Characterization of Falling Weight Deflectometer Deflection Basin

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Deflection basins from any nondestructive testing device can be characterized by parameters that describe the structural characteristics of an existing pavement. An exponential curve of the form $Y = A * e^{BX}$, where Y is the deflection in mils and X is the radial distance in inches, approximates the deflection basins simulated from elastic layer theory and measured by the falling weight deflectometer (FWD). The coefficients A and B describe the structural characteristics of the pavement. Usually, a pavement with a stiffer upper layer or layers is indicated by a lower A value, whereas a stiff subgrade or the presence of a rigid bottom at a shallow depth (or both) is indicated by a higher B value. The value of the coefficient of determination for the exponential fit, R^2, was found useful for judging the suitability of an FWD-measured basin for backcalculation of layer moduli in a deflection-matching technique. Generally, a low value of R^2 for an exponential curve fitted to an FWD-measured basin indicates that there will be a high error in the backcalculation of layer moduli using elastic layer theory. Guidelines are presented for using the value of R^2 to indicate the error between measured and computed deflections that can be expected during a backcalculation analysis.

Early static deflection devices could measure deflection at only one point. This point deflection was successfully related to the structural performance of the pavement by many researchers and was the basis for a number of overlay design methods. Later, vibratory devices, such as Dynaflect and Road Rater, provided deflection measurements near the load and at fixed distances from the load, resulting in a measured deflection basin. Falling weight deflectometers (FWDs) can measure deflection under the load and at a number of locations away from the load, resulting in a much larger basin. Thus, more information is expected from the FWD basin than from other devices.

Work of other researchers on FWD basin parameters to characterize the pavement is available (*1,2*). An approach for characterization of the FWD basin has been developed during this research. The objective was to find new parameters from the deflection basin that define the structural characteristics of the pavement.

INTERPRETATION OF DEFLECTION BASIN

Deflection basin parameters are widely used for three major applications: (*a*) to check the structural integrity of in-service pavements, (*b*) to relate to critical pavement response, and (*c*) to calculate the in situ layer moduli of the pavements. A number of basin parameters, which are functions of deflection values at one or more sensors, are available for characterization of deflection basins produced by the Dynaflect, Road Rater, and FWD. Table 1 summarizes deflection basin parameters available in the literature (*1,3–8*). Figure 1 shows the Dynaflect deflection basin parameters. The area parameter for the Road Rater deflection basin is shown in Figure 2. Table 1 indicates that not much effort has been made to characterize the deflection basin of FWDs.

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CHARACTERIZATION OF DEFLECTION BASINS FROM ELASTIC LAYER THEORY

The surface deflection basins for pavement systems from elastic layer theory can be characterized by Boussinesq's theory of linear-elastic half-space. Jung (*9*) has shown that the deflections (Y) on the top of the half-space around a concentrated load are a simple hyperbola with a linear term for the distance (X) from the load in the denominator:

$$Y = Z/X \tag{1}$$

For the quasi-concentrated FWD test load, the constant (Z) is

$$Z = P * A(1 - \nu^2)/Em \tag{2}$$

where

P = concentrated load,
A = radius of the loaded area,
ν = Poisson's ratio of the subgrade, and
Em = elastic stiffness of the subgrade (assuming infinite depth of the subgrade).

The computed surface deflections' distance from the load axis will closely follow the hyperbola given by Equations 1 and 2. Unfortunately, the equations are not valid when the subgrade is of finite depth (i.e., when a rigid layer is encountered below the subgrade at a shallow depth, say 120 in.). The equations are also not valid for nonlinear behavior of bases and subgrades. This necessitates the characterization of the deflection basin by some other method.

An empirical approach was taken to characterize the deflection basins from elastic layer theory. The intent was to find a characteristic curve with a minimum number of parameters that closely approximates the deflection basin. Several functional forms of equations were evaluated for fitting the deflection basin. An exponential curve was found to have the

TABLE 1 SUMMARY OF DEFLECTION BASIN PARAMETERS

Parameters	Definition	NDT Device	Reference
Dynaflect Maximum Deflection, DMD	$DMD = W_1$	Dynaflect	3
Surface Curvature Index, SCI	$SCI = W_1 - W_2$	Dynaflect	3,4
		Road Rater 400	3
Base Curvature Index, BCI	$BCI = W_4 - W_5$	Dynaflect	3
Spreadability, SP	$SP = \frac{\sum_{i=1,5} W_i}{5W_i} \times 100$	Dynaflect	3,5
	$SP = \frac{\sum_{i=1,4} W_i}{4W_i} \times 100$	Road Rater 2008	
Basin Slope, SLOP	$SLOP = W_1 - W_5$	Dynaflect	5
W_5	$W_5 = W_5$	Dynaflect	6
Area (inch), A	$A = 6\,(1 + 2W_1/W_0 + 2W_2/W_0 + W_3/W_0)$	Road Rater 2008, FWD	1
Shape Factors, F_1, F_2	$F_1 = (W_1 - W_3)/W_2$	Road Rater 2008, FWD	1
	$F_2 = (W_2 - W_4)/W_3$		
Tangent Slope, TS	$TS = (W_m - W_x)/x$	None	7
Deflection Ratio, Q_r	$Q_r = W_r/W_o$	FWD	8

W = Deflection; subscripts: 1,2,..., 5 = sensor locations

0 = center of load

r = radial distance

m = maximum deflection

x = distance of the tangent point from the point of maximum deflection

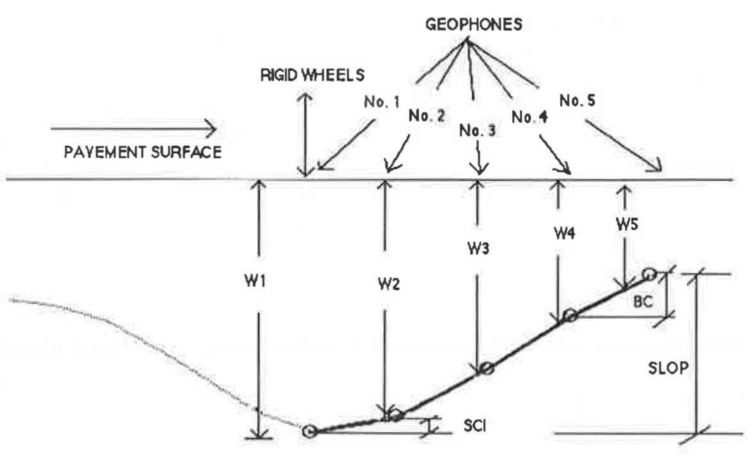

FIGURE 1 Dynaflect deflection basin parameters.

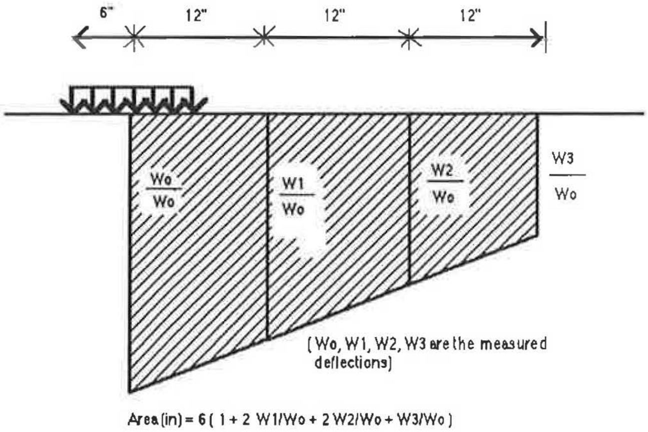

FIGURE 2 Road Rater deflection basin area parameter.

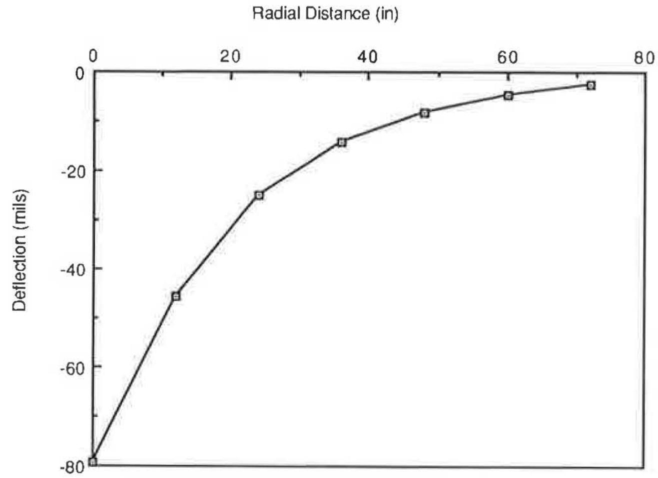

FIGURE 3 Typical exponential curve for fitting the deflection basin.

desired characteristics. The form of the equation is

$$Y = A * e^{BX} \quad (3)$$

where

Y = deflection value in mils,
X = radial distance from the load axis in inches, and
A, B = constants.

A typical shape for the exponential curve is shown in Figure 3.

Simulated deflection basins were generated by running the CHEVRON program (*10*), using a 9,000-lb load uniformly distributed over a circular area 11.8 in. in diameter and computing surface deflections at the load center and six other locations uniformly spaced at 12 in. The locations correspond to the typical sensor locations used by the Arizona Department of Transportation (ADOT) in FWD testing (*11*). The basins were generated by a combination of layer thickness and moduli in a matrix for five-layer pavement systems, as shown in Table 2.

In order to pick realistic pavement sections, the ADOT pavement management system data base was searched, and a frequency analysis of the structural number, SN (*12*), was done mile by mile to classify the pavements as stiff, medium, or weak. Table 3 gives the frequency analysis results. The target SNs selected on the basis of the frequency analysis corresponding to weak, medium, and stiff pavements were 3.0, 6.0, and 8.0, respectively. Layer thicknesses for 12 pavements from all roadway types in Arizona—Interstates, U.S. routes, and state routes—were statistically analyzed to find the representative thicknesses of layers corresponding to the target SNs. Because a sufficient number of pavement sections with a granular base and an SN of 8 were unavailable, the layer thicknesses of the stiff pavements were calculated to correspond to an SN of 8. Layer thicknesses for other pavements were selected on the basis of the statistical analysis shown in Table 4 and engineering judgment. Representative moduli values were selected on the basis of a literature search.

The matrix in Table 2 has eight factors each at three levels, yielding 3^8 = 6,561 pavement structures having SNs between 1.51 and 7.98. The SNs were calculated by using the equation for SN in the *AASHTO Guide* (*12*). The drainage coefficients for the base and subbase layers were assumed to be unity, and the structural layer coefficients were computed from ADOT's *Materials Preliminary Engineering Design Manual* (*11*). An exponential curve with the form of Equation 3 was fitted to each deflection basin. Table 5 gives the summary statistics for A and B for each pavement type, and Table 6 shows the frequency distribution of R^2 for each pavement type. Figure 4 shows the CHEVRON and fitted basins for pavements of each category. These deflection basin shapes were qualitatively observed by Jung (*9*).

From Table 5, it is seen that the pavements fall into three distinct classes on the basis of the values of A. Again, the R^2 values indicate that exponential curves can be fitted to the CHEVRON deflection basins well.

The coefficient of determination, R^2, is an important diagnostic tool for judging the suitability of applying elastic layer theory for backcalculation of layer moduli. Figure 5 shows the CHEVRON and exponential curve–fitted deflection basins with low R^2. It is apparent that the deflection basin with a low R^2 will have a higher error in a deflection-matching technique. In general, the higher the value of the coefficient of determination, the lower will be the absolute sum of the percentage errors between the measured and the fitted deflection basin in a backcalculation routine. The absolute sum of the percentage errors between an exponential curve–fitted basin and the measured basin may be used as a limit for setting the lowest sum of percentage errors desired in the backcalculation process. Usually, the iteration should be carried out until the absolute sum of the percentage errors is less than or equal to that between the exponential curve–fitted and the measured deflection basins.

A high value of R^2 also indicates the suitability of modeling of pavements by elastic layer theory. Table 6 indicates that about 12 percent of pavements in the weak category have R^2 values less than 0.90, compared with less than 2.2 percent in the medium category and less than 1.1 percent in the stiff category. Thus, the frequency analysis of Table 6 indicates that, if an exponential curve of the form $Y = A * e^{BX}$ approximates the deflection basin closely, the application of

TABLE 2 PAVEMENT MATRIX USED FOR CHEVRON DEFLECTION BASIN GENERATION

LEVELS	FACTORS							
	T_{AC} (in)	T_{AB} (in)	T_{SM} (in)	D (in)	E_{AC} (ksi)	E_{AB} (ksi)	E_{SM} (ksi)	E_{SG} (ksi)
(1) LOW	3.0	4.0	9.0	120	100	15	10	3
(2) MED	6.0	4.0	12.0	240	450	30	20	7
(3) HIGH	10.0	6.0	18.0	s-i	850	50	30	14

Note: 1) D: Depth to Rigid Layer, s-i: semi-infinite subgrade

2) AC: Asphalt Concrete, AB: Aggregate Base, SM: Select Material/ Subbase, SG: Subgrade

TABLE 3 FREQUENCY ANALYSIS OF STRUCTURAL NUMBERS ON THE ARIZONA HIGHWAY SYSTEM

From	To Below	Frequency	Percent	Cumulative Percent
0.0	1.0	1144	16.37	16.37
1.0	2.0	1440	20.60	36.97
2.0	3.0	1353	19.36	56.33
3.0	4.0	2116	30.27	86.60
4.0	5.0	473	6.76	93.36
5.0	6.0	185	2.65	96.01
6.0	7.0	47	0.67	96.68
7.0	8.0	106	1.52	98.20
8.0	9.0	130	1.86	100.00

TABLE 4 REPRESENTATIVE THICKNESSES OF ARIZONA PAVEMENTS

SN	Statistic	T_{AC} (in)	T_{AB} (in)	T_{SM} (in)
3.0	Mean	4.0	4.0	9.0
	Std. Dev.	0.75	1.5	3.0
	Sample Size	12	12	12
6.0	Mean	7.25	4.0	13.5
	Std. Dev.	4.0	2.0	7.5
	Sample Size	12	12	12

Note: AC; Asphalt Concrete, AB; Aggregate Base, SM; Select Material/Subbase.

TABLE 5 SUMMARY STATISTICS FOR PARAMETERS OF THE CHEVRON BASINS

Pavement Type	Statistic	A	B	R^2
Weak	Mean	32.14	-.034	0.958
(3" AC)	Std. Dev.	12.12	-.009	0.048
	C.V. (%)	3.8	2.6	5.1
	Sample Size	2187	2187	2187
Medium	Mean	24.64	-.028	0.974
(6" AC)	Std. Dev.	9.52	-.008	0.021
	C.V. (%)	3.9	2.9	2.2
	Sample Size	2187	2187	2187
Stiff	Mean	18.07	-.020	0.976
(10" AC)	Std. Dev.	7.73	-.005	0.020
	C.V. (%)	4.3	2.5	2.0
	Sample Size	2187	2187	2187

TABLE 6 FREQUENCY ANALYSIS OF R^2 FOR SIMULATED DEFLECTION BASINS OF DIFFERENT PAVEMENT TYPES

Pavement Type	From	To Below	Frequency	%	Cumulative %
Weak	0.74	0.78	8	0.3	0.3
(3" AC)	0.78	0.82	45	2.1	2.4
	0.82	0.86	52	2.3	4.8
	0.86	0.90	156	7.1	11.9
	0.90	0.94	306	13.9	25.9
	0.94	0.98	730	33.3	59.3
	0.98	1.00	890	40.6	100.0
Medium	0.85	0.88	6	0.27	0.27
(6" AC)	0.88	0.91	42	1.92	2.19
	0.91	0.94	131	6.0	8.19
	0.94	0.97	342	15.63	23.82
	0.97	1.00	1601	73.2	97.02
	= 1.00		65	2.98	100.0
Stiff	0.85	0.88	2	0	0
(10" AC)	0.88	0.91	22	1	1.1
	0.91	0.94	102	4.66	5.76
	0.94	0.97	441	20.2	25.96
	0.97	1.00	1576	72.06	98.02
	= 1.00		44	1.98	100.0

elastic layer theory to thin pavements will result in a slightly higher error in backcalculation of layer moduli. The limitations of applying layer theory to thin pavements have also been demonstrated by Thrower et al. (*13*) and Yazdani and Scullion (*14*).

Low values of R^2 (e.g., less than 0.90) for CHEVRON basins are also indicative of other situations. Out of 308 deflection basins having R^2 values less than 0.90, 190 pavements are so-called "inverted" structures in which the modulus of an upper layer is smaller than the modulus of a lower layer. For 62 pavements the modulus of either the base or the subbase layer is close to that of the next layer, and others are extreme cases in which either a thin asphalt concrete (AC) layer of very low modulus exists in combination with stiff subgrades or a thick pavement with a high modulus is on a very weak subgrade. In general, these conditions may not be detected in a backcalculation process, but they can be used to explain some badly shaped deflection basins.

On the basis of the frequency analysis of R^2 in Table 6, the following guidelines are suggested for values of R^2 (corresponding to 99th percentile or greater values in the table) for deflection basins that can be backcalculated by elastic layer theory using an iterative technique without large errors:

If 3 in. ≤ AC thickness < 6 in., R^2 should be greater than 0.78.

If 6 in. ≤ AC thickness, R^2 should be greater than 0.88.

Correlation tables were computed to investigate the relationships among *A*, *B*, SN, depth to rigid layer (D), and subgrade modulus (Esg), and *t*-tests were used to test significance. SN was assumed to quantify the stiffness of the upper layers. Table 7 is the correlation table for pavements with finite subgrade thicknesses of 120 and 240 in., and Table 8 shows the correlation table for pavements with semi-infinite subgrade. Table 7 indicates that for pavements with rigid layers at shallow depth, *A* is negatively correlated with both SN and Esg, but the correlation with SN is better. Thus, as SN or Esg increases, *A* decreases. *B* is positively correlated with SN (i.e., as the stiffness of the upper layers increases, *B* increases), whereas *B* is negatively correlated with Esg. *B* is also significantly correlated with D. As the depth decreases,

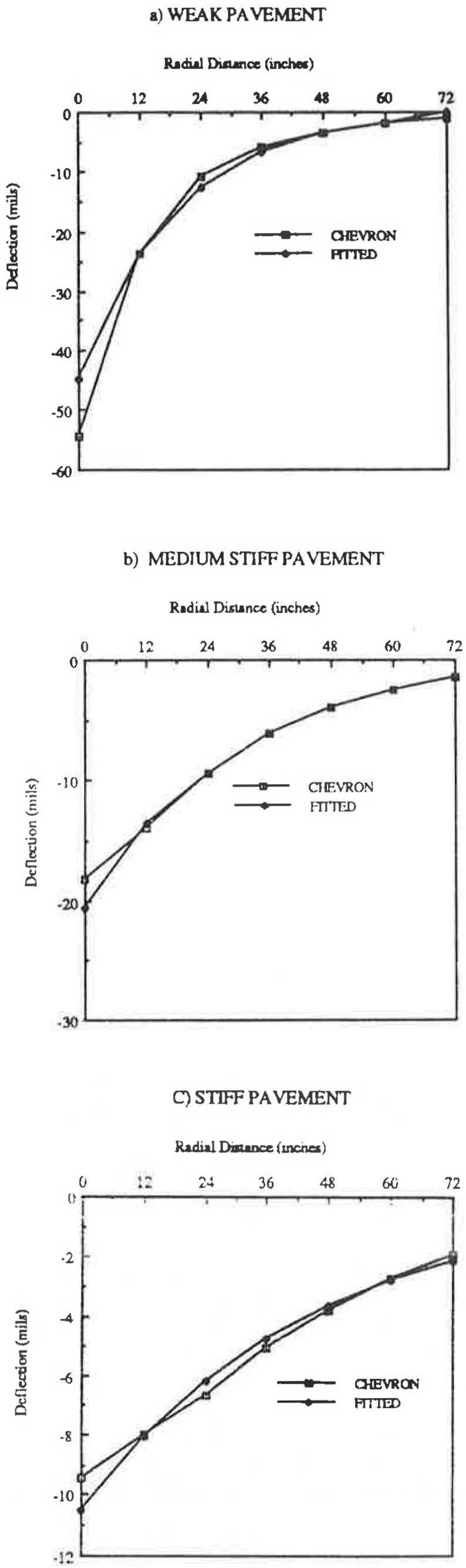

FIGURE 4 Actual and fitted deflection basins for different pavements.

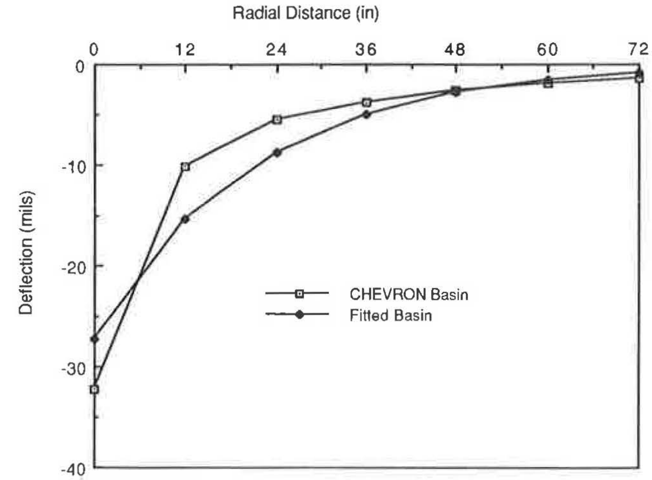

FIGURE 5 CHEVRON and exponential curve–fitted deflection basins with low R^2 (R^2 = 0.775).

B increases. For infinite subgrade, *A* is correlated with both SN and Esg. However, the subgrade modulus seems to be better correlated with *A* (Table 8). In this case, *B* is also correlated with SN and Esg. However, an increase in the stiffness of the upper layers results in an increase in the value of *B*, whereas an increase in Esg results in a decrease in the value of *B*.

Evidently these parameters describe the deflection basin structurally. They can be used to classify the pavements according to structural integrity for a network-level pavement management system. The combination of *A* and *B* is usually unique for a particular structural number when the subgrade characteristics are similar. Two pavements with similar structural numbers and subgrade moduli would yield deflection basins having identical *A* and *B* parameters. Figure 6 shows an example of such pavements from the matrix in Table 2. Because of the high correlation of *A* and *B* with Esg, they can be used in estimating Esg (see the companion paper in this Record by Hossain and Zaniewski).

VERIFICATION WITH FIELD DATA

Field deflection basins from sites in the Arizona State University overlay study (*15*) were used to verify the applicability

TABLE 7 CORRELATION AMONG *A*, *B*, SN, D, AND Esg FOR PAVEMENTS WITH FINITE DEPTH OF SUBGRADE

	A	B	SN	D	Esg
A	1.0	-.06	-0.68*	0.07	-0.60*
B		1.0	0.64*	0.33*	-0.63*
SN			1.0	0.0	0.0
D				1.0	0.0
Esg					1.0

* Significant at α = 5%

TABLE 8 CORRELATION AMONG *A*, *B*, SN, AND Esg FOR PAVEMENTS WITH INFINITE DEPTH OF SUBGRADE

	A	B	SN	Esg
A	1.0	0.09	-0.58*	-0.71*
B		1.0	0.68*	-0.68*
SN			1.0	0.0
Esg				1.0

*Significant at α = 5%

of the exponential curve–fitting technique in characterizing deflection basins. Table 9 gives the sites used in this study, and Table 10 shows the pavement sections of the sites. Deflection testing was done using the Dynatest Model 8002 FWD on the outer wheelpath of the travel lane at these sites. Deflections were measured at 10 stations at each site, spaced at 10-ft intervals. The target load was 9,000 lb, and seven sensors were arranged at a uniform spacing of 12 in., the first sensor being at the center of the load.

For each site, Table 11 shows Parameters *A* and *B*; the coefficient of determination, R^2, of the exponential curve–fitted deflection basins; and the structural number, subgrade modulus, and depth to rigid layer. Figure 7 shows the actual and fitted FWD basins for two sites. Figure 7 indicates that the fitted basins closely approximate the shapes of the FWD-measured basins.

Table 11 indicates that the exponential curve fits the FWD-measured deflection basins well, with R^2 values varying from 0.856 to 0.996. In order to find the relationships between *A*, *B*, SN, backcalculated subgrade modulus, and calculated depth to rigid layer, Tables 12 and 13 were formed for pavements having finite and infinite subgrade thicknesses, respectively. Student's *t*-tests were used to determine significance. Table 12 indicates that *A* is significantly correlated with SN and D. As SN (the stiffness of upper layers) increases, *A* decreases. Again, when the depth of the rigid layer increases, *A* increases. There is no significant correlation between *A* and the backcalculated subgrade modulus. However, the trend shows that as the subgrade modulus decreases, *A* increases. *B* is significantly correlated with SN and the backcalculated modulus of the subgrade. The trend is similar to that of the CHEVRON basins. *B* increases with increasing SN and decreases with increasing backcalculated subgrade modulus. For FWD basins, *B* is not significantly correlated with the depth to the rigid layer. But the trend suggests that as the depth to rigid layer increases, *B* decreases.

Table 13 indicates that when the subgrade is semi-infinite, *B* is significantly influenced by the subgrade modulus. As the subgrade modulus increases, *B* decreases. Though no significant correlation exists among *A*, SN, and backcalculated subgrade modulus, trends are similar to those observed for the CHEVRON basins. The relationship between *B* and SN follows the same trend as for the CHEVRON basins.

For FWD-measured basins, the backcalculated subgrade modulus is significantly correlated with SN for both finite and infinite subgrades. Because SN is largely influenced by the thickness of the layers above the subgrade, it is clear that the

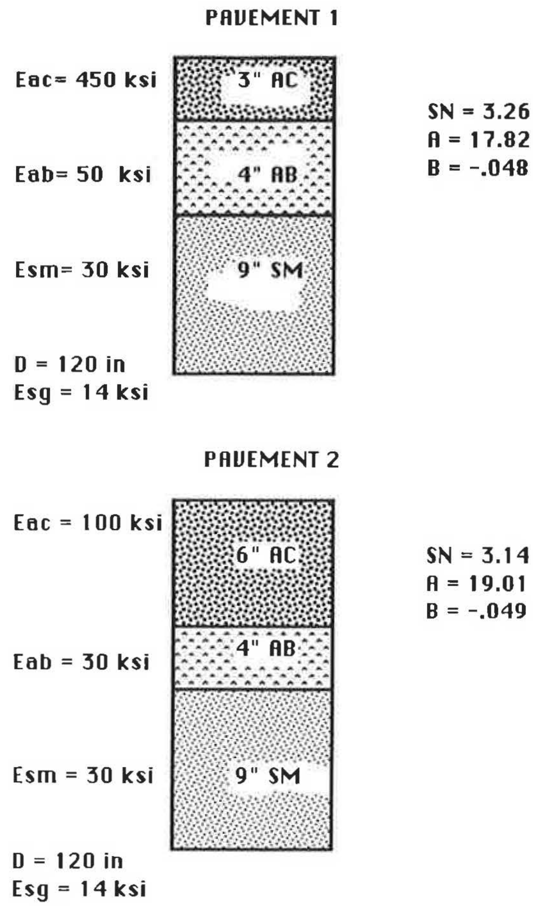

FIGURE 6 ***A* and *B* for pavements with similar SNs.**

backcalculation of the subgrade modulus is influenced by the thickness of the upper layers.

A, *B*, and R^2 are important diagnostic tools for identifying the deflection basins. For example, Sites 3 and 4 are adjacent pavement sections with the same structural number and subgrade modulus. The pavements were tested at identical loads and temperatures. The *A* and *B* values for FWD deflection basins on these pavements are remarkably similar. Thus, *A* and *B* values of normalized deflection basins can be used to define the structural integrity of the pavements in a network-level pavement management system. The approach may also be useful in subsectioning a project when a rehabilitation is considered without backcalculating layer moduli for individual deflection basins. However, more study is needed to decide this point.

INTERPRETATION OF ERROR IN BACKCALCULATION

The sum of the absolute percentage errors between a measured basin and an exponential curve–fitted basin can be used as a guideline for how far the iteration should be carried or for setting the tolerance for the sum of absolute percentage errors in a backcalculation routine using elastic layer theory. The BKCHEVM (*16*) backcalculation program was used to backcalculate the layer moduli of a number of the sites of

TABLE 9 LOCATION OF TEST SITES AND PAVEMENT TYPES

Site	Location	Route	Mile Post	Pavement Type
1	Benson	I10W	300.07	5-layer
3	Winslow	I40E	260.21	4-layer
4	Minnetonka	I40E	261.78	4-layer
5	Dead River	I40E	317.06	4-layer
6	Flagstaff	I17N	337.00	4-layer
7	Crazy Creek	I40E	323.78	4-layer
9	Sunset Point	I17N	251.41	5-layer
10	Seligman	I40W	131.71	4-layer
12	Benson East	I10W	303.00	4-layer
14	Jacob Lake	US89AN	578.00	4-layer
18	Morristown	US60W	120.00	4-layer
19	McNary	US260E	369.00	5-layer
20	Kingman	I40E	59.00	4-layer

TABLE 10 LAYER TYPES AND THICKNESSES AT DIFFERENT SITES

Site/ Sta	Layer 1		Layer 2		Layer 3		Layer 4		Layer 5	
	Mat	Thk (in)	Mat	Thk (in)	Mat	Thk (in)	Mat	Thk (in)	Mat	Thk (in)
1/1	AC	7	BS	2.5	AB	2	SB	12	SC-SM*	
3/1	AC	12	BTB	3	SB	5	SM*	-	-	-
4/1	AC	11.5	BTB	2	SB	3	SM*	-	-	-
5/1	AC	8	CTB	4.5	SB	7	SM*	-	-	-
6/1	AC	9	AB	4	SB	12	-	-	-	-
7/1	AC	8	CTB	6	SB	6	SM*	-	-	-
9/1	AC	6	BS	4	SB	26	SGS	6	CL-CH*	-
10/1	AC	6	AB	6	SB	24	CH*	-	-	-
12/1	AC	6	AB	6	SB	18	SC-SM*	-	-	-
14/1	AC	9	BS	4	AB	4	SC-CH*	-	-	-
18/1	AC	4.25	AB	4	SB	15	-	-	-	-
19/1	AC	4.8	BS	2.2	AB	3	SB	6		
20/1	AC	9.5	AB	4	SB	15	-	-		

* Subgrade Classification based on Unified Method.

Note: AC: Asphalt Concrete, BS: Bituminous Surface, BTB: Bituminous Treated Base, CTB: Cement Treated Base, AB: Aggregate Base, SGS: Subgrade Seal, SB: Sub Base (Select Material)

TABLE 11 CHARACTERISTICS OF FITTED FWD DEFLECTION BASINS

Site/ Sta [1]	FWD Test Temp (^{o}F)	A	B	R^2	SN	Esg^2 (ksi)	D^2 (in)
1/1	70	17.79	-.0510	0.984	3.58	18	140
3/7	64	7.89	-.0221	0.994	5.30	20	>480 [3]
4/1	64	7.27	-.0211	0.986	5.30	20.5	>480 [3]
5/1	55	10.23	-.0261	0.977	5.32	7	85
6/1	43	7.55	-.0221	0.981	6.37	6.5	60
7/4	61	17.58	-.0296	0.985	5.24	13.5	>480 [3]
9/1	70	12.80	-.0334	0.996	3.94	8.5	72
10/1	48	16.18	-.0336	0.995	6.52	19	>480 [3]
12/1	62	15.46	-.0403	0.988	4.42	10.5	100
14/4	97	15.85	-.0539	0.856	0.97	25	120
18/1	71	9.74	-.0430	0.924	4.08	50	>480 [3]
19/1	31	19.03	-.0325	0.996	2.06	10	240
20/1	61	7.38	-.0413	0.948	4.30	45	150

Notes:
1. Station locations correspond to drilling and cone penetration test sites
2. Computed from manual matching of deflection basins (After Mamlouk et al. (15))
3. D > 480 in. signifies semi-infinite subgrade

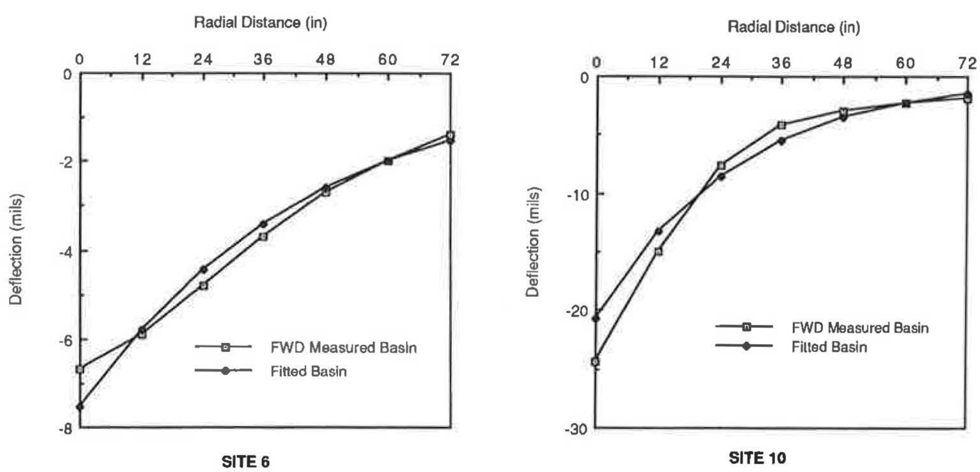

FIGURE 7 FWD-measured and fitted deflection basins for Sites 6 and 10.

TABLE 12 PAVEMENTS WITH FINITE DEPTH OF SUBGRADE—CORRELATION AMONG *A*, *B*, SN, D, AND Esg FOR FWD DEFLECTION BASINS

	A	B	SN	D	Esg
A	1.0	-.53**	-.73*	0.57*	-.24
B		1.0	0.68*	-0.26	-0.54**
SN			1.0	-0.61*	-0.27
D				1.0	0.29
Esg					1.0

* Significant at α = 5%
** Significant at α = 10%

TABLE 13 PAVEMENTS WITH INFINITE DEPTH OF SUBGRADE—CORRELATION AMONG *A*, *B*, SN, AND Esg FOR FWD DEFLECTION BASINS

	A	B	SN	Esg
A	1.0	-.33	-0.45	-0.36
B		1.0	0.37	-0.75*
SN			1.0	0.75*
Esg				1.0

* Significant at α = 10%

Table 9. Table 14 shows the sum of the absolute percentage errors from backcalculation and that from the exponential fit. It is evident that the better the exponential fit, the lower is the sum of absolute percentage errors. In all cases except two, the error in the BKCHEVM calculation is less than that from the exponential fit. Therefore, the iteration for deflection matching should be carried out until the error from backcalculation is less than that from the exponential fit; in other words, the tolerance should be based on the sum of the absolute error percentages in the exponential fit. However, the tolerance should also be based on the desired accuracy and the cost of computation.

The results from BKCHEVM also support the recommendation for values of R^2 presented earlier for deflection basins that are suitable for backcalculation with an iteration technique using the elastic layer theory without large error. For example, Site 14 has an AC thickness of 9 in. For this AC thickness, R^2 for an exponentially fitted basin should be greater than or equal to 0.88 if the backcalculation is to be done without large errors. But the R^2 value for the deflection basin at this site is 0.856, resulting in an absolute error of 214.3 percent. Figure 8 shows the actual FWD-measured and exponential curve–fitted deflection basins for this site. From the figure, it appears that the FWD-measured basin has an unusual shape that can be explained by judging the value of R^2 of the exponential fit. Thus, in the deflection-matching scheme, a high error tolerance should be used to terminate the iteration process for this basin.

CONCLUSIONS

An alternative approach was developed for characterizing the FWD deflection basin. An exponential curve of the form $Y = A * e^{BX}$, where Y is the deflection in mils and X is the radial distance in inches, was suggested for approximating deflection basins simulated from elastic layer theory and measured by the FWD. The coefficients *A* and *B* appear to describe the pavement structurally. Recommendations were made to classify pavements on the basis of the values of *A* and *B* for network-level pavement classification or subsectioning a project when a rehabilitation is considered. The value of the coefficient of determination of the exponential fit, R^2, was found useful for judging the suitability of an FWD-measured basin for backcalculation of layer moduli in a deflection-matching technique. Values of R^2 were suggested for back-

TABLE 14 SUM OF ABSOLUTE PERCENTAGE ERRORS FOR FWD DEFLECTION BASINS

Site/Station	R^2	BKCHEVM Error (%)	EXP. Fit Error (%)
4/1	0.986	28.0	37.5
5/1	0.977	90.0	51.0
7/4	0.985	16.1	54.7
9/1	0.996	8.4	31.5
10/1	0.995	8.3	34.1
12/1	0.988	16.7	77.68
14/4	0.856	214.3	329.76
18/1	0.924	42.9	192.4
19/1	0.996	39.2	28.4
20/1	0.948	39.6	142.9

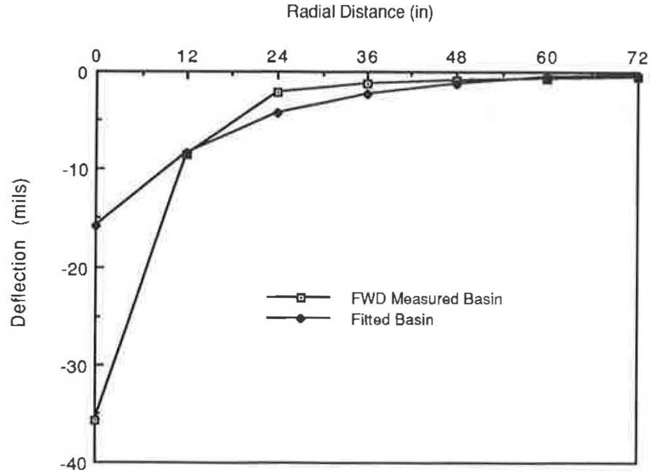

FIGURE 8 FWD-measured and fitted deflection basins for Site 14.

calculation of layer moduli in an iteration scheme using elastic layer theory. Guidelines were presented for using the value of R^2 to indicate the error between measured and computed deflections that can be expected during a backcalculation analysis.

REFERENCES

1. M. S. Hoffman and M. R. Thompson. Backcalculating Nonlinear Resilient Moduli from Deflection Data. In *Transportation Research Record 852*, TRB, National Research Council, Washington, D.C., 1982, pp. 42–51.
2. E. Horak. The Use of Surface Deflection Basin Measurements in the Mechanistic Analysis of Flexible Pavements. *Proc., 6th International Conference on Structural Design of Asphalt Pavements*, Ann Arbor, Mich., Vol. 1, 1987, pp. 990–1,001.
3. K. Majidzadeh. *Pavement Condition Utilizing Dynamic Deflection Measurements*. Research Report OHIO-DOT-13-77. FHWA, U.S. Department of Transportation, 1977.
4. W. P. Kilareski and B. A. Anani. Evaluation of In Situ Moduli and Pavement Life from Deflection Basin. *Proc., 5th International Conference on Structural Design of Asphalt Pavements*, Delft, the Netherlands, Vol. 1, 1982, pp. 349–366.
5. N. K. Vaswani. Method for Separately Evaluating Structural Performance of Subgrades and Overlaying Flexible Pavements. In *Highway Research Record 362*, HRB, National Research Council, Washington, D.C., 1971, pp. 48–62.
6. A. Taute, B. F. McCullough, and W. R. Hudson. *Improvements to the Material Characterization and Fatigue Life Prediction Methods of the Texas Rigid Pavement Overlay Design Procedure*. Research Report 249-1. Center for Transportation Research, The University of Texas at Austin, Austin, 1981.
7. A. F. Stock and J. Yu. Use of Surface Deflection for Pavement Design and Evaluation. In *Transportation Research Record 954*, TRB, National Research Council, Washington, D.C., 1984.
8. A. J. M. Classen, C. P. Valkering, and R. Ditmarsch. Pavement Evaluation with the Falling Weight Deflectometer. *Proc., Association of Asphalt Paving Technologists*, Vol. 45, 1976.
9. F. W. Jung. Interpretation of Deflection Basin for Real-World Materials in Flexible Pavements. Presented at 69th Annual Meeting of the Transportation Research Board, Washington, D.C., 1990.
10. L. J. Painter. *CHEVRON N-Layer Program—Improved Accuracy*. California Research Corporation, Richmond, Calif., 1980.
11. *Materials Preliminary Engineering Design Manual*, 3rd ed. Arizona Department of Transportation, Phoenix, 1989.
12. *AASHTO Guide for Design of Pavement Structures*. AASHTO, Washington, D.C., 1986.
13. E. N. Thrower, N. W. Lister, and J. F. Potter. Experimental and Theoretical Studies of Pavement Behavior Under Vehicular Loading in Relation to Elastic Theory. *Proc., 3rd International Conference on Structural Design of Asphalt Pavements*, London, 1972, pp. 521–535.
14. J. I. Yazdani and T. Scullion. Comparing Measured and Theoretical Depth Deflections Under a Falling Weight Deflectometer Using a Multidepth Deflectometer. In *Transportation Research Record 1260*, TRB, National Research Council, Washington, D.C., 1990, pp. 216–225.
15. M. S. Mamlouk, W. N. Houston, S. L. Houston, and J. P. Zaniewski. *Rational Characterization of Pavement Structures Using Deflection Analysis*. Report FHWA-AZ 88-254, Vol. 1. Arizona Department of Transportation, Phoenix, 1988.
16. BKCHEVM, Modified Microcomputer Version of CHEVDEF Backcalculation Program. Modified in the project *Rational Characterization of Pavement Structures Using Deflection Analysis*, Project HPR-PL-1(31)-254, Arizona Department of Transportation, Phoenix, 1988.