed moduli have no significant effect on the backcalculated moduli.
7. The backcalculated AC surfacing modulus using MODCOMP2 is very sensitive to the thickness of the surface and base layers. It is also sensitive to the input percent tolerance.
8. The predicted moduli for all pavement layers using SEARCH are sensitive to the thickness of the pavement layers.
9. The computer program SEARCH requires the least amount of user-supplied inputs and uses the least amount of computer time.

Based on the findings, the following recommendations appear warranted:

1. For all three backcalculation procedures, special attention should be paid to the determination of the pavement layer thicknesses. If possible, a number of cores should be taken at each site to determine the pavement layer thicknesses.
2. When using BISDEF, calibrations should be carried out using typical deflection basins to determine the depth of the stiff layer that gives the smallest deflection match differences. Further, the range of layer moduli used should be as close as possible to the actual modulus range found in practice for the material under consideration.

3. When using MODCOMP2, attention should be paid to deflection match tolerance, which should be kept at or below the suggested value of 0.15 percent.

4. For all three programs, attention should be paid to the variations in surface deflection measurement.

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