

INFORMATION AND CHAPTERS IN SUPPORT OF THE
BACKCALCULATION TOOL WERE EXTRACTED FROM:

EVERSERIES[®] USER'S GUIDE

Pavement Analysis Computer Software and Case Studies

August 2005



Washington State
Department of Transportation

Environmental and Engineering Programs
Materials Laboratory - Pavements Division

Forward

This user's guide includes descriptions of four computer software programs and three case studies, which will highlight hot mix asphalt overlay and design procedures.

The units used in this guide will be US customary. The three WSDOT computer programs – Everstress[®], Evercalc[®], and Everpave[®] – are capable of calculating in both US customary and in metric units. The AASHTO computer program AASHTO DARWin[®], at the writing of this user's guide, was only capable of using US customary units.

Additional References

Additional references for the Everseries[®] pavement analysis software programs can be found in the following publications:

1. Bu-Bushait, A., "Development of a Flexible Pavement Fatigue Model for Washington State", Ph. D. Dissertation, University of Washington, Seattle, Washington, 1985.
2. Newcomb, D. E., "Development and Evaluation of a Regression Method to Interpret Dynamic Pavement Deflections", Ph. D. Dissertation, University of Washington, Seattle, Washington, 1986.
3. Lee, S. W., "Backcalculation of Pavement Moduli by Use of Pavement Surface Deflections", Ph. D. Dissertation, University of Washington, Seattle, Washington, 1988.
4. Lee, S. W., Mahoney, J. P., and Jackson, N. C., "A Verification of Backcalculation of Pavement Moduli", *Transportation Research Board* No. 1196, Transportation Research Board, Washington DC, 1988.
5. Sivaneswaran, N., Kramer, S. L., and J. P. Mahoney, "Advanced Backcalculation Using a Nonlinear Least Squares Optimization Technique", *Transportation Research Board* No. 1293, Transportation Research Board, Washington DC, 1991.
6. Sivaneswaran, N., "Applications of System Identification in Geotechnical Engineering", Ph. D. Dissertation, University of Washington, Seattle, Washington, 1993.
7. Mahoney, J. P., Winters, B. C., Jackson, N. C., and Pierce, L. M., "Some Observations about Backcalculation and Use of a Stiff Layer Condition", *Transportation Research Board* No. 1384, Transportation Research Board, Washington DC, 1993.
8. Pierce, L. M., Jackson, N. C., and Mahoney, J. P., "Development and Implementation of a Mechanistic-Empirical Based Overlay Design Procedure for Flexible Pavements", *Transportation Research Board* No. 1388, Transportation Research Board, Washington DC, 1993.
9. Mahoney, J. P. and Pierce, L. M., "An Examination of WSDOT Transfer Functions for Mechanistic-Empirical AC Overlay Design", *Transportation Research Board* No. 1539, Transportation Research Board, Washington DC, 1996.
10. Pierce, L. M. and Mahoney, J. P., "Asphalt Concrete Overlay Design Case Studies", *Transportation Research Board* No. 1543, Transportation Research Board, Washington DC, 1996.

Software Disclaimer

The Washington State Department of Transportation does not warrant anything concerning any of the programs or files, which make up the Everseries[®] Pavement Analysis Programs. We accept no responsibility for any loss or damage of any kind, which results from the use or purported use of the Everseries[®] Pavement Analysis Programs, or any files in the package, for any purpose whatsoever.

2.1 FUNDAMENTALS OF BACKCALCULATION

Backcalculation is essentially a mechanistic evaluation, usually an elastic analysis of pavement surface deflection basins generated by various pavement deflection devices. Backcalculation is where measured and calculated surface deflection basins are matched (to within some tolerable error) and the associated layer moduli required to achieve that match are determined. The backcalculation process is usually iterative and normally done with software that can run on microcomputers. General backcalculation guidelines are contained in paragraph 2.5. An illustration of the backcalculation process is shown in Figure 7 and Figure 8.

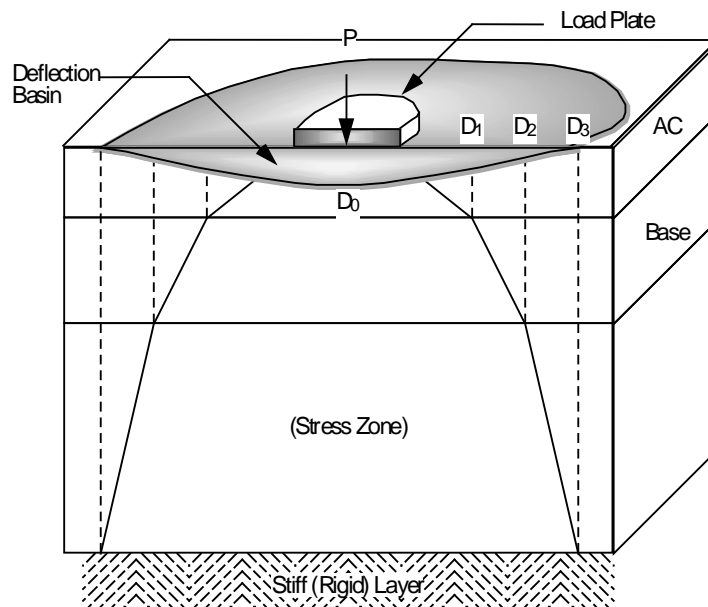


Figure 1. Illustration of Backcalculation to Estimate Layer Moduli

2.1.1 Typical Flowchart

A basic flowchart which represents the fundamental elements in all known backcalculation programs is shown in Figure 9. This flowchart was patterned after one shown by Lytton [2]. Briefly, these elements include:

- (a) Measured deflections:
Includes the measured pavement surface deflections and associated distances from the load.
- (b) Layer thicknesses and loads:
Includes all layer thicknesses and load levels for a specific test location.

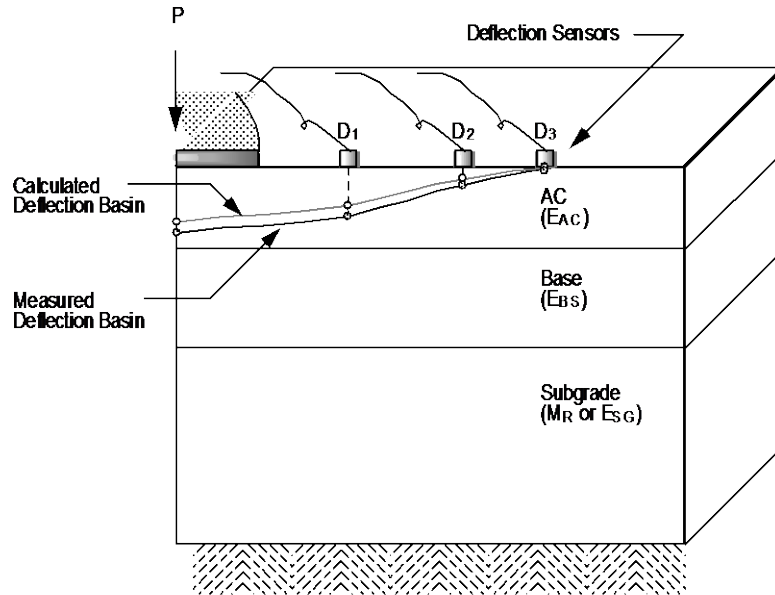


Figure 2. The Backcalculation Process – Matching Measured and Calculated Deflection Basins

- (c) Seed moduli:
The seed moduli are the initial moduli used in the computer program to calculate surface deflections. These moduli are usually estimated from user experience or various equations.
- (d) Deflection calculation:
Layered elastic computer programs such as CHEVRON, BISAR, or ELSYM5 are generally used to calculate a deflection basin.
- (e) Error check:
This element simply compares the measured and calculated basins. There are various error measures, which can be used to make such comparisons.
- (f) Search for new moduli:
Various methods have been employed within the various backcalculation programs to converge on a set of layer moduli, which produces an acceptable error between the measured and calculated deflection basins.
- (g) Controls on the range of moduli:
In some of the backcalculation programs, a range (minimum and maximum) of moduli are selected or calculated to prevent program convergence to unreasonable moduli levels (could be too high or low).

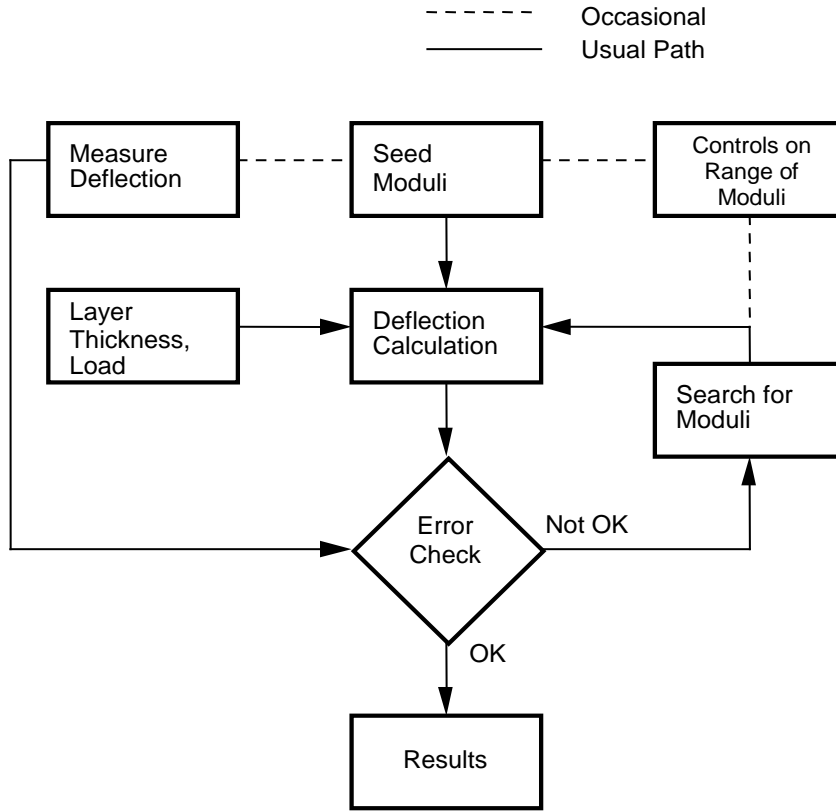


Figure 3. Common Elements of Backcalculation Programs

2.2 MEASURE OF CONVERGENCE

2.2.1 Measure of Deflection Basin Convergence

The primary measure of convergence will be Root Mean Square (RMS) or Root Mean Square Error (RMSE). Both terms are taken to be the same.

$$RMS (\%) = \sqrt{\frac{1}{n} \sum_{i=1}^n \left(\frac{d_{ci} - d_{mi}}{d_{mi}} \right)^2} \times 100 \quad \text{Equation 1}$$

where,

- RMS = root mean square error,
- d_{ci} = calculated pavement surface deflection at sensor i,
- d_{mi} = measured pavement surface deflection at sensor i, and
- n_d = number of deflection sensors used in the backcalculation process.

Example RMS calculation

N_d	Deflections (mils)	
	Measured	Calculated
1 (0")	5.07	4.90
2 (8")	4.32	3.94
3 (12")	3.67	3.50
4 (18")	2.99	3.06
5 (24")	2.40	2.62
6 (36")	1.69	1.86
7 (60")	1.01	0.95

$$\text{RMS (\%)} = \frac{1}{7} \left(\frac{4.90 - 5.07}{1.01} \right)^2 + \dots + \left(\frac{0.95 - 1.01}{1.01} \right)^2$$

$$= 6.9\% \text{ (which is very high)}$$

Generally an adequate range of RMS is 1 to 2 percent.

2.3 DEPTH OF STIFF LAYER

Recent literature provides at least two approaches for estimating the depth to stiff layer [3, 4]. The approach used by Rohde and Scullion [3] will be summarized below. There are two reasons for this selection: (1) initial verification of the validity of the approach is documented, and (2) the approach is used in MODULUS 4.0 — a backcalculation program widely used in the U.S.

(a) Basic Assumptions and Description

A fundamental assumption is that the measured pavement surface deflection is a result of deformation of the various materials in the applied stress zone; therefore, the measured surface deflection at any distance from the load plate is the direct result of the deflection below a specific depth in the pavement structure (which is determined by the stress zone). This is to say that only that portion of the pavement structure which is stressed contributes to the measured surface deflections. Further, no surface deflection will occur beyond the offset (measured from the load plate) which corresponds to the intercept of the applied stress zone and the stiff layer (the stiff layer modulus being 100 times larger than the subgrade modulus). Thus, the method for estimating the depth to stiff layer assumes that the depth at which zero deflection occurs (presumably due to a stiff layer) is related to the offset at which a zero surface deflection occurs. This is illustrated in Figure 10 where the surface deflection D_C is zero.

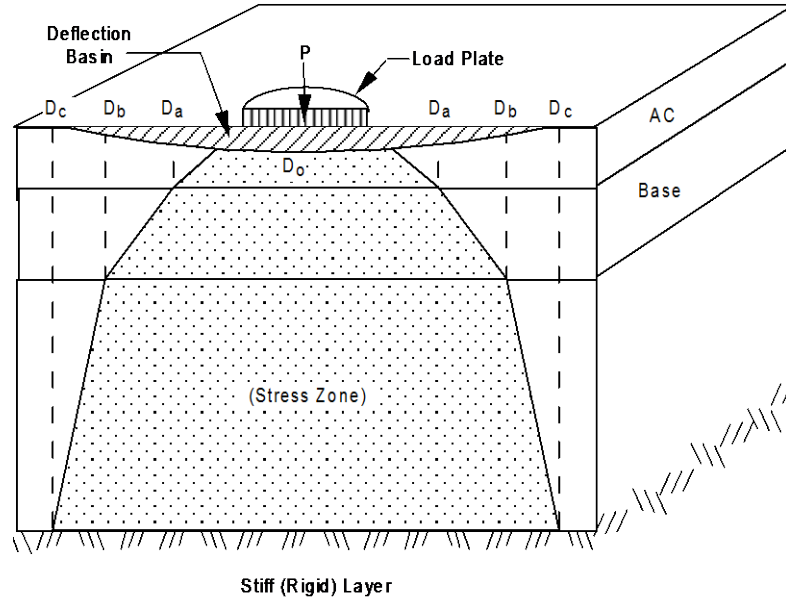


Figure 4. Illustration of Zero Deflection Due to a Stiff Layer

An estimate of the depth at which zero deflection occurs can be obtained from a plot of measured surface deflections and the inverse of the corresponding offsets $\left(\frac{1}{r}\right)$. This is illustrated in Figure 11. The middle portion of the plot is linear with either end curved due to nonlinearities associated with the upper layers and the subgrade. The zero surface deflection is estimated by extending the linear portion of the D vs. $\frac{1}{r}$ plot to a $D = 0$, the $\frac{1}{r}$ intercept being designated as r_0 . Due to various pavement section-specific factors, the depth to stiff layer cannot be directly estimated from r_0 — additional factors must be considered. To do this, regression equations were developed based on BISAR computer program generated data for the following factors and associated values:

Load = $P = 9000$ lbs (40 kN) (only load level considered)

Moduli ratios: $\frac{E_1}{E_{SG}} = 10, 30, 100$

$$\frac{E_2}{E_{SG}} = 0.3, 1.0, 3.0, 10.0$$

$$\frac{E_{rigid}}{E_{SG}} = 100$$

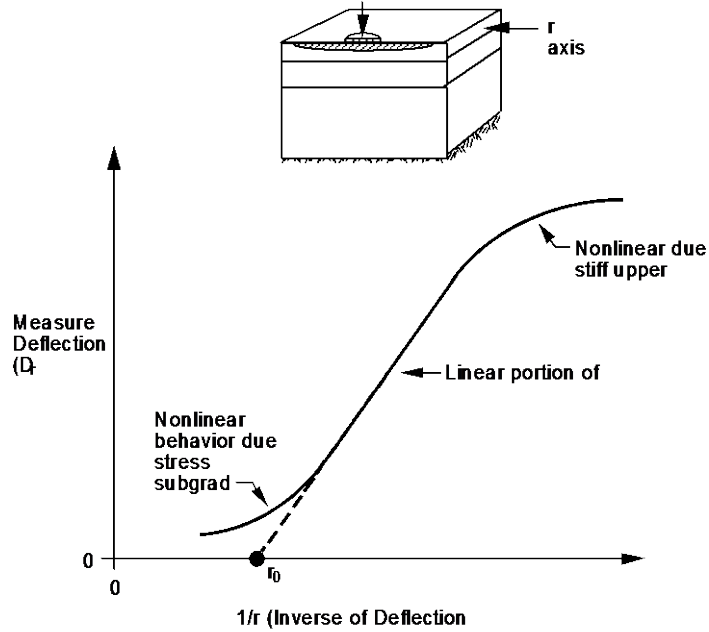


Figure 5. Plot of Inverse of Deflection Offset vs. Measured Deflection

Thickness levels: $T_1 = 1, 3, 5, \text{ and } 10 \text{ inches (25, 75, 125, 250 mm)}$
 $T_2 = 6, 10, \text{ and } 15 \text{ inches (150, 250, 375 mm)}$
 $B = 5, 10, 15, 20, 25, 30, \text{ and } 50 \text{ feet}$
 $(1.5, 3.0, 4.5, 6.0, 7.5, 9.0, 15.0 \text{ m})$

where

- $E_i =$ elastic modulus of layer i ,
- $T_i =$ thickness of layer i ,
- $B =$ depth of the rigid (stiff) layer measured from the pavement surface (feet).

The resulting regression equations follow in (b).

(b) Regression Equations

Four separate equations were developed for various HMA layer thicknesses. The dependent variable is $\frac{1}{B}$ and the independent variables are r_0 (and powers of r_0) and various deflection basin shape factors such as SCI, BCI, and BDI (see Appendix A).

(i) HMA less than 2 inches (50 mm) thick:

$$\frac{1}{B} = 0.0362 - 0.3242 (r_0) + 10.2717 (r_0^2) - 23.6609 (r_0^3) - 0.0037 (BCI) \quad \text{Equation 2}$$

$$R^2 = 0.98$$

(ii) HMA 2 to 4 inches (50 to 100 mm) thick:

$$\frac{1}{B} = 0.0065 + 0.1652 (r_0) + 5.4290 (r_0^2) - 11.0026 (r_0^3) - 0.0004 (BDI) \quad \text{Equation 3}$$

$$R2 = 0.98$$

(iii) HMA 4 to 6 inches (100 to 150 mm) thick:

$$\frac{1}{B} = 0.0413 + 0.9929 (r_0) - 0.0012 (SCI) + 0.0063 (BDI) - 0.0778 (BCI) \quad \text{Equation 4}$$

$$R2 = 0.94$$

(iv) HMA greater than 6 inches (150 mm) thick:

$$\frac{1}{B} = 0.0409 + 0.5669 (r_0) + 3.0137 (r_0^2) + 0.0033 (BDI) - 0.0665 \log (BCI) \quad \text{Equation 5}$$

$$R2 = 0.97$$

where

- r_0 = $\frac{1}{r}$ intercept (extrapolate steepest section of D vs $\frac{1}{r}$ plot) in units of $\frac{1}{ft}$
- SCI = D0 - D12" (D0 - D305 mm), Surface Curvature Index
- BDI = D12" - D24" (D305 - D610 mm), Base Damage Index
- BCI = D24" - D36" (D610 - D914 mm) Base Curvature Index
- Di = surface deflections (mils) normalized to a 9,000 lb (40 kN) load at an offset i in feet

(c) Example

Use some typical deflection data to estimate B (depth to stiff layer). The drillers log suggests a stiff layer might be encountered at a depth of 198 inches (5.0 m) (deflection data originally from SHRP).

(i) First, calculate normalized deflections (9,000 lb (40 kN) basis):

Load Level	Deflections (mils)						
	D ₀	D ₈	D ₁₂	D ₁₈	D ₂₄	D ₃₆	D ₆₀
9,512 lb	5.07	4.32	3.67	2.99	2.40	1.69	1.01
(normalized) 9,000 lb	4.76	4.04	3.44	2.80	2.26	1.59	0.95
6,534 lb	3.28	2.69	2.33	1.88	1.56	1.09	0.68

- (ii) Second, estimate r_0 . Plot D_r vs. $\frac{1}{r}$ (refer to Figure 12):

D_r (mils)	r (inch)	$\frac{1}{r}$ ($\frac{1}{ft}$)
4.76	0	—
4.04	8	1.50
3.44	12	1.00
2.80	18	0.67
2.26	24	0.50
1.59	36	0.33
0.95	60	0.20

where all D_r normalized to 9,000 lb (40 kN)

- (iii) Third, use regression equation in (b)(iv) (for HMA = 7.65 inches (194 mm)) to calculate B:

$$\frac{1}{B} = 0.0409 + 0.5669 (r_0) + 3.0137 (r_0^2) + 0.0033 (BDI) - 0.0665 \log (BCI)$$

where

$$r_0 = \frac{1}{r} \text{ intercept (refer to Figure 12)}$$

$$\cong 0 \text{ (used steepest part of deflection basin which is for Sensors at 36 and 60 inches)}$$

$$BDI = D_{12"} - D_{24"} = 3.44 - 2.26 = 1.18 \text{ mils}$$

$$BCI = D_{24"} - D_{36"} = 2.26 - 1.59 = 0.67 \text{ mils}$$

$$\frac{1}{B} = 0.0409 + 0.5669 (0) + 3.0137 (0^2) + 0.0033 (1.18) - 0.0665 \log (0.67)$$

$$= 0.0564$$

$$\frac{1}{B} = \frac{1}{0.0564} = 17.7 \text{ feet (213 inches or 5.4 m)}$$

This value agrees fairly well with "expected" stiff layer conditions at 16.5 feet (5.0 m) as indicated by the drillers log even though the $\frac{1}{r}$ value equaled zero.

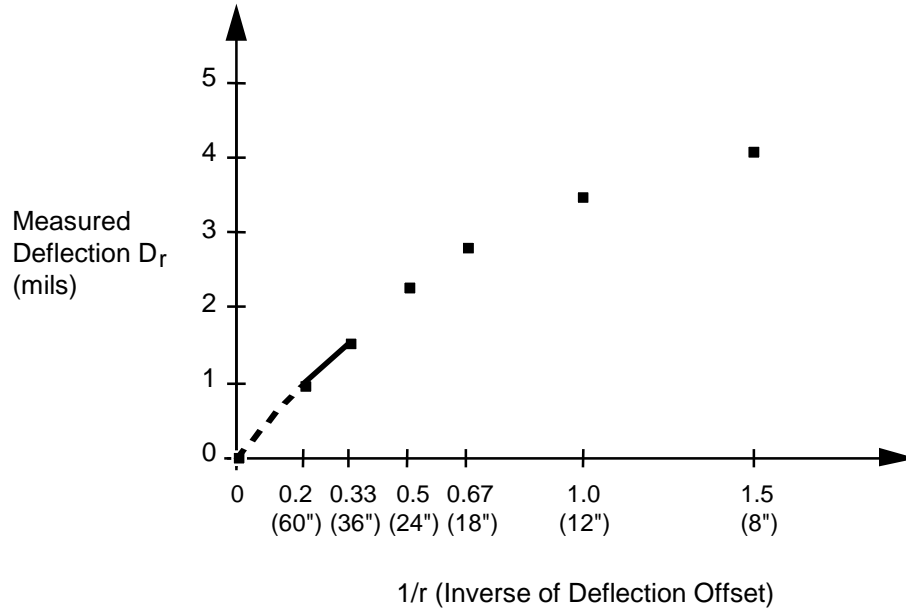


Figure 6. Plot of Inverse of Deflection Offset vs. Measured Deflection

2.3.1 Example of Depth to Stiff Layer Estimates — Road Z-675 (Sweden)

(a) Overview

This road located in south central Sweden is used to illustrate calculated and measured depths to stiff layers (the stiff layer apparently being rock for the specific road).

(b) Measurement of Measured Depth

The depth to stiff layer was measured using borings (steel drill) and a mechanical hammer. The hammer was used to drive the drill to "refusal." Thus, the measured depths could be to bedrock, a large stone, or hard till (glacially deposited material). Further, the measured depths were obtained independently of the FWD deflection data (time difference of several years).

(c) Deflection Measurements

A KUAB 50 FWD was used to obtain the deflection basins. All basins were obtained within ± 16 feet (5 m) of a specific borehole. The deflection sensor locations were set at 0, 7.9, 11.8, 17.7, 23.6, 35.4, and 47.2 inches (0, 200, 300, 450, 600, 900, and 1200 mm) from the center of the load plate.

(d) Calculations

The equations described in Paragraph 2.3 were used to calculate the depth to stiff layer. Since the process requires a 9000 lb (40 kN) load and 1 foot (305 mm) deflection sensor spacings, the measured deflections were adjusted linearly according to the ratio of the actual load to a 9000 lb (40 kN) load.

(e) Results

The results of this comparison are shown in Figure 13. Given all the uncertainties concerning the measured depths, the agreement is quite good.

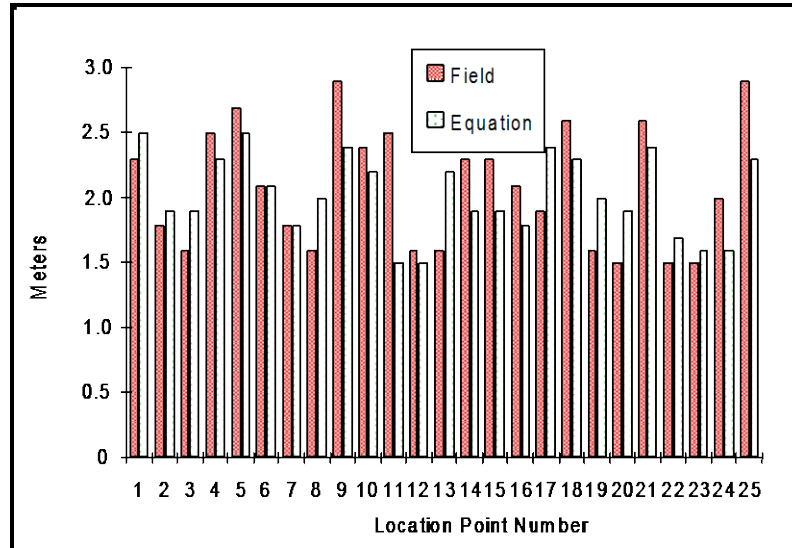


Figure 7. Plot of Measured and Calculated Depths to Stiff Layer (Road Z-675, Sweden)

2.4 VERIFICATION OF BACKCALCULATION RESULTS

There have been and, undoubtedly, will be a number of attempts to verify that backcalculated layer moduli are "reasonable." One way to do this is to compare measured, in-situ strains to calculated (theoretical) strains based on layered elastic analyses.

Two recent studies have done this. The first study summarized [5] was conducted at the PACCAR Technical Center located at Mt. Vernon, Washington. Horizontal strains were measured on HMA instrumented cores (inserted into the original HMA surface material). The HMA layer was approximately 5.5 inch thick over a 13.0 inch thick base course. The WSDOT FWD was used to apply a known load to induce the strain response (measured strain). The calculated strains were determined by use of the EVERCALC program (which used FWD deflection basins to backcalculate layer moduli which, in turn, were used to calculate the corresponding strains.)

Figure 14 and Figure 15 show the measured and calculated strains in the two horizontal directions at the bottom of the HMA layer (longitudinal and transverse). This specific testing was conducted during February 1993. In general, the agreement is good.

The second study was reported by Lenngren [6]. That work was conducted for RST Sweden and used backcalculated layer moduli (from a modified version of the EVERCALC program) to estimate strains at the bottom of two thicknesses of HMA (3.1 and 5.9 n. thick). The pavement structures were located in Finland. Table 2 and Table 3 are used as summaries. The backcalculated strains are generally within ± 5 percent of the measured strains.

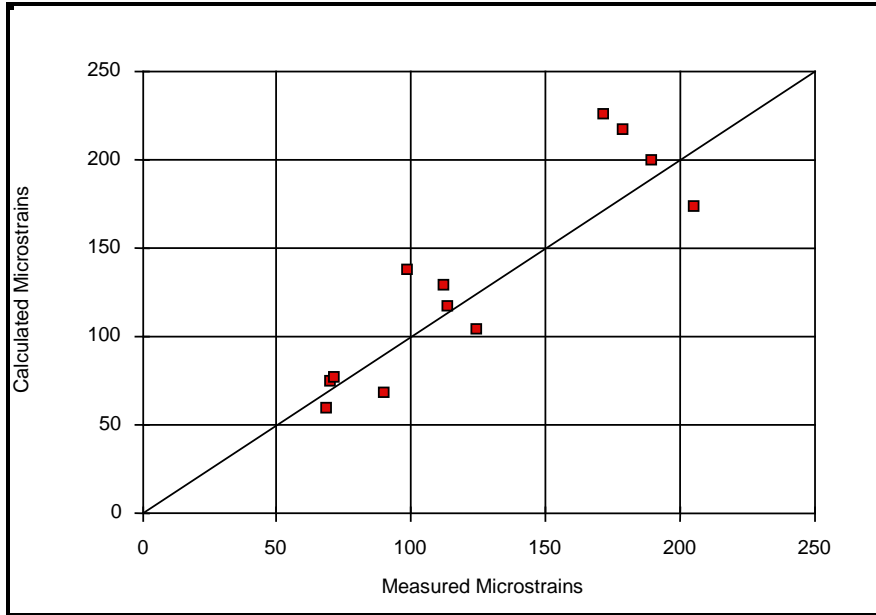


Figure 8. Measured vs. Calculated Strain for Axial Core Bottom Longitudinal Gauges – February 1993 FWD Testing [6]

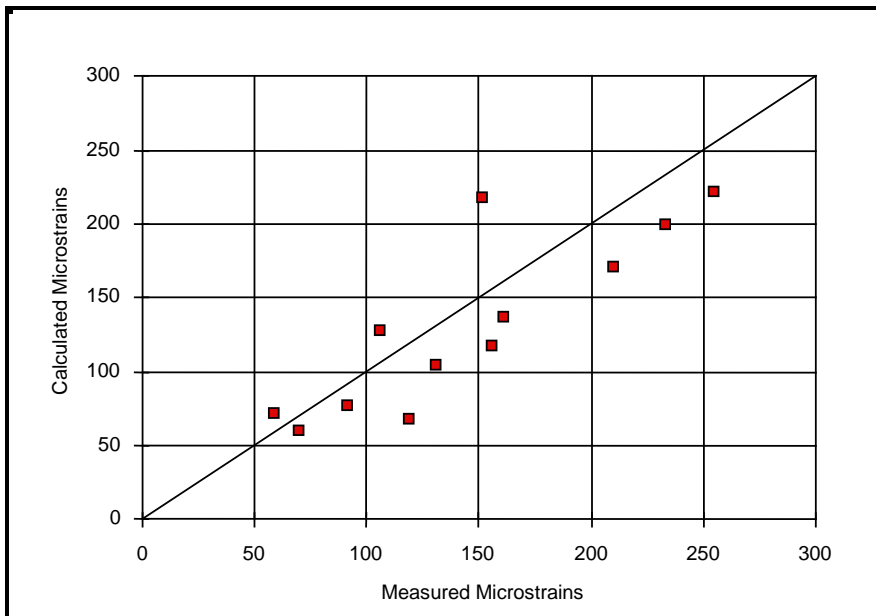


Figure 9. Measured vs. Calculated Strain for Axial Core Bottom Transverse Gauges – February 1993 FWD Testing [6]

Table 1. Backcalculated and Measured Tensile Strains — 3.1 inch HMA Section [6]

Time of Day (a.m. or p.m.)	Tensile Strain Bottom of HMA ($\times 10^{-6}$)		
	Backcalculated*	Measured	% Difference
a.m.	119	123	-3
a.m.	119	122	-2
a.m.	74	65	+14
a.m.	60	65	-8
p.m.	284	292	-3
p.m.	284	283	~0
p.m.	167	159	+5
p.m.	167	158	+6
p.m.	87	85	+2
p.m.	81	84	-4

*Backcalculation process used sensors @ D₀, D₁₂, D₂₄, D₃₆, and D₄₈

Table 2. Backcalculated and Measured Tensile Strains — 5.9 inch Section [6]

Time of Day (a.m. or p.m.)	Tensile Strain Bottom of HMA ($\times 10^{-6}$)		
	Backcalculated*	Measured	% Difference
a.m.	66	70	-6
a.m.	71	69	+3
a.m.	68	69	-1
a.m.	38	35	+9
a.m.	127	130	-2
a.m.	119	130	-8
p.m.	178	185	-4
p.m.	182	183	-1
p.m.	104	96	+8
p.m.	51	48	+6
p.m.	56	49	+14

*Backcalculation process used sensors @ D₀, D₁₂, D₂₄, D₃₆, and D₄₈

2.5 BACKCALCULATION GUIDELINES

The general guidelines, which follow, are rather broad in scope and should be considered only “rules-of-thumb” at best. These guidelines were developed from WSDOT experience and the SHRP LTPP Expert Task Group for Deflection Testing and Backcalculation. Undoubtedly, they will change and software such as Evercalc[®] will continue to be improved.

2.5.1 Number of Layers

Generally, one should use no more than 3 or 4 layers of unknown moduli in the backcalculation process (preferably, no more than 3 layers).

If a three-layer system is being evaluated, and questionable results are being produced (extremely weak base moduli, for example), it is sometimes advantageous to evaluate this pavement structure as a two-layer system. This modification would possibly indicate that the

base material has been contaminated by the underlying subgrade and is weaker due to the presence of fine material. Alternatively, a stiff layer should be considered if not done so previously.

If a pavement structure consists of a stiffer layer between two weak layers, it may be difficult to obtain realistic backcalculated moduli, such as HMA over a cement treated base.

2.5.1 Thickness of Layers

2.5.1.2 Surfacing

It can be rather difficult to “accurately” backcalculate HMA/BST moduli for bituminous surface layers less than 3 inches (75 mm) thick. Such backcalculation can be attempted for layers less than 3 inches (75 mm), but caution is suggested. In theory, it is possible to backcalculate separate layer moduli for various types of bituminous layers within a flexible pavement. Generally, it is not advisable to do this since one can quickly be attempting to backcalculate too many unknown layer moduli (i.e., greater than 3 or 4). By necessity, one should expect to combine all bituminous layers (seal coats, HMA, etc.) into “one” layer unless there is evidence (or the potential) for distress, such as stripping, in an HMA layer or some other such distress, which is critical to pavement performance.

2.5.1.3 Unstabilized Base/Subbase Course

“Thin” base course beneath “thick” surfacing layers (say HMA or PCC) often result in low base moduli. There are a number of reasons why this can occur. One, a thin base is not a “significant” layer under a very stiff, thick layer. Second, the base modulus may be relatively “low” due to the stress sensitivity of granular materials. The use of a stiff layer generally improves the modulus estimate for base/subbase layers.

2.5.1.4 Subgrade

If unusually high subgrade moduli are calculated, check to see if a stiff layer is present. Stiff layers, if unaccounted for in the backcalculation process, will generally result in unrealistically high subgrade moduli. This is particularly true if a stiff layer is within a depth of about 20 to 30 feet (6 to 9 m) below the pavement surface.

2.5.1.5 Stiff Layer

Often, stiff layers are given “fixed” stiffness ranging from 100,000 to 1,000,000 psi (700 to 7000 MPa) with semi-infinite depth. This, in effect, makes the “subgrade” a layer with a “fixed” depth (instead of the normally assumed infinite depth). Currently, it appears advisable to use backcalculation software, which uses an algorithm such as described and illustrated in Paragraph 2.3, “Depth to Stiff Layer.” What is not so clear is whether one should always fix the depth to stiff layer at say 20, 30, or possibly 50 feet (6, 9, or 15 m) if no stiff layer is otherwise indicated (i.e., use a semi-infinite depth for the subgrade). The depth to stiff layer should be verified whenever possible with other non-destructive testing (NDT) data or borings.

The stiffness (modulus) of the stiff layer apparently can vary. If the stiff layer is due to saturated conditions (e.g. water table) then moduli of about 50,000 psi (345 MPa) appear more appropriate. If rock or stiff glacial tills are the source of the stiff layer then moduli of about 1,000,000 psi (6 900 MPa) appear to be more appropriate.

2.5.2 Initial Moduli and Moduli Ranges

2.5.2.1 HMA - Initial Moduli

There are several ways one can estimate the initial HMA modulus (often referred to as “seed modulus”). One can use a modulus-temperature plot as illustrated in Figure 16, if the HMA temperature at the time of testing is known; however, data such as shown in Figure 16 are based on laboratory resilient moduli (load pulse = 100 msec).

2.5.2.2 Cracked HMA Initial Moduli

Generally, fatigue cracked HMA (less than 10 percent wheel path hairline cracks) is often observed to have backcalculated moduli of about 100,000 to 200,000 psi (700 to 1400 MPa). What is most important in the backcalculation process, assuming surface fatigue cracking is present, is to determine whether the cracks are confined to only the immediate wearing course or go through the whole depth of the HMA layer? For HMA layers greater than 6 inches (150 mm) thick, WSDOT has observed that the cracking is confined to the upper wearing course (top-down cracking).

2.5.2.3 HMA Moduli Ranges

If an HMA modulus range is required, use your best estimate of the E_{ac} , then $0.25 E_{ac}$ to $5.00 E_{ac}$.

2.5.2.4 Unstabilized Bases and Subbases

Material Type	Initial Modulus ksi (MPa)	Moduli Range ksi (MPa)
Crushed Stone or Gravel Bases	35 (240)	10 to 150 (70 to 7000)
Crushed Stone or Gravel Subbases	30 (210)	10 to 100 (70 to 700)
Sand Bases	20 (140)	5 to 80 (35 to 550)
Sand Subbases	15 (100)	5 to 80 (35 to 550)

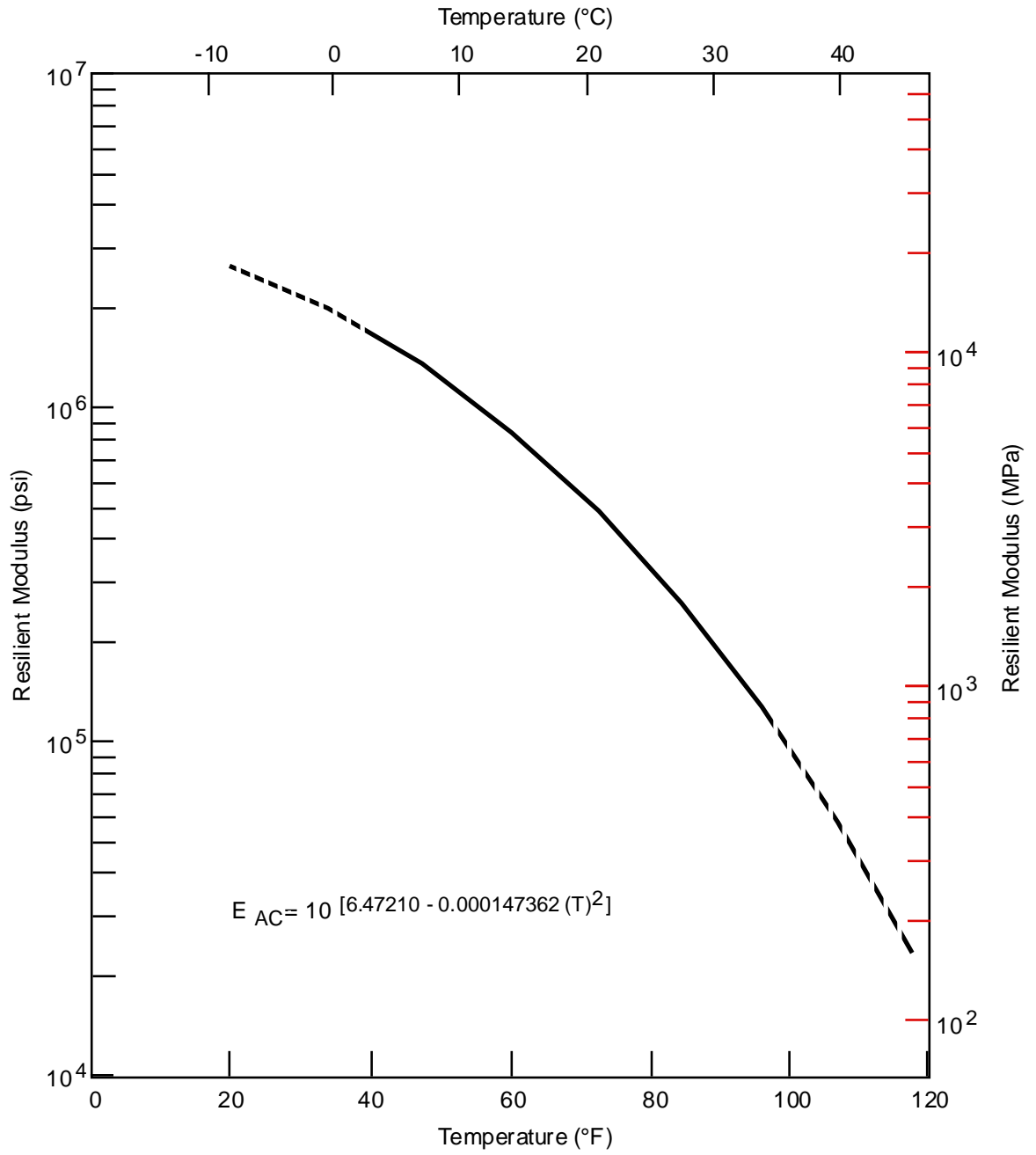


Figure 10. General Stiffness-Temperature Relationship for Class B (Dense Graded) Hot Mix Asphalt in Washington State

2.5.2.5 Stabilized Bases and Subbases

If unconfined compressive strength data is available:

Material Type	Unconfined		
	Compressive Strength ksi (MPa)	Initial Modulus ksi (MPa)	Moduli Range ksi (MPa)
Lime Stabilized	< 250 (< 1.7)	30 (200)	5 to 100 (35 to 690)
	250 to 500 (1.7 to 3.4)	50 (340)	15 to 150 (100 to 1000)
	> 500 (> 3.4)	70 (480)	20 to 200 (140 to 1400)
	< 750 (< 5.2)	400 (2800)	100 to 1500 (700 to 10000)
Cement Stabilized	750 to 1250 (5.2 to 8.6)	1000 (7000)	200 to 3000 (1400 to 20000)
	> 1250 (> 8.6)	1500 (10000)	300 to 4000 (2000 to 28000)

If not, assume unconfined compressive strength is 250 to 500 psi (1.7 to 3.4 MPa) for lime stabilized and 750 to 1250 psi (5.2 to 8.6 MPa) for cement stabilized and use corresponding moduli values.

2.5.2.6 Subgrade

The resilient modulus of the subgrade can be determined by

- NDT and backcalculation,
- laboratory testing, or
- other sources/correlations.

WSDOT will normally use the FWD and appropriate equations to estimate M_R . The basic equation for subgrade modulus is [7]:

$$M_R = \frac{P(1 - \mu^2)}{(p)(r)(dr)} \quad \text{(Equation 6)}$$

If $\mu = 0.5$, then the equation reduces to

$$MR = \frac{0.24(P)}{(r)(dr)} \quad \text{(Equation 7)}$$

where

- M_R = elastic modulus of subgrade (psi),
- P = load (lbs),
- r = radial distance from the center of the load plate (inch) and
- dr = pavement deflection at distance r from the applied load (inch).

Refer to Table 4 for suggested typical values or the following discussion and equations to use in estimating E_{sg} (or M_R) from the deflection basin.

Table 3. Typical Values of Subgrade Moduli [7]

Material	Climate Condition			
	Dry	Wet — No Freeze	Wet - Freeze	
			Unfrozen	Frozen
psi (MPa)	psi (MPa)	psi (MPa)	psi (MPa)	
Clay	15,000 (103)	6,000 (41)	6,000 (41)	50,000 (345)
Silt	15,000 (103)	10,000 (69)	5,000 (34)	50,000 (345)
Silty or Clayey Sand	20,000 (138)	10,000 (69)	5,000 (34)	50,000 (345)
Sand	25,000 (172)	25,000 (172)	25,000 (172)	50,000 (345)
Silty or Clayey Gravel	40,000 (276)	30,000 (207)	20,000 (138)	50,000 (345)
Gravel	50,000 (345)	50,000 (345)	40,000 (276)	50,000 (345)

Several researchers have developed regression equations to predict E_{SG} from plate load and deflections measured at distances from about 24 inches (600 mm) to 48 inches (1200 mm) from the center of the plate load. Newcomb developed such regression equations to predict E_{SG} as part of an overall effort to develop a mechanistic empirical overlay design procedure for WSDOT [8]. For two layer cases, the subgrade modulus can be estimated from:

$$E_{SG} = -466 + 0.00762 (P/D3) \quad \text{Equation 8}$$

$$E_{SG} = -198 + 0.00577 (P/D4) \quad \text{Equation 9}$$

$$E_{SG} = -371 + 0.00671 (2P/(D3 + D4)) \quad \text{Equation 10}$$

and for three layer cases

$$E_{SG} = -530 + 0.00877 (P/D3) \quad \text{Equation 11}$$

$$E_{SG} = -111 + 0.00577 (P/D4) \quad \text{Equation 12}$$

$$E_{SG} = -346 + 0.00676 (2P/(D3 + D4)) \quad \text{Equation 13}$$

The $R^2 \approx 99\%$ for all equations and the sample sizes were 180 (two layer case) and 1,620 (three layer case). These equations were developed from generated data (ELSYM5) with the following levels of input data:

<u>Two Layer Case</u>	Load, P, lb (kN)	Surface Thickness, h _{HMA} , inch (mm)	Surface Modulus, E _{HMA} , psi (MPa)	Subgrade Modulus, E _{SG} , psi (MPa)
	5,000 (22)	2 (50)	2,000,000 (13800)	50,000 (345)
	10,000 (44)	6 (150)	500,000 (3450)	30,000 (207)
	15,000 (67)	12 (300)	100,000 (690)	10,000 (69)
		18 (450)		5,000 (35)
				2,500 (17)

<u>Three Layer Case</u>	Load, P, lb (kN)	Surface Thickness, h _{HMA} , inch (mm)	Base Thickness, h _B , inch (mm)	Surface Modulus, E _{HMA} , psi (MPa)	Base Modulus, E _B , psi (MPa)	Subgrade Modulus, E _{SG} , psi (MPa)
	5,000 (22)	2 (50)	4 (100)	2,000,000 (13800)	100,000 (690)	50,000 (345)
	10,000 (44)	6 (150)	10 (250)	500,000 (3450)	50,000 (345)	30,000 (207)
	15,000 (67)	12 (300)	18 (450)	100,000 (690)	30,000 (207)	10,000 (69)
					10,000 (69)	5,000 (35)
						2,500 (17)

(assumed that load applied on a 12.0 inch diameter load plate)

From this generated data (no rigid base), regression equations were also developed for estimating the surface modulus (HMA) for a two layer case (for example a "full-depth" pavement):

$$\log E_{HMA} = -0.53740 - 0.95144 \log_{10} E_{SG} - 1.21181 \sqrt[3]{h_{HMA}} + 1.78046 \log_{10} (PA_1/D_0^2) \quad \text{Equation 14}$$

$$R^2 = 0.83$$

For a three-layer case, equations were developed for both E_{HMA} and E_B as follows:

If both E_{HMA} and E_B unknown:

$$\log E_{HMA} = -4.13464 + 0.25726 (5.9/h_{HMA}) + 0.92874 \sqrt{5.9/h_B} - 0.69727 \sqrt{h_{HMA}/h_B} - 0.96687 \log_{10} E_{SG} + 1.88298 \log_{10} (PA_1/D_0^2) \quad \text{Equation 15}$$

$$R^2 = 0.78.$$

$$\log E_B = 0.50634 + 0.03474 (5.9/h_{HMA}) + 0.12541 \sqrt{5.9/h_B} - 0.09416 \sqrt{h_{HMA}/h_B} + 0.51386 \log_{10} E_{SG} + 0.25424 \log_{10} (PA_1/D_0^2) \quad \text{Equation 16}$$

where $R^2 = 0.70.$

The following variables were used in the equations shown above:

- P = applied load (lbs) on a 11.8 inch plate,
- h_{HMA} = surface course thickness (inch),
- h_B = base course thickness (inch),
- E_{HMA} = surface course modulus (psi),
- E_B = base course modulus (psi),
- E_{SG} = subgrade modulus (psi),
- D_0 = deflection under center of applied load (inch),
- $D_{0.67}$ = deflection at 8 inches from center of applied load (inch),
- D_1 = deflection at 1 foot from center of applied load (inch),
- D_2 = deflection at 2 feet from center of applied load (inch),
- D_3 = deflection at 3 feet from center of applied load (inch),
- D_4 = deflection at 4 feet from center of applied load (inch), and
- A_1 = approximate area under deflection basin out to 3 feet
 $= 2 [2 (D_0 + D_{0.67}) + (D_{0.67} + D_1) + 3(D_1 + D_2) + 3(D_2 + D_3)]$
 $= 4D_0 + 6D_{0.67} + 8D_1 + 12D_2 + 6D_3$

2.5.2.7 Assumed Poisson’s Ratio

Material Type	Poisson’s Ratio	
Hot mix asphalt	0.35	
Portland Cement Concrete	0.15 - 0.20	
Base or Subbase	Stabilized	0.25 - 0.35
	Unstabilized	0.35
Subgrade Soils	Cohesive (fine grain)	0.45
	Cohesion less (coarse grain)	0.35 - 0.40
Stiff Layer	0.35 or less	

2.5.2.8 Convergence Errors

Root Mean Square Error (RMS)

One should attempt to obtain matches between the calculated and measured deflection basins, in terms of RMS, of about 1 to 2 percent. Often, this cannot be achieved and suggests that the basic input data be checked (such as layer thicknesses). The Area value (see Appendix A) might help in this regard.

General

“High” convergence errors suggest that there exists some fundamental problem with a specific backcalculation effort. The problem could be with the deflection data, layer types, and thicknesses, or lack of material homogeneity, which could include cracked and uncracked conditions. “High” convergence errors do not necessarily mean that the backcalculated layer moduli are “no good.”

2.6 EVERCALC®

Evercalc® is a pavement analysis computer program that estimates the “elastic” moduli of pavement layers. Evercalc® estimates the elastic modulus for each pavement layer, determines the coefficients of stress sensitivity for unstabilized materials, stresses and strains at various depths, and optionally normalizes HMA modulus to a standard laboratory condition (temperature).

Evercalc[®] uses an iterative approach in changing the moduli in a layered elastic solution to match theoretical and measured deflections. A simplified flow diagram of this method is shown in Figure 17.

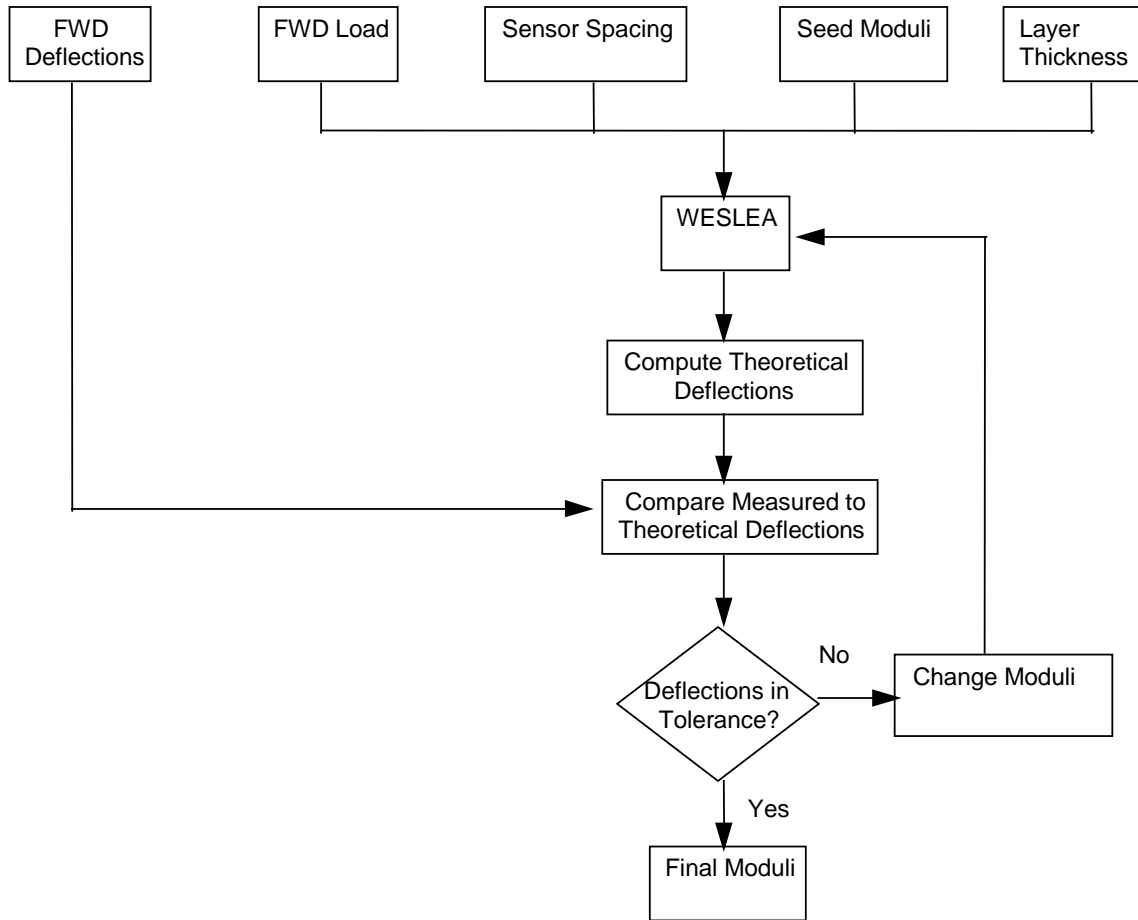


Figure 11. Simplified Flow Chart for Evercalc[®]

2.6.1 Characteristics of Evercalc[®]

The Evercalc[®] program uses WESLEA (provided by the Waterways Experiment Station, U. S. Army Corps of Engineers) as the layered elastic solution to compute the theoretical deflections and a modified Augmented Gauss-Newton algorithm for optimization. Basic assumptions of layered elastic theory include the following:

- Layers are infinitely long in the horizontal directions
- Layers have uniform thickness
- Bottom layer is semi infinite in the vertical direction
- Layers are composed of homogeneous, isotropic, linearly elastic materials, characterized by elastic modulus and Poisson's ratio.

An inverse solution technique is used to determine elastic moduli from FWD pavement surface deflection measurements. The program can handle up to ten sensors and twelve drops per station. The program is capable of evaluating a flexible pavement structure containing up to five layers. From an initial, rough estimate of layer moduli (seed moduli), the program iteratively searches for the "final" modulus for each pavement layer. The deflections calculated using

WESLEA is compared with the measured ones at each iteration. When the discrepancies in the calculated and measured deflections as characterized by root mean square (RMS) error (Equation 23), or the changes in modulus (Equation 24) falls within the allowable tolerance, or the number of iterations has reached a limit the program terminates. Using the final set of moduli, the stresses and strains at the bottom of the HMA layer, middle of the other layers except the subgrade, and at the top of the subgrade is calculated. When deflection data for more than one load level is available at a given point, coefficients of stress sensitivity for unstabilized materials are also computed. Optionally, HMA layer modulus is normalized to a standard laboratory condition.

2.6.1.1 Seed Moduli

Two options for estimating the seed moduli are available. When a pavement structure containing up to three layers is being analyzed, a set of internal regression equations can be used [8]. These regression equations determine a set of seed moduli from the relationships between the layer modulus, surface deflections, applied load, and layer thickness. Alternatively, the user can provide these values. When more than one deflection data set at a given location is analyzed, the final moduli from the previous deflection data set is used as seed moduli for the next one in order to improve the performance of the program.

2.6.1.2 Termination

The program terminates when one or more of the following conditions are satisfied:

- i) Deflection Tolerance:

$$\text{RMS (\%)} = \sqrt{\frac{1}{n_d} \sum_{i=1}^n \left(\frac{d_{ci} - d_{mi}}{d_{mi}} \right)^2} (100) \quad \text{Equation 17}$$

where, d_{ei} and d_{mi} are the measured and calculated deflections at i -th sensor and n - is the number of sensors.

Normally a deflection tolerance of one percent is considered adequate.

- ii) Moduli Tolerance:

$$\varepsilon_m = \frac{|E_{(k+1)i} - E_{ki}|}{E_{ki}} \times (100) \quad \text{Equation 18}$$

where, E_{ki} and $E_{(k+1)i}$ are the i -th layer moduli at the k -th and $(k+1)$ -th iteration, respectively, and m - is the number of layers with unknown moduli.

Again, a modulus tolerance of one percent is considered adequate.

- iii) Number of iterations has reached the Maximum Number of Iterations. At every iteration a minimum of $(m + 1)$ calls to WESLEA is made, where m - is the number of layers with unknown moduli. Normally, a maximum number of ten iterations is adequate.

2.6.1.3 Coefficients of Stress Sensitivity

The stress sensitivity characteristics of unstabilized material moduli are usually formulated as follows:

$$E_b = k_1 \theta^{k_2} \text{ for coarse grained soils} \quad \text{Equation 19}$$

$$E_s = k_3 \sigma_d^k \quad \text{for fine grained soils} \quad \text{Equation 20}$$

where,

E_b = resilient modulus of coarse grained soils,
 E_s = resilient modulus of fine grained soils,
 θ = bulk stress,
 σ_d = deviator stress, and
 $k_1, k_2, k_3,$ and k_4 = regression coefficients

The program determines the stress sensitivity coefficients using a linear regression method when FWD deflection data for two or more load levels at a given point are available.

2.6.1.4 Temperature Correction

The stiffness of HMA is primarily affected by temperature and loading rate. While FWD loads occur over a 25 to 35 millisecond loading time (approximately) and at ambient temperature, the standard laboratory condition is taken to be a 77°F (25°C) temperature and a 100 millisecond loading time. Thus, the stiffness of HMA can be normalized to view the backcalculated modulus in terms of the “traditional” laboratory values (at least this is what is being attempted).

Temperature normalization of HMA is accomplished using the relationship between the modulus and temperature. The relationship for WSDOT Class B HMA was found as follows [9]:

$$\log E_{ac} = 6.4721 - 1.47362 \times 10^{-4} (T_p)^2 \quad \text{Equation 21}$$

where,

E_{ac} = modulus of HMA (psi), and
 T_p = pavement temperature (°F)

From the above modulus-temperature relationship, the backcalculated HMA modulus at the insitu field temperatures is multiplied by an adjustment factor in order to obtain a “standard” modulus at a temperature of 77° F:

$$\text{TAF} = 100.000147362(T_p^2 - 77^2) \quad \text{Equation 22}$$

where,

TAF = temperature adjustment factor, and
 T_p = pavement temperature (°F)

Pavement temperature is determined either by direct measurement or Southgate’s method, which uses pavement surface temperature, the previous five-day mean temperature, and pavement thickness. Both measurement methods are incorporated in the program.

It should be noted that the temperature correction is based on regression equations that were developed for the WSDOT Class B HMA and its validity to other classes of HMA are not known. However, Class B is a traditional, typical dense HMA mixture.

2.6.1.5 Depth to Stiff Layer

A depth to stiff layer (paragraph 2.3) is estimated using the scheme reported by Rhode and Scullion [3]. The basic assumption is that no surface deflection will occur beyond the offset

(measured from the load plate), which corresponds, to the intercept of the applied stress zone and a stiff layer (the stiff layer modulus being 100 times larger than the subgrade modulus). Thus, the method for estimating the depth to stiff layer assumes that the depth at which zero deflection occurs (presumably due to a stiff layer) is related to the offset at which zero deflection occurs.

This feature in Evercalc[®] is optional within the GENERAL DATA File (to be discussed in later SECTIONS). It is common to expect a stiff layer condition within a 30 foot depth. Accounting for a stiff layer condition generally reduces the subgrade modulus (layer above the stiff layer) and increases the base course modulus. If multiple deflection basins and associated loads exist at a specific station, the program calculates the depth to stiff layer for each basin adjusted to a 9000 lb (40 kN) load. The mean depth and associated standard deviation is calculated. Any depths outside of the limits of the mean \pm the standard deviation are removed and the mean depth recalculated. This depth is then used in the subsequent layer moduli calculations at that station. If only one deflection basin and associated load is used, then the program linearly adjusts the required deflections to a 9000 lb (40 kN) load to estimate the depth to stiff layer.

2.6.2 Hardware Requirements

The Evercalc[®] program is coded in Microsoft Visual Basic and Microsoft FORTRAN Power Station 4.0 and designed to run on IBM or compatible personal computers with Microsoft Windows 95/NT 4.0 or higher.

2.6.3 Installation of the Program

To install the program, start Windows, click on the **Start** button, select Run and type a:\setup or select **Browse** and locate SETUP.EXE. Prior to installation of the program(s) the user will be shown the README.TXT. It is highly recommended that this file be reviewed prior to the installation of the program(s). Once README.TXT has been reviewed, the user is asked to select the source directory (default - a:\), the target directory (default = C:\EVERSERS), and which programs are to be installed. The user has the option of selecting Everstress[®], Evercalc[®], Everpave[®], or any combination of the above. Once satisfied with the selection, select **Start Install**.

2.6.4 Program Contents

The following paragraphs describe each of the various menus and inputs of the program.

2.6.4.1 File

Open GENERAL DATA File – This menu option provides a form to create a new GENERAL DATA File or edit an existing one. GENERAL DATA File contains information that does not change from station to station, such as load plate radius, unit, sensor offsets, etc.

Open DEFLECTION DATA File – This menu option provides a form to create a new DEFLECTION DATA File or edit an existing one. This menu option requires an existing GENERAL DATA File. The DEFLECTION DATA File contains station specific data such as layer thickness, pavement temperature, number of drops, plate load and sensor deflection for each drop.

Perform Backcalculation – This menu option performs the backcalculation process. This menu option requires the GENERAL DATA File and DEFLECTION DATA File. Backcalculation is carried out in a DOS window and it is advised that you don't switch windows until the completion of backcalculation. If the Stiff Layer option is used, then depth to stiff layer is calculated first and then the actual backcalculation is performed. Backcalculation can be performed in either interactive or batch mode.

Interactive Mode: In interactive mode, the backcalculation is carried out in the foreground and the progress during each iteration and the calculated and measured deflection basins at the end of iteration are displayed on the screen.

Batch Mode: In batch mode, the backcalculation is carried out in the background. The iteration details are saved in a log file having the same name as the DEFLECTION DATA File with the extension .LOG.

If stiff layer option is used the user is presented with a histogram and a table of depth to apparent stiff layer and with the station identifier. The user can choose to accept the calculated depth to stiff layer values or modify it before performing the backcalculation.

Convert FWD DATA File – This menu option converts a raw FWD (Dynatest Model 8000) data file to an Evercalc[®] DEFLECTION DATA File. This menu option requires an existing GENERAL DATA File. If the deflection data is generated from any other NDT device, other than the Dynatest 8000, this option will not generate the appropriate file format.

Modify Standard Temperature – Since asphalt materials are temperature sensitive and FWD data collection temperature may vary within a specific location and from one location to the next, the establishment of a standard temperature is necessary. WSDOT default standard temperature for the determination of the asphalt moduli to be 77°F (25°C).

Exit – Exit the program and return to the Windows screen.

2.6.4.2 Print

Print/View Output

Displays formatted output data on the screen and provides the option to print on the default printer. The output data contains all calculations for all required iterations and can result in at least 2 pages per station.

Options – standard Windows protocols are used for viewing various pages, zoom, selecting font style for screen view and printing, printing and exiting print screen.

Print/View Summary

Displays formatted summary data on the screen and provides the option to print on the default printer. This data contains the station, layer thickness, moduli for each specified layer, the RMS error.

Options – standard Windows protocols are used for viewing various pages, zoom, selecting font style for screen view and printing, printing and exiting print screen.

Page Setup

Allows the user to modify the page margins. The default settings are shown.

Select Font

Allows the user to choose any available font for use in displaying and printing the output and summary information. This font is also saved as the default font for future output display.

2.6.4.3 Help

Contents – Contains descriptions of the various program menus and entry requirements for program operation. The help screen is derived from the field descriptions contained in this User's Guide.

Search for Help on... - Typical Windows format for searching for key program descriptions.

About EVERCALC® - lists program version information, responsible agency and personnel contacts, system memory and resources.

2.6.4.4 Open General File

Title - Any text that describes the GENERAL DATA File

No of Layers - Total number of layers (including the stiff layer, if a stiff layer option is selected). The minimum number of layers is two, and the maximum number of layers is five. Seed moduli will need to be provided if the number of layers is more than three.

No of Sensors - Total number of FWD sensors. Maximum number of sensors is limited to ten.

Units - Units of **measurement** and output, either Metric or US Customary.

Stiff Layer - Check this option to include a stiff layer. The depth to stiff layer is calculated prior to beginning the backcalculation process. The stiff layer moduli should be provided.

Temp. Correction - Check this option to adjust the moduli of the first layer to the standard temperature.

Temp. Measurement - Required only when temperature correction is required. Select the appropriate temperature measurement option. Choose the Direct Method option if using an HMA mid-depth temperature measurement. Use the Southgate Method option if pavement temperature is to be calculated from surface temperatures and five-day mean air temperatures (requires additional data).

Plate Radius - Radius of the FWD loading plate.

Seed Moduli - Seed moduli are the initial estimates of unknown layer moduli. Choose Internal if you want the program to estimate the seed moduli. The internal option cannot be used when the number of layers is more than three. The user can also specify seed moduli by selecting User Supplied.

Sensor Weigh Factor – This field allows the user to select amongst three options for calculating the error function that drives the backcalculation process. Evercalc® uses uniform as the default method. The three options are described as follows:

- Uniform: Each sensor deflection is weighed uniformly in constructing the error function. The error being minimized is:

$$100 \sqrt{\frac{\sum_{i=1}^N \left(\frac{dm - dc}{dm} \right)^2}{N}} \quad \text{Equation 23}$$

- Inverse First Sensor: Each sensor is weighed by the inverse of the first sensor deflection. The error being minimized is:

$$100 \sqrt{\frac{\sum_{i=1}^N \left(\frac{dm}{d1} \left(\frac{dm - dc}{dm} \right) \right)^2}{N}} \quad \text{or} \quad 100 \sqrt{\frac{\sum_{i=1}^N \left(\frac{dm - dc}{d1} \right)^2}{N}} \quad \text{Equation 24}$$

- User Supplied: User specified weigh factors. User must provide weigh factors for each sensor. The error being minimized is:

$$100 \sqrt{\frac{\sum_{i=1}^N \left(wm \left(\frac{dm - dc}{dm} \right) \right)^2}{N}} \quad \text{Equation 25}$$

where,

- d1 = measured deflection at load cell
- d2 = measured deflection at 8 inches (20 cm) from load cell
- dc = calculated deflections
- dm = measured deflections
- wm = user specified weighing factor
- N = number of loads

Note: The RMS error reported in the output and summary output are always calculated with uniform weight -i.e.:

$$\text{RMS Error} = 100 \sqrt{\frac{\sum_{i=1}^N \left(\frac{dm - dc}{dm} \right)^2}{N}} \quad \text{Equation 26}$$

This is done so that the convergence can be compared regardless of the weighing factor used.

Radial Offsets - Radial offsets of the sensors from the center of the loading plate.

Layer Information

No - Layer number. The upper most layer is designated as number one and proceeds sequentially downward.

Layer ID - Enter 0 if the moduli of this layer is to be backcalculated (unknown moduli). Enter 1 if the moduli of this layer is fixed (known).

Poisson's Ratio - Enter the Poisson's ratio of this layer.

Initial Moduli - Enter seed moduli for this layer if the User Supplied option is selected for Seed Moduli or 0.0 if the Internal option is selected.

Min. Moduli - Enter the minimum value of the layer moduli for this layer (must be greater than or equal to 0.0). Can be set to 0.0 if no minimum limit is required.

Max. Moduli - Enter the maximum value of the layer moduli for this layer (must be greater than or equal to 0.0). Can be set to 0.0 if no minimum limit is required.

Max. Iteration - Maximum number of iterations allowed during the optimization. A value of ten is typically used.

RMS Tol. (%) - Root mean square error tolerance between the measured and calculated deflections (percentage). A value of 1.0 is typical.

Modulus Tol. (%) - Modulus percentage tolerance in successive iterations. A value of 1.0 is typical.

Stress and Strain Location – allows user to input up to 10 locations for stress and strain computation. The default locations are beneath the center load at the bottom of the asphalt layer, at the middle of the base layer, and at the top of the subgrade.

Save - Saves the current GENERAL DATA File under the same name. The user must save the file after the data is entered. The program will not save automatically or prompt user to save the data file.

Save As - Saves the current GENERAL DATA File under a different name.

Cancel - Discards any changes made without saving and returns the user to the Main Screen.

2.6.4.5 **Open DEFLECTION DATA File**

Route - Name of the Route or any other descriptive information.

Station Information

Station - Station identification, such as milepost. A maximum character limit of ten.

H(1) to H(4) - Thickness of each pavement layer, up to 5 layers. The last layer thickness is excluded (subgrade or stiff layer are considered to be infinite in depth).

No. of Drops - Total number of drops at this station. A maximum of twelve drops is allowed.

Pavement Temperature - Pavement temperature (if Direct Method) or five-day mean air temperature (if Southgate Method).

Deflection Information

Drop No – The drop number if more than one drop is input. The program allows up to eight drops per station.

Load - Plate load for each drop.

Sensor Deflection - Measured sensor deflection for each drop at each sensor starting from the closest sensor to the farthest sensor.

Add Station - Adds a station after the current station.

Plot – Allows user to view and print data plots of deflection basins (per station and all load levels), layer thickness, and normalized deflections (standard load of 9,000 lbs (80 kN)).

Delete Station - Deletes the current station.

Save - Saves the current DEFLECTION DATA File. The user must save the data file, the **program** will not automatically save or prompt the user to save the data file.

Save As - Saves the current DEFLECTION DATA File under a different name.

Cancel - Discards any changes made without saving and returns the user to the Main screen.

2.6.4.6 Perform Backcalculation

Interactive – this option requires user to initiate backcalculation process.

Batch – the option allows the user to backcalculate without requiring user intervention for completion. This option will turn off the iteration graphics so that multiple analysis can be started one after another. After starting one analysis the user can start additional analysis by selecting the batch mode menu item. However, all analyses are run in the background sharing the same computer resources and the CPU and memory limitation will dictate the number of analysis that can be started simultaneously.

2.6.4.7 FWD Conversion

GENERAL DATA File – Name of the GENERAL DATA File.

FWD DATA File - Name of the FWD raw data file including its path. Recall that this feature is only available with the Dynatest 8000 FWD's (version 20).

DEFLECTION DATA File - Name of the DEFLECTION DATA File where the converted FWD data will be saved.

Project Data – this information (route name, number of layers, number of sensors, etc.) will automatically be displayed and is the contents of the GENERAL DATA File. The station locations will also be displayed based on the specified FWD DATA File.

Layer Thickness Information - FWD raw data file does not contain layer thickness information. When the user chooses an FWD file to be processed, a table is displayed with station identifiers in the first column (non-editable), selection option in the second column, and columns for thicknesses for each of the layers excluding the last layer and stiff layer, if any. The user can choose to include or exclude selected stations from the FWD file by clicking the "Selected" column to be checked on or off, respectively. If the stationing is alphanumeric then thicknesses should be provided for all stations selected for backcalculation. If the stationing is numeric then thicknesses need only be provided where it changes and the layer thicknesses for each station (mile post) in the FWD raw data file is chosen to be the same as that of the closest previous station from this list of thicknesses. A minimum of one set of data needs to be provided.

If layer thickness does not change through the project length, the user only needs to enter layer thickness at the first station. If various layer thickness depths exist, the user is only

required to enter thicknesses where changes occur. For example, project limits are from station 0 to station 5, and the following layer thickness exist:

<u>Station</u>	Thickness of Asphalt H(1)	Thickness of Base H(2)
0	4.0 inches	6.0 inches
2.5	6.0 inches	8.0 inches

The user would then click on box adjacent to Station 0 and then type in 4.0 for H(1) and 6.0 for H(2). The same process would then be necessary next to station 2.5, click on the box adjacent to Station 2.5 and type in 6.0 for H(1) and 8.0 for H(2). The program will then use 4 inches for the asphalt layer and 6 inches for the base layer from Station 0 to Station 2.5, and 6 inches for the asphalt layer and 8 inches for the base layer from Station 2.5 to Station 5.0.

Select All – Selects all station locations for layer moduli determination.

Deselect All – Deselects all station locations. User selects specific locations for layer moduli determination.

Multiple Drops – Allows user various methods for analyzing data when multiple drops at the same load level are collected.

No – use all the load-deflection data in the backcalculation process. This option is recommended when only one drop per load level has been collected.

Average Normalized – FWD data was collected using multiple drops at each load level. The average load at each load level is determined and then the deflections are averaged and normalized at each load level. For this method the user must enter the number of drops per load. For example, the deflection data is collected using three drops at each load level. This option would then calculate the average load for all three drops (for each load level), then each of the three deflection readings are normalized to the average load and then the normalized deflections are averaged to obtain a single load-deflection data at that load level.

Average – FWD data was collected using multiple drops at each load level. This method averages the load and deflection data. For this method the user must enter the number of drops per load. If the deflection data was collected using multiple drops at each load level, this is the recommended procedure to minimize the random error that is associated with deflection and/or load measurements.

Convert - Converts the FWD raw data file to the necessary format. This process is extremely quick and the user is not prompted that the process is complete.

Exit – Exits the Convert screen and returns to the main screen.

2.6.4.8 Modify Standard Temperature

Allows user to modify the standard temperature for determining the asphalt layer moduli. WSDOT uses 77°F (25°C) as the standard temperature.

2.6.4.9 Exit

Exits the program and returns to Windows.

2.6.5 Execution of the Program

As a general note, any time you save a file in Evercalc[®], use the same extension as designated by the program. The program calls the required files according to their extension. It will save the user time and keystrokes if the program extension protocols are followed. In addition, the program will not automatically save any data, the user must click on the “Save” or “Save As” buttons once data has been entered.

After the user has started Windows, the program can be initiated by double clicking on the Evercalc[®] icon. The screen as shown in Figure 18 will be displayed.



Figure 12. About Evercalc[®] Screen

Press the **OK** button and the screen as shown in Figure 19 will be displayed.

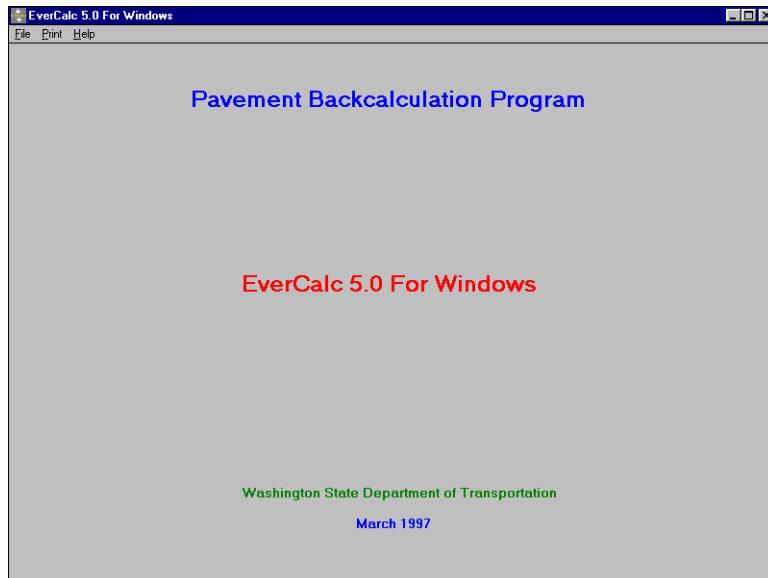


Figure 13. Evercalc[®] Main Screen

The first step for performing the backcalculation process is the development of the GENERAL DATA File. The GENERAL DATA File contains general pavement data and the general specifications of the nondestructive testing device. Select **File** and then select **Open General File** to create the GENERAL DATA File. The program will prompt the user for a filename, either select a file that is listed or enter a nonexistent filename to create a new GENERAL DATA File. Once the file has been generated the screen as shown in Figure 20 will be displayed.

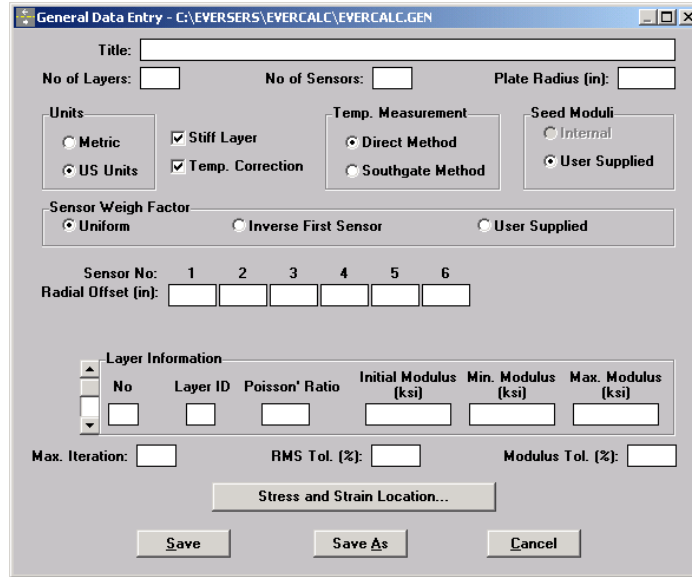


Figure 14. General Data Entry Screen

Begin by entering the following data:

- * The title of the project
- * The number of pavement layers. The number of layers is limited to five layers, including a stiff layer, if used
- * The number of FWD sensors
- * The radius of the FWD loading plate
- * The units of measure
- * Presence of a stiff layer?
- * Is temperature correction desired for the HMA layer? Default value for temperature correction is 77°F (25°C) or can be established by the user by selecting **File** and **Modify Standard Temperature**.
- * Pavement temperature measured using the Direct or Southgate Method?
- * Are the seed moduli to be internal or user supplied? If a stiff layer is used, the user must supply the seed (initial) moduli.
- * What sensor weigh factor will be used?
- * The radial offset (inch or cm) of each sensor from the load plate. WSDOT uses the following sensor spacing: 0, 8 inches (20.3 cm), 12 inches (30.5 cm), 24 inches (61.0 cm), 36 inches (91.5 cm), and 48 inches (122.0 cm). Care must be taken to insure that the most distant sensor from the load is actually measuring a deflection. If this sensor is located too far from the loading plate, the sensor may pick up more “noise” than an actual deflection and may result in higher error than necessary.
- * Layer information. Using the scroll bar, input the layer number, layer ID, Poisson’s ratio, initial modulus (ksi or MPa), and if supplied by the user, the minimum and maximum moduli (ksi or MPa) for each of the pavement layers.
- * Enter the program termination values: maximum number of iterations, RMS tolerance (in percent) and the modulus tolerance (in percent).

- * Modify stress and strain locations, if necessary.
- * Prior to exiting this screen the data must be saved. Select the **Save** button and the data will be saved using the same filename. Selecting the **Save As** button will save the data as a different filename. Selecting the **Cancel** button will return the user to the Main Screen without saving any modifications to the file.

Following the creation of the GENERAL DATA File, the user must then create the DEFLECTION DATA File. The DEFLECTION DATA File contains the data collected from the nondestructive testing device. There are two methods of entering deflection data. The first method is by “hand” entering the load and deflection data. The second method is by converting a raw FWD (Dynatest 8000 version 20 only) data file. The latter of these two will be described later. To “hand” enter in the load and deflection data, select **File** and then select **Open DEFLECTION DATA File**. The user will be prompted to select the GENERAL DATA File to be used (the GENERAL DATA File must have already been created). Then the user will be prompted to open an existing DEFLECTION DATA File or to create a new DEFLECTION DATA File by entering a nonexistent filename. Once the file has been generated the following screen as shown in Figure 21 will be displayed.

Station Information						
Station	H(1) (in)	H(2) (in)	No. of Drops	Pavement Temp (F)		
			4			

Deflection Information							
Sensor Deflection (mils)							
Drop No.	Load(lbf)	1	2	3	4	5	6
1							
2							
3							
4							

Figure 15. Deflection Data Entry Screen

At this screen, enter in the following data:

- Route, which can be any text that identifies the project.
- Station or milepost number, thickness of the HMA layer, thickness of the base layer, subbase layer(s) (if appropriate) number of drops, and the pavement temperature at the time of testing.
- For each station, enter the load(s) and the corresponding deflections.
- Additional stations may be added by selecting the **Add Station** button. Likewise, a station that is currently shown can be deleted by selecting the **Delete Station** button.
- Prior to exiting this screen the data must be saved. Select the **Save** button and the data will be saved using the same filename. Selecting the **Save As** button will save the data as a different filename. Selecting the **Cancel** button will return the user to the Main Screen without saving any modifications to the file.

To convert a raw FWD DATA File to a DEFLECTION DATA File, select file and then select **Convert FWD DATA File**. The user will be prompted to select the GENERAL DATA File and the

FWD DATA File to be converted. The screen similar to what is shown in Figure 22 will be displayed.

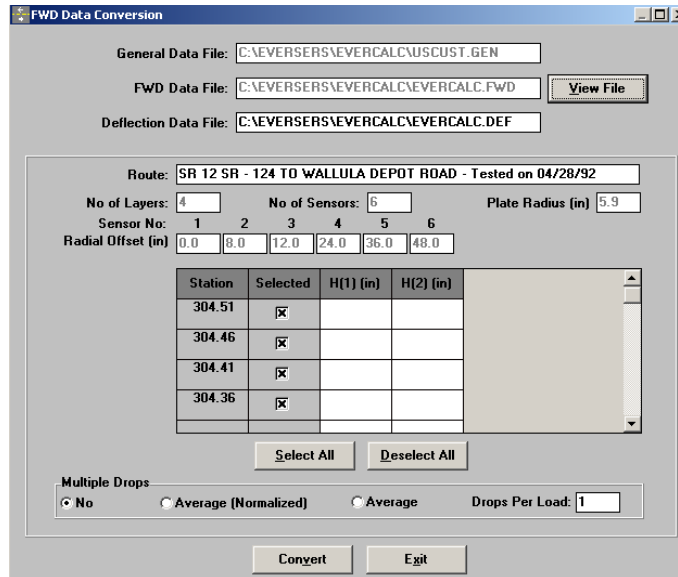


Figure 16. FWD Data Conversion Screen

The GENERAL DATA File and FWD DATA File that was selected by the user will be shown on the upper portion of this screen. The program will automatically name the DEFLECTION DATA File according to the name used for the FWD DATA File. The program will assign “.DEF” as the DEFLECTION DATA File extension. This screen will convert the raw FWD file into a format to be used in the backcalculation process. In addition, this screen will allow the user to input layer thickness for each of the layers as designated in the GENERAL DATA File. The stations to be included in the deflection data file are selected and the corresponding layer thicknesses are entered as explained earlier. Once all data has been entered, select **Convert** and the program will execute, and then select **Exit** to return to the Main screen.

The plot routines that are available in the **Deflection Data Entry** screen are deflection basin, layer thickness, and normalized deflection. Selecting the Plot button, the following screen will be displayed.

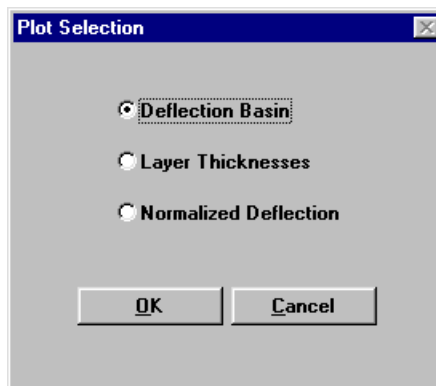


Figure 17. Deflection Data Plot Screen

Each one of these options will be briefly described.

Deflection Basin – the deflection basin (for all load levels) will be displayed for each individual station location. The buttons across the top of the screen will allow the user various options for presenting the data.

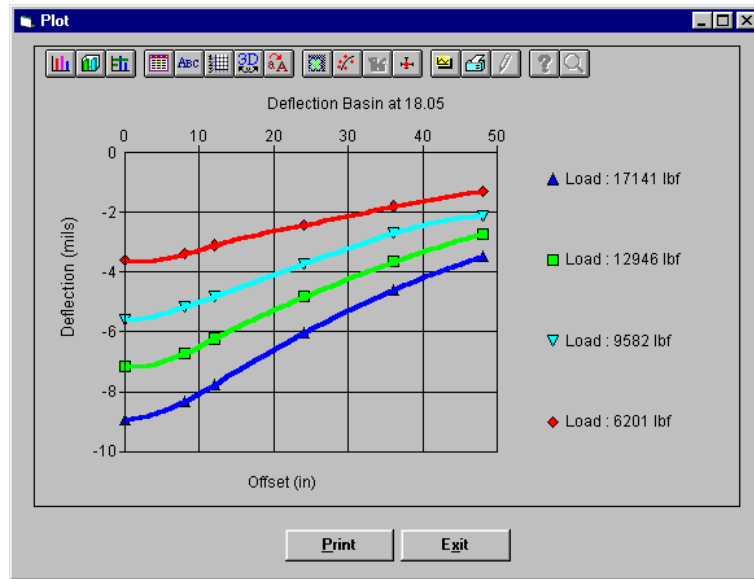


Figure 18. Plot Deflection Basin

Layer Thickness –the various layer thicknesses for the entire deflection data file will be displayed.

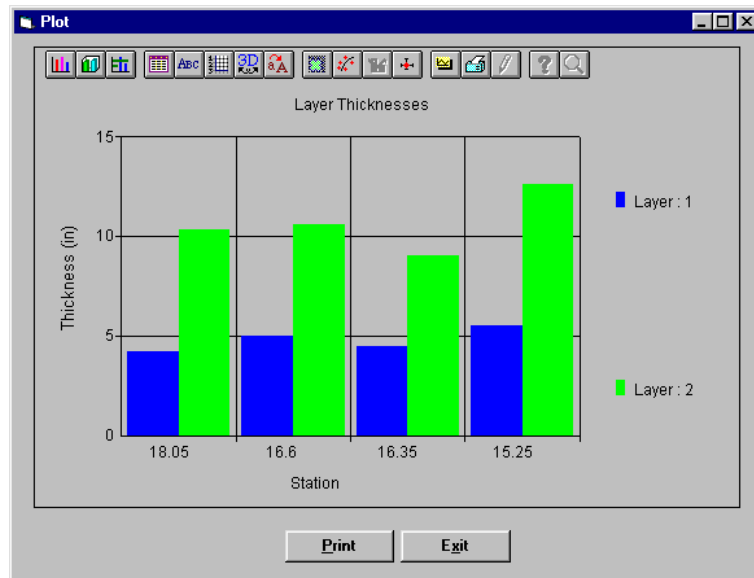


Figure 19. Plot Layer Thickness

Normalized Deflection – the normalized (to the standard temperature and 9000 lb (40 kN)) deflection will be displayed according to each sensor for the entire deflection data file.

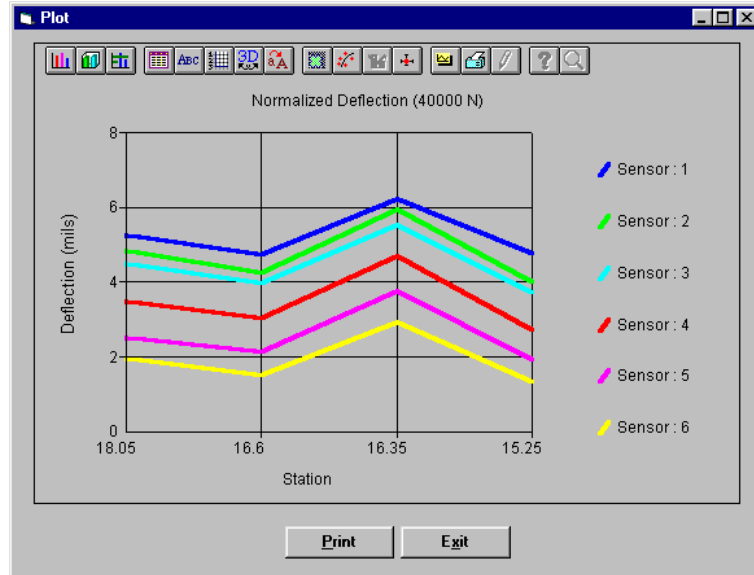


Figure 20. Plot Normalized Deflections

After creating the GENERAL DATA File and the DEFLECTION DATA File, the user is now able to begin the backcalculation process. Select **File** and then select **Perform Backcalculation**. The user will then have the choice to either run the backcalculation in the interactive or batch mode. If numerous deflection files are to be analyzed and the user does not want to be prompted to complete the analysis (run process over night for example) then the batch mode should be selected. In the interactive mode, the user will be prompted to select the GENERAL DATA File, the DEFLECTION DATA File, and to confirm the Output Filename. If the user selected to not use a stiff layer (GENERAL DATA File), the backcalculation process will begin. If the user selected a stiff layer, then the depth to stiff layer screen will be displayed and the user will be asked to modify the estimated depth to stiff layer or to accept the data as shown (see Figure 27).

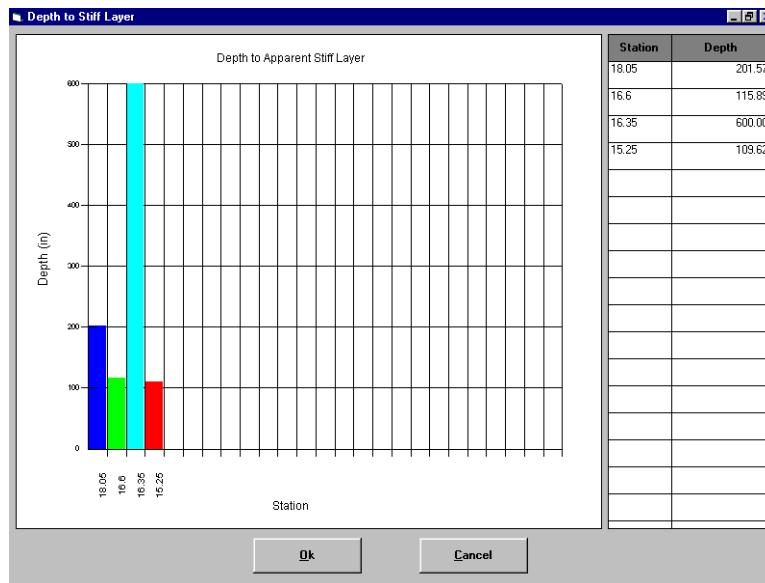


Figure 21. Depth to Apparent Stiff Layer Screen

If the user has actual borings to depth of stiff layer (or saturated layer) they can be entered directly onto this screen. Clicking on the depth to be modified will allow the user to enter the necessary values.

Click on the **OK** button and the backcalculation process will begin. The program will then display on the screen the measured and calculated deflections in the determination of the layer moduli. The computer will display this screen for each load level at each station. The process is completed when the word "Finished" is displayed in the lower left-hand corner as shown in Figure 28.

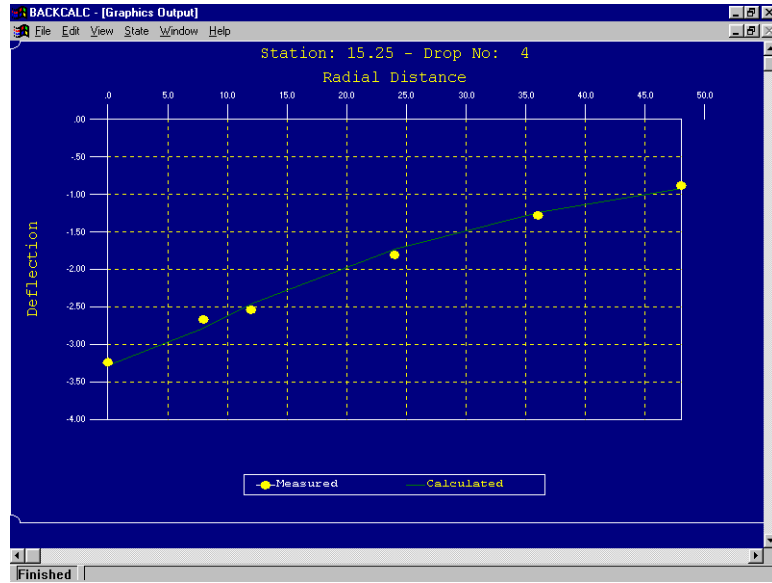


Figure 22. Backcalculation Screen

To return back to the main menu, select **File** and then **Exit** or close the screen using the X button in the upper right hand corner. The data can then be viewed or printed by selecting **Print** on the main menu tool bar. To exit the Evercalc[®] program, select **File** and then select **Exit**.

2.6.6 EVERCALC Deflection File Format

2.6.6.1 Sample of Evercalc[®] Deflection File

SR 14 6TH AVE. TO EVERGREEN BLVD. - Tested on 12/06/95	(description)
18.05 4 4.200 10.320 0.000 0.000 37.000 0.000	(test location 1/description)
17141.0 8.910 8.320 7.760 6.040 4.600 3.460	(load 1/deflection)
12946.0 7.150 6.720 6.220 4.830 3.650 2.720	(load 2/deflection)
9582.0 5.590 5.160 4.800 3.730 2.690 2.110	(load 3/deflection)
6201.0 3.590 3.390 3.100 2.420 1.800 1.290	(load 4/deflection)
16.6 4 5.000 10.560 0.000 0.000 37.000 0.000	(test location 2/description)
16240.0 8.280 7.400 6.970 5.320 3.800 2.690	(load 1/deflection)
12279.0 6.460 5.810 5.440 4.150 2.980 2.080	(load 2/deflection)
9077.0 4.770 4.280 4.020 3.050 2.160 1.520	(load 3/deflection)
5883.0 2.900 2.680 2.480 1.880 1.330 0.830	(load 4/deflection)
16.35 4 4.500 9.000 0.000 0.000 37.000 0.000	(test location 3/description)
15819.0 11.010 10.290 9.870 8.250 6.650 5.280	(load 1/deflection)
12180.0 8.620 8.240 7.690 6.540 5.260 4.120	(load 2/deflection)
9284.0 6.450 6.160 5.710 4.850 3.890 3.030	(load 3/deflection)
6062.0 3.980 3.930 3.690 3.060 2.430 1.940	(load 4/deflection)

2.6.6.2 File Description

The file is in free format – the values should be separated by a space, comma or hard TAB.

Line 1 – Route information (CHARACTER STRING, max length = 80)

Line 2

Item 1 – station (CHARACTER STRING, max length = 10)

Item 2 – number of drops at this station (Integer)

Item 3 through Item 6 – four layer thickness (single precision). If there are less than four thickness (i.e. less than five layers), enter 0.0 for the rest. For example, for a three-layer case, enter the 1st and 2nd layer thickness first then enter 0.0 for the next two (inches or cm).

Item 7 through Item 8 – temperature values (single precision). The temperature correction is defined in the GENERAL DATA File. If there is no temperature correction then enter 0.0 for both. If direct method then enter the temperature for Item 7 and enter 0.0 for Item 8. If Southgate method then enter surface temperature for Item 7 and mean temperature for Item 8 (°F or °C).

The following line is repeated for each drop at this station (defined in Line 2, Item 2)

Line 3

Item 1 – Plate load (single precision) (lbf or N)

Item 2 – Item x deflections (single precision). Enter as many deflection readings as the number of sensors defined in the GENERAL DATA File, starting from the sensor closest to the load plate (mils or microns)

The units should be consistent with that defined in the GENERAL DATA File. You can open this file in Evercalc[®] (Open Deflection Data) and check for its correctness.

2.6.7 Example No. 1 — No Stiff Layer

2.6.7.1 GENERAL DATA File

Number of layers = 3

No stiff layer

Temperature measurement = Direct Method

Seed Moduli = User Supplied

Plate Radius = 5.9 inches

Sensor Number	1	2	3	4	5	6
Radial Offset (in)	0	8	12	24	36	48

Layer Information

No	Layer ID	Poisson's Ratio	Initial Modulus (ksi)	Minimum Modulus (ksi)	Maximum Modulus (ksi)
1	0	0.35	400	100	2000
2	0	0.40	25	5	500
3	0	0.45	15	5	500

Maximum Iteration = 10

RMS Tolerance (%) = 1.0

Modulus Tolerance (%) = 1.0

2.6.7.2 Deflection Data File

Station = 210.00
 H(1) = 4 inches
 H(2) = 16 inches
 Number of drops = 4
 Pavement Temperature = 50°F

Drop Number	Load (lb)	1	2	3	4	5	6
1	16717.69	35.98	29.21	25.16	16.77	11.22	7.56
2	12022.78	27.80	22.60	19.29	12.72	8.39	5.71
3	9421.52	22.32	17.99	15.28	9.84	6.38	4.37
4	6170.11	15.16	12.09	10.08	6.30	3.98	2.76

2.6.7.3 Backcalculation Results (No Stiff Layer)

BACKCALCULATION by Evercalc® 5.0 - Detail Output

Route: Example No. 1 - No Stiff Layer		No. of Layers: 3
Plate Radius (in): 5.9		Stiff Layer: No
No of Sensors: 6		P-Ratio: .350 .400 .450
Offsets (in) .0.0 8.0 12.0 24.0 36.0 48.0		
Station: 210	No of Drops: 4	Average RMS Error (%): 2.30
Thickness (in): 4.00 16.00		Pavement Temperature (F): 50.0

Drop No: 1	Load (N): 16717.7			No of Iterations: 5		
Convergence: Modulus Tolerance Satisfied				RMS Error (%): 2.73		
Sensor No:	1	2	3	4	5	6
Measured Deflection (microns):	35.980	29.210	25.160	16.770	11.220	7.560
Calculated Deflection (microns):	34.678	29.791	25.998	16.550	10.873	7.731
Difference (%):	3.62	-1.99	-3.33	1.31	3.10	-2.26

Layer No:	1	2	3	1-(adj)
Seed Moduli (MPa)	400.00	25.00	15.00	N/A
Calculated Moduli (MPa):	1666.63	14.76	12.36	520.638

Layer No:	1	2	3
Radial Distance (in):	0.00	0.00	0.00
Position	Bottom	Middle	Top
Vertical Stress (psi):	-22.91	-12.80	-7.86
Radial Stress (psi):	796.86	-1.41	-9.98
Bulk Stress (psi):	1570.81	-15.62	-9.83
Deviator Stress (psi):	-819.77	-11.39	-6.88
Vertical Strain (10 ⁻⁶):	-348.43	-790.78	-564.76
Radial Strain (10 ⁻⁶):	315.59	289.57	242.65

Drop No: 2	Load (N): 12022.8			No of Iterations: 2		
Convergence: Modulus Tolerance Satisfied				RMS Error (%): 2.46		
Sensor No:	1	2	3	4	5	6
Measured Deflection (microns):	27.800	22.600	19.290	12.720	8.390	5.710
Calculated Deflection (microns):	26.911	22.960	19.927	12.519	8.182	5.824
Difference (%):	3.20	-1.59	-3.30	1.58	2.47	-1.99

Layer No:	1	2	3	1-(adj)
Seed Moduli (MPa)	1666.63	14.76	12.36	N/A
Calculated Moduli (MPa):	1439.79	14.17	11.74	449.776

Layer No:		1	2	3
Radial Distance (in):		0.00	0.00	0.00
Position		Bottom	Middle	Top
Vertical Stress (psi):		-17.48	-9.61	-5.83
Radial Stress (psi):		555.45	-99	-69
Bulk Stress (psi):		1093.43	-11.60	-7.22
Deviator Stress (psi):		-572.93	-8.62	-5.13
Vertical Strain (10 ⁻⁶):		-282.19	-622.18	-443.16
Radial Strain (10 ⁻⁶):		255.01	220.25	190.85

Drop No: 3		Load (N): 9421.5				No of Iterations: 2	
Convergence: Modulus Tolerance Satisfied						RMS Error (%): 2.25	
Sensor No:	1	2	3	4	5	6	
Measured Deflection (microns):	22.320	17.990	15.280	9.840	6.380	4.370	
Calculated Deflection (microns):	21.659	18.284	15.733	9.669	6.254	4.448	
Difference (%):	2.96	-1.63	-2.97	1.74	1.98	-1.78	

Layer No:		1	2	3	1-(adj)
Seed Moduli (MPa)		1439.79	14.17	11.74	N/A
Calculated Moduli (MPa):		1271.06	14.21	11.95	397.067

Layer No:		1	2	3
Radial Distance (in):		0.00	0.00	0.00
Position		Bottom	Middle	Top
Vertical Stress (psi):		-14.73	-7.97	-4.78
Radial Stress (psi):		417.82	-80	-55
Bulk Stress (psi):		820.92	-9.57	-5.87
Deviator Stress (psi):		-432.55	-7.18	-4.23
Vertical Strain (10 ⁻⁶):		-241.69	-516.41	-358.89
Radial Strain (10 ⁻⁶):		217.72	190.83	154.89

Drop No: 4		Load (N): 6170.1				No of Iterations: 2	
Convergence: Modulus Tolerance Satisfied						RMS Error (%): 2.07	
Sensor No:	1	2	3	4	5	6	
Measured Deflection (microns):	15.160	12.090	10.080	6.300	3.980	2.760	
Calculated Deflection (microns):	14.771	12.242	10.382	6.160	3.931	2,801	
Difference (%):	2.56	-1.26	-2.99	2.22	1.22	-1.49	

Layer No:		1	2	3	1-(adj)
Seed Moduli (MPa)		1271.06	14.21	11.95	N/A
Calculated Moduli (MPa):		1039.24	14.40	12.29	324.646

Layer No:		1	2	3
Radial Distance (in):		0.00	0.00	0.00
Position		Bottom	Middle	Top
Vertical Stress (psi):		-10.87	-5.72	-3.36
Radial Stress (psi):		254.65	-.53	-.35
Bulk Stress (psi):		498.43	-6.78	-4.06
Deviator Stress (psi):		-265.52	-5.19	-3.00
Vertical Strain (10 ⁻⁶):		-181.98	-367.81	-247.23
Radial Strain (10 ⁻⁶):		162.93	136.82	107.09

Layer No:		1	2	3	1-(adj)
Mean Moduli (MPa)		1354.18	14.38	12.09	423.03
Normalized Moduli (MPa)		1241.01	14.23	12.00	387.678
K1 (MPa):		N/A	14.45	12.10	
K2:		N/A	.03	.00	
R-Squared:		N/A	49.97	3.93	
Soil Type:		N/A	Coarse	Coarse	

BACKCALCULATION by Evercalc® 5.0 - Summary Output

Route: Example No. 1 - No Stiff Layer						
Plate Radius (in): 5.9				No of Layers: 3		
No of Sensors: 6				Stiff Layer: No		
Offsets (in) 0.0 8.0 12.0 24.0 36.0 48.0				P-Ratio: .350 .400 .450		
Station	Load (lb)	Eadj(ksi)	E(1)(ksi)	E(2)(ksi)	E(3)(ksi)	RMS Error
210	Thickness (in)	-	4.00	16.00	-	-
210	16717.7	520.6	1666.6	14.8	12.4	2.73
210	12022.8	449.8	1439.8	14.2	11.7	2.46
210	9421.5	397.1	1271.1	14.2	12.0	2.25
210	6170.1	324.6	1039.2	14.4	12.3	2.07
210	Norm.	387.7	1241.0	14.2	12.0	2.38

2.6.8 Example No. 2 - Stiff Layer at 50 ksi

2.6.8.1 GENERAL DATA File

Number of layers = 4

Stiff layer

Temperature measurement = Direct Method

Seed Moduli = User Supplied

Plate Radius = 5.9 inches

Sensor Number	1	2	3	4	5	6
Radial Offset (in)	0	8	12	24	36	48

Layer Information

No	Layer ID	Poisson's Ratio	Initial Modulus (ksi)	Minimum Modulus (ksi)	Maximum Modulus (ksi)
1	0	0.35	400	100	2000
2	0	0.40	25	5	500
3	0	0.45	15	5	500
4	1	0.20	50		

Maximum Iteration = 10

RMS Tolerance (%) = 1.0

Modulus Tolerance (%) = 1.0

2.6.8.2 DEFLECTION DATA FILE

Station = 210.00

H(1) = 4 inches

H(2) = 16 inches

Number of drops = 4

Pavement Temperature = 50°F

Drop Number	Load (lb)	1	2	3	4	5	6
1	16717.7	35.98	29.21	25.16	16.77	11.22	7.56
2	12022.78	27.80	22.60	19.29	12.72	8.39	5.71
3	9421.52	22.32	17.99	15.28	9.84	6.38	4.37
4	6170.11	15.16	12.09	10.08	6.30	3.98	2.76

2.6.8.3 BACKCALCULATION RESULTS

BACKCALCULATION by Evercalc[®] 5.0 - Detail Output

Route: Example No. 1 - Stiff Layer	
Plate Radius (in): 6.9	No. of Layers: 4
No of Sensors: 6	Stiff Layer: Yes
Offsets (in) .0 8.0 12.0 24.0 36.0 48.0	P-Ratio: .350 .400 .450 .200

Station: 210	No of Drops: 4	Average RMS Error (%): 1.85
Thickness (in): 4.00 16.00 284.83		Pavement Temperature (F): 50.0

Drop No: 1	Load (lbf): 16717.7				No of Iterations: 5	
Convergence: Modulus Tolerance Satisfied					RMS Error (%): 2.23	
Sensor No:	1	2	3	4	5	6
Measured Deflection (microns):	35.980	29.210	25.160	16.770	11.220	7.560
Calculated Deflection (microns):	35.031	29.744	25.806	16.474	10.955	7.719
Difference (%):	2.64	-1.83	-2.57	1.76	2.36	-2.10

Layer No:	1	2	3	4	1-(adj)
Seed Moduli (MPa)	400.00	25.00	15.00	50.00	N/A
Calculated Moduli (MPa):	1361.51	20.81	10.17	50.00	425.321

Layer No:	1	2	3
Radial Distance (in):	0.00	0.00	0.00
Position	Bottom	Middle	Top
Vertical Stress (psi):	-30.10	-14.29	-7.42
Radial Stress (psi):	691.08	.31	-.58
Bulk Stress (psi):	1352.06	-13.67	-8.58
Deviator Stress (psi):	-721.17	-14.60	-6.83
Vertical Strain (10 ⁻⁶):	-377.41	-698.32	-677.40
Radial Strain (10 ⁻⁶):	337.67	283.48	296.51

Drop No: 2	Load (lbf): 12022.8				No of Iterations: 3	
Convergence: Modulus Tolerance Satisfied					RMS Error (%): 1.93	
Sensor No:	1	2	3	4	5	6
Measured Deflection (microns):	27.800	22.600	19.290	12.720	8.390	5.710
Calculated Deflection (microns):	27.188	22.914	19.770	12.470	8.253	5.808
Difference (%):	2.20	-1.39	-2.54	1.97	1.63	-1.72

Layer No:	1	2	3	4	1-(adj)
Seed Moduli (MPa)	1361.51	20.81	10.17	50.00	N/A
Calculated Moduli (MPa):	1173.31	19.72	9.66	50.00	366.529

Layer No:	1	2	3
Radial Distance (in):	0.00	0.00	0.00
Position	Bottom	Middle	Top
Vertical Stress (psi):	-22.81	-10.69	-5.48
Radial Stress (psi):	479.81	.25	-.41
Bulk Stress (psi):	936.81	-10.19	-6.31
Deviator Stress (psi):	-502.63	-10.94	-5.07
Vertical Strain (10 ⁻⁶):	-305.70	-552.22	-529.28
Radial Strain (10 ⁻⁶):	272.62	224.42	232.00

Drop No: 3	Load (lbf): 9421.5				No of Iterations: 2	
Convergence: Modulus Tolerance Satisfied					RMS Error (%): 1.70	
Sensor No:	1	2	3	4	5	6
Measured Deflection (microns):	22.320	17.990	15.280	9.840	6.380	4.370
Calculated Deflection (microns):	21.879	18.240	15.604	9.640	6.315	4.430
Difference (%):	1.97	-1.39	-2.12	2.03	1.02	-1.36

Layer No:	1	2	3	4	1-(adj)
Seed Moduli (MPa)	1173.31	19.72	9.66	50.00	N/A
Calculated Moduli (MPa):	1041.23	19.28	9.89	50.00	325.270

Layer No:	1	2	3
Radial Distance (in):	0.00	0.00	0.00
Position	Bottom	Middle	Top
Vertical Stress (psi):	-18.89	-8.80	-4.51
Radial Stress (psi):	361.37	.13	.33
Bulk Stress (psi):	703.85	-8.54	-5.16
Deviator Stress (psi):	-380.27	-8.93	-4.18
Vertical Strain (10 ⁻⁶):	-261.09	-462.02	-425.88
Radial Strain (10 ⁻⁶):	231.94	186.73	186.85

Drop No: 4 Load (lbf): 6170.1 No of Iterations: 2
 Convergence: Modulus Tolerance Satisfied RMS Error (%): 1.51

Sensor No:	1	2	3	4	5	6
Measured Deflection (microns):	15.160	12.090	10.080	6.300	3.980	2.760
Calculated Deflection (microns):	14.927	12.204	10.287	6.151	3.977	2.783
Difference (%):	1.54	-.94	-2.06	2.36	0.7	-.84

Layer No:	1	2	3	4	1-(adj)
Seed Moduli (MPa)	1041.23	19.28	9.89	50.00	N/A
Calculated Moduli (MPa):	851.63	18.93	10.25	50.00	266.039

Layer No:	1	2	3
Radial Distance (in):	0.00	0.00	0.00
Position	Bottom	Middle	Top
Vertical Stress (psi):	-13.68	-6.26	-3.17
Radial Stress (psi):	219.42	.05	-.21
Bulk Stress (psi):	425.15	-6.16	-3.60
Deviator Stress (psi):	-233.09	-6.31	-2.96
Vertical Strain (10 ⁻⁶):	-196.41	-332.97	-290.69
Radial Strain (10 ⁻⁶):	173.09	133.93	127.77

Layer No:	1	2	3	4	1-(adj)
Mean Moduli (MPa)	1106.92	19.68	9.99	50.00	345.79
Normalized Moduli (MPa)	1016.65	19.23	9.93	50.00	317.591
K1 (MPa):	N/A	20.36	9.80	N/A	
K2:	N/A	.15	-.02	N/A	
R-Squared:	N/A	96.79	21.17	N/A	
Soil Type:	N/A	Coarse	Fine	N/A	

BACKCALCULATION by Evercalc[®] 5.0 - Summary Output

Route: Example No. 1 - Stiff Layer
 Plate Radius (in): 5.9 No of Layers: 4
 No of Sensors: 6 Stiff Layer: Yes
 Offsets (in) 0.0 8.0 12.0 24.0 36.0 48.0 P-Ratio: .350 .400 .450 .200

Station	Load (lbf)	Eadj(ksi)	E(1)(ksi)	E(2)(ksi)	E(3)(ksi)	E(4)(ksi)	RMS Error
210	Thickness (in)	-	4.00	16.00	284.83	-	-
210	16717.7	425.3	1361.5	20.8	10.2	50.0	2.23
210	12022.8	366.5	1173.3	19.7	9.7	50.0	1.93
210	9421.5	325.3	1041.2	19.3	9.9	50.0	1.70
210	6170.1	266.0	851.6	18.9	10.2	50.0	1.51
210	Norm.	317.6	1016.7	19.2	9.9	50.0	1.85

2.6.9 Example No. 2 - Stiff Layer at 50 ksi

From the summary outputs for the no stiff layer and stiff layer examples, the following normalized (9000 lb.) results show:

Example	E_{adj}	E₁	E₂	E₃	RMSE
No stiff layer	387.7	1241.0	14.2	12.0	2.38
Stiff layer	317.6	1016.7	19.2	9.9	1.85

From this summary both the no stiff and stiff layer examples provide reasonable results with low RMSE. With the lower base moduli, it appears that the base material may have been compromised (infiltrated with fine material) due to the low stiffness (weak) subgrade (field evaluation could be used to verify this result). Use of either result would be appropriate. However, the results of the stiff layer provide a lower RMSE and more realistic moduli for the base and subgrade moduli.

References

- 1 Michelow, J., Analysis of Stress and Displacements in an n-Layered Elastic System under a Load Uniformly Distributed on a Circular Area California Research Corporation, Richmond, California, 1963.
- 2 Lytton, R.L., "Backcalculation of Pavement Layer Properties," Nondestructive Testing of Pavements and Backcalculation of Moduli, ASTM STP 1026, American Society for Testing and Materials, Philadelphia, 1989, pp. 7-38.
- 3 Rhode, G. T. And Scullion, T., "MODULUS 4.0: Expansion and Validation of the Modulus Backcalculation System," Research Report 1123-3, Texas Transportation Institute, Texas A&M University, College Station, Texas, November 1990.
- 4 Hossain, A.S.M., and Zaniewski, J.P., "Detection and Determination of Depth of Rigid Bottom in Backcalculation of Layer Moduli from Falling Weight Deflectometer Data," Transportation Research Record No. 1293, Transportation Research Board, Washington, D.C., 1991.
- 5 Winters, B.C., "The PACCAR Pavement Test Section — Instrumentation and Validation," Master's thesis, Department of Civil Engineering, University of Washington, Seattle, Washington, March 1993.
- 6 Lenngren, C.A., "Relating Bearing Capacity to Pavement Condition," Ph.D. Dissertation, Royal Institute of Technology, Department of Highway Engineering, Stockholm, Sweden, 1990.
- 7 Darter, M.I., Elliott, R.P., and Hall, K.T., "Revision of AASHTO Pavement Overlay Design Procedure," Project 20-7/39, National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C., September 1991.
- 8 Newcomb, D. E., "Development and Evaluation of Regression Method to Interpret Dynamic Pavement Deflections," Ph.D. Dissertation, Department of Civil Engineering, University of Washington, Seattle, Washington, 1986.
- 9 Bu-Bushait, A. A., "Development of a Flexible Pavement Fatigue Model for Washington State," Ph.D. Dissertation, Department of Civil Engineering, University of Washington, Seattle, Washington, 1985.
- 10 The Asphalt Institute, Thickness Design — Asphalt Pavement for Highways and Streets, Manual Series No. 1 (MS-1), College Park, Maryland, September 1981.
- 11 Shook, J.F., Finn, F.N., Witczak, M.W., and Monismith, C.L., "Thickness Design of Asphalt Pavements — The Asphalt Institute Method," Proceedings, Fifth International Conference on the Structural Design of Asphalt Pavements, The Delft University of Technology, The Netherlands, 1982.
- 12 Monismith, C.L., and Epps, J.A., "Asphalt Mixture Behavior in Repeated Flexure," Institute of Transportation and Traffic Engineering, University of California, Berkeley, 1969.
- 13 Finn, F.N., et al., "The Use of Distress Prediction Subsystems for the Design of Pavement Structures," Proceedings, 4th International Conference on the Structural Design of Asphalt Pavements, University of Michigan, Ann Arbor, 1977.
- 14 Mahoney, J.P., Lee, S.W., Jackson, N.C., and Newcomb, D.E., "Mechanistic Based Overlay Design Procedure or Washington State Flexible Pavements," Research Report

- WA-RD 170.1, Washington State Department of Transportation, Olympia, Washington, 1989.
- 15 Southgate, H. F., and Deen, R. C., "Temperature Distributions in Asphalt Concrete Pavements", *Highway Research Record No. 549*, Highway Research Board, Washington, D.C., 1975, pp. 39-46.
 - 16 Horak, E., "The Use of Surface Deflection Basin Measurements in the Mechanistic Analysis of Flexible Pavements," Proceedings, Vol. 1, Sixth International Conference Structural Design of Asphalt Pavements, University of Michigan, Ann Arbor, Michigan, USA, 1987.
 - 17 The Asphalt Institute, "Asphalt Overlays for Highway and Street Pavement Rehabilitation," Manual Series No. 17, the Asphalt Institute, College Park, Maryland, June 1983.
 - 18 Rutherford, M.S., Mahoney, J.P., Hicks, R.G., and Rwebangira, T., "Guidelines for Spring Highway Use Restrictions," Research Report WA-RD 80.1 (WSDOT) and FHWA-RD-86-501 (FHWA), August 1985.
 - 19 Kono, F., Takahashi, T., Kubo, H. and Hiraoka, H., "Pavement Design in Cold Areas," Proceedings, Symposium on Frost Action on Roads, Norwegian Road Research Laboratory, Oslo, Norway, October 1973.

Appendix A – Nondestructive Testing Interpretation Techniques

Clearly, there are all kinds of NDT data which can be collected on or about pavements but concentration is placed on measured surface deflections.

DEFLECTION BASIN PARAMETERS

Over the years numerous techniques have been developed to analyze deflection data from various kinds of pavement deflection equipment. A fairly complete summary of deflection basin parameters was provided by Horak at the Sixth International Conference Structural Design of Asphalt Pavement [15] and is shown in Table A-1.

Table A-1. Summary of Deflection Basin Parameters [modified from 15]

Parameter	Formula	Measuring device
Maximum deflection	D_0	Benkelman Beam, Lacroux deflectometer, FWD
Radius of curvature	$R = \frac{r^2}{2D_0(D_0/D_r - 1)}$ $r = 5"$	Curvaturemeter
Spreadability	$S = \left(\frac{[(D_0 + D_1 + D_2 + D_3)/5]100}{D_0} \right)$ D1 ... D3 spaced 12" apart	Dynalect
Area	$A = 6[1 + 2(D_1/D_2) + 2(D_2/D_0) + (D_3/D_0)]$ 0, 1, 2, 3 feet	FWD
Shape factors	$F1 = (D_0 - D_2) / D_1$ $F2 = (D_1 - D_3) / D_2$	FWD
Surface curvature index	$SCI = D_0 - D_r$ where $r = 12"$ or $r = 20"$	Benkelman Beam Road Rater FWD
Base curvature index	$BCI = D_{24"} - D_{36"}$	Road Rater
Base damage index	$BDI = D_{12"} - D_{24"}$	Road Rater
Deflection ratio	$Q_r = D_r/D_0$ where $D_r = D_0/2$	FWD
Bending index	$BI = D/a$ where $a =$ Deflection basin	Benkelman Beam
Slope of deflection	$SD = \tan^{-1} (D_0 - D_r)/r$ where $r = 24$ inches	Benkelman Beam

All of these parameters tend to focus on four major areas:

- (a) Plate or center load deflection which represents the total deflection of the pavement. This was obviously the first deflection parameter which came with the Benkelman Beam. It has been used for many years as the primary input for several overlay design procedures.

- (b) The slope or deflection differences close to the load such as Radius of Curvature (R), Shape Factor (F1), and Surface Curvature Index (SCI). These parameters tend to reflect the relative stiffness of the bound or upper regions of the pavement section.
- (c) The slope or deflection differences in the middle of the basin about 11.8 inches to 35.4 inches from the center of the load. These parameters tend to reflect the relative stiffness of the base or lower regions of the pavement section.
- (d) The deflections toward the end of the basin. Deflections in this region relate quite well to the stiffness of the subgrade below the pavement surfacing.

The subsequent parameters to be presented were developed to provide a means of obtaining the resilient modulus values of the surfacing layers more easily or quickly than full backcalculation. In general, the success of these regression equations to predict the resilient modulus of the surfacing layers has been limited. There is a clear consensus; however, that the deflections measured beyond the primary effects of the load stress bulb relate quite well to the resilient modulus of the subgrade, (ESG).

AREA PARAMETER

Over the years WSDOT has found that the use of selected indices and algorithms provide a "good picture" of the relative conditions found throughout a project. This picture is very useful in performing backcalculation and may at times be used by themselves on projects with large variations in surfacing layers.

WSDOT is currently using deflections measured at the center of the test load combined with Area values and ESG computed from deflections measured at 24 inches presented in a linear plot to provide a visual picture of the conditions found along the length of any project (as illustrated in Figure A-1).

The Area value represents the normalized area of a slice taken through any deflection basin between the center of the test load and 3 feet. By normalized, it is meant that the area of the slice is divided by the deflection measured at the center of the test load, D_0 . Thus the Area value is the length of one side of a rectangle where the other side of the rectangle is D_0 . The actual area of the rectangle is equal to the area of the slice of the deflection basin between 0 and 3 feet.

The original Area equation is:

$$A = 6(D_0 + 2D_1 + 2D_2 + D_3)/D_0$$

where D_0 = surface deflection at center of test load,
 D_1 = surface deflection at 1 foot,
 D_2 = surface deflection at 2 feet, and
 D_3 = surface deflection at 3 feet.

The approximate metric equivalent of this equation is:

$$A = 150(D_0 + 2D_{300} + 2D_{600} + D_{900})/D_0$$

where D0 = deflection at center of test load,
 D300 = deflection at 300 mm,
 D600 = deflection at 600 mm, and
 D900 = deflection at 900 mm.

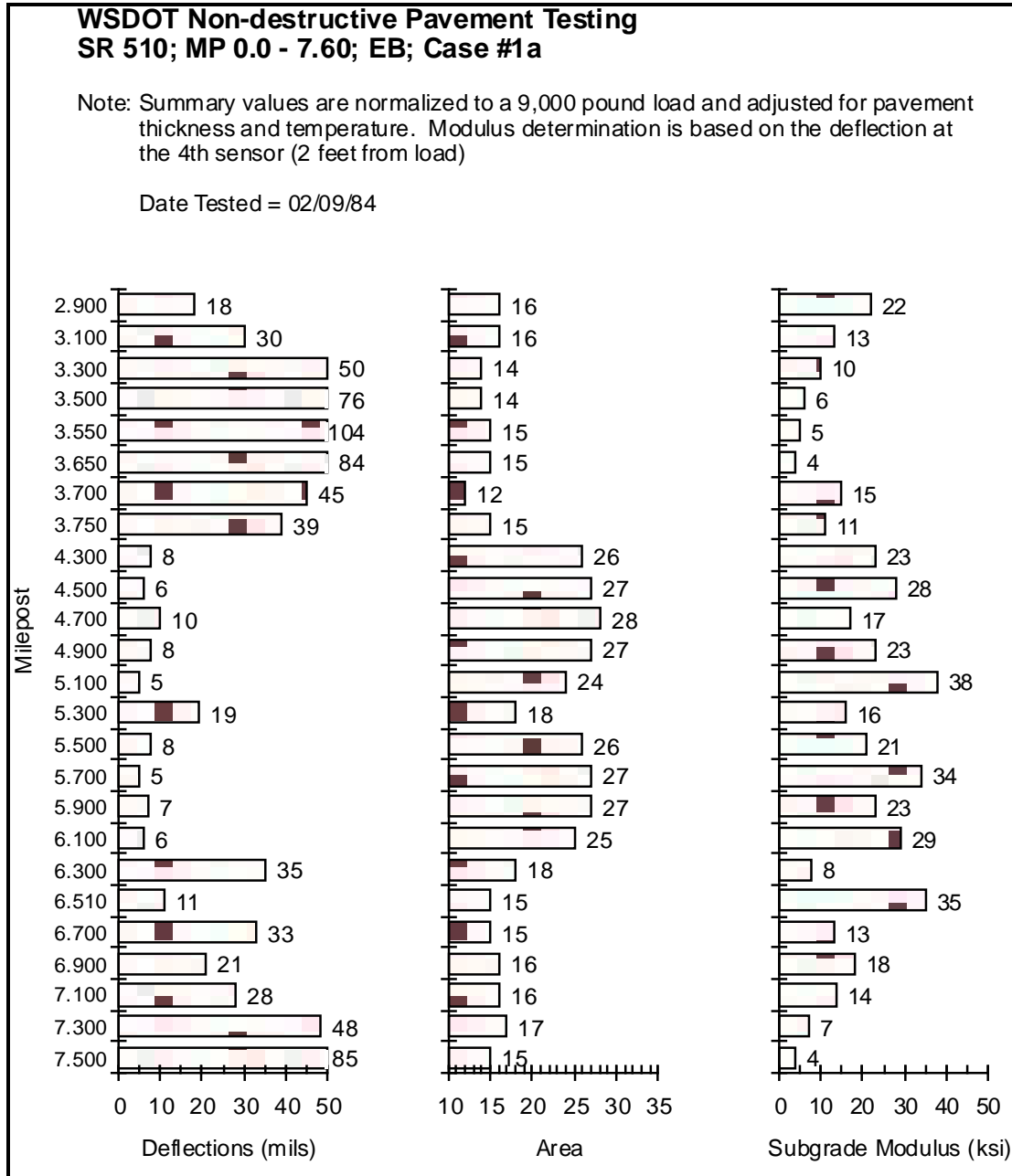


Figure A-1. Illustration of Basic NDT Parameters as used by WSDOT

Figure A-2 shows the development of the normalized area for the Area value using the Trapezoidal Rule to estimate area under a curve.

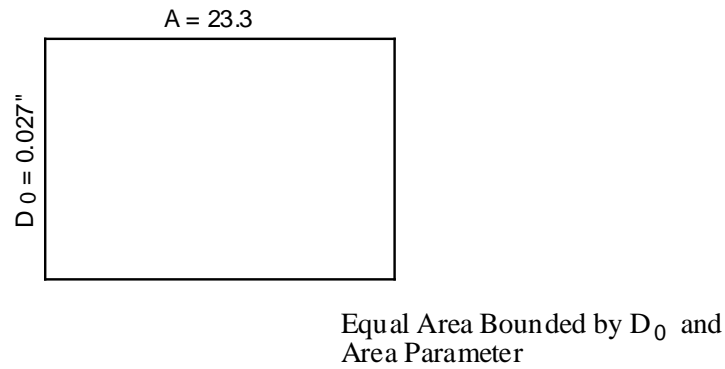
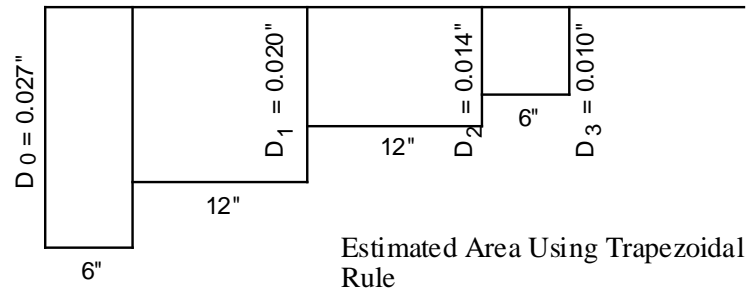
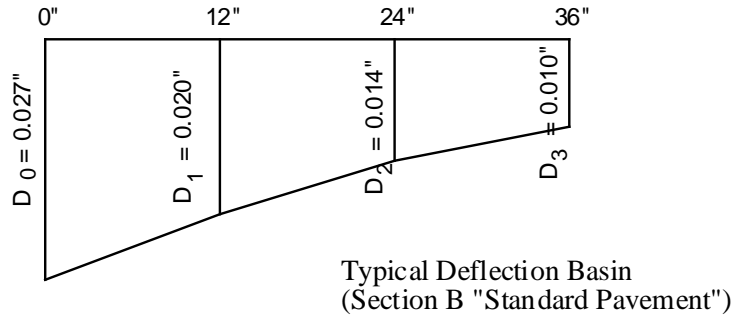


Figure A-2. Computing an Area Parameter

The basic Trapezoidal Rule is:

$$K = h \left(\frac{1}{2}y_0 + y_1 + y_2 + \frac{1}{2}y_3 \right)$$

where K = any planar area,
 y_0 = initial chord,
 y_1, y_2 = immediate chords,
 y_3 = last chord, and
 h = common distance between chords.

Thus, to estimate the area of a deflected basin using $D_0, D_1, D_2,$ and $D_3,$ and $h = 6$ inches, then:

$$K = 6 (D_0 + 2D_1 + 2D_2 + D_3)$$

Further, normalize by dividing by D_0 :

$$\text{Area} = \frac{6}{D_0} (D_0 + 2D_1 + 2D_2 + D_3) \quad \text{or} \quad \text{Area} = 6 \left(1 + \frac{2D_1}{D_0} + \frac{2D_2}{D_0} + \frac{D_3}{D_0} \right)$$

Thus, since we normalized by D_0 , the Area Parameter's unit of measure is inches (or mm) not in^2 or mm^2 as one might expect.

The maximum value for Area is 36.0 inches and occurs when all four deflection measurements are equal (not likely to actually occur) as follows:

$$\text{If, } D_0 = D_1 = D_2 = D_3$$

$$\text{Then, Area} = 6(1 + 2 + 2 + 1) = 36.0 \text{ inches}$$

For all four deflection measurements to be equal (or nearly equal) would indicate an extremely stiff pavement system (like portland cement concrete slabs or thick, full-depth HMA.)

The minimum Area value should be no less than 11.1 inches.

This value can be calculated for a one-layer system which is analogous to testing (or deflecting) the top of the subgrade (i.e., no pavement structure). Using appropriate equations, the ratios of

$$\frac{D_1}{D_0}, \frac{D_2}{D_0}, \frac{D_3}{D_0}$$

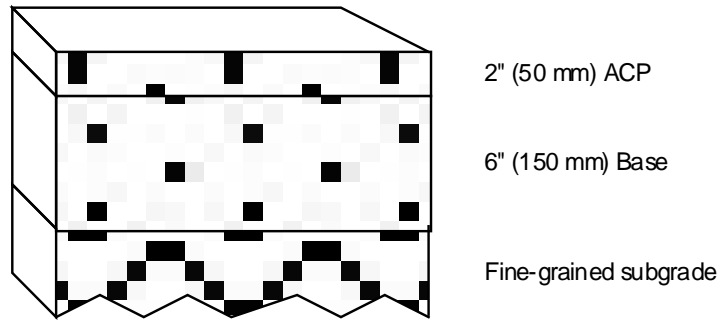
always result in 0.26, 0.125, and 0.083, respectively. Putting these ratios in the Area equation results in

$$\text{Area} = 6(1 + 2(0.26) + 2(0.125) + 0.083) = 11.1 \text{ inches}$$

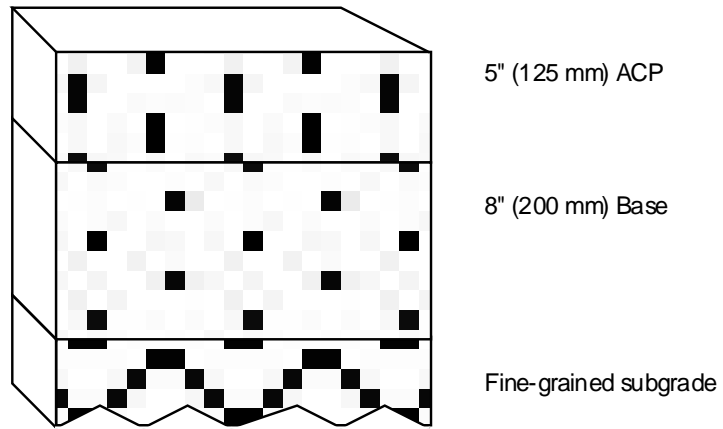
Further, this value of Area suggests that the elastic moduli of any pavement system would all be equal (e.g., $E_1 = E_2 = E_3 = \dots$). This is highly unlikely for actual, in-service pavement structures. Low area values suggest that the pavement structure is not much different from the underlying subgrade material (this is not always a bad thing if the subgrade is extremely stiff — which doesn't occur very often).

Typical Area values were computed for pavement Sections A, B, and C (refer to Figure A-3) and are shown in Table A-2 (along with the calculated surface deflections (D_0, D_1, D_2, D_3)). The following provides a general guide in the use of Area values obtained from FWD pavement surface deflections.

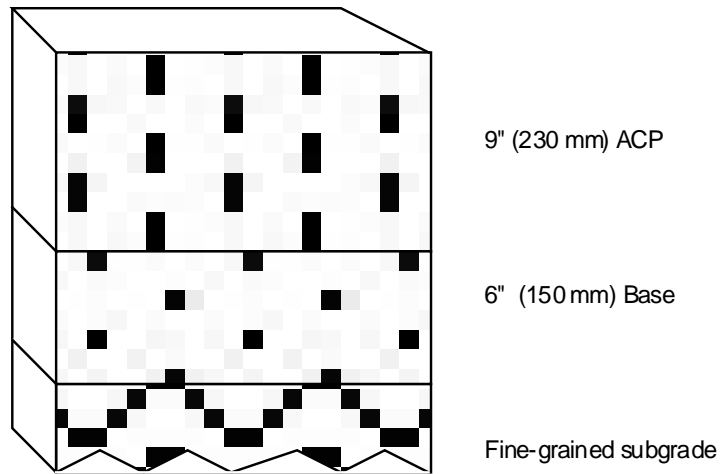
Pavement	Area	
	(inch)	(mm)
PCCP	24-33	610-840
"Sound" PCC*	29-32	740-810
Thick HMA (≥ 0.35 feet)	21-30	530-760
Thin HMA (< 0.35 feet)	16-21	410-530
BST flexible pavement (relatively thin structure)	15-17	380-430
Weak BST	12-15	300-380



Section A (Thin Thickness Section)



Section B (Medium Thickness Section)



Section C (Thick Section)

Figure A-3. "Typical" Pavement Sections

Table A-2. Estimates of Area from Pavement Sections — Cases A, B, and C

Pavement Cases	Pavement Surface Deflections, inches				Area	
	D ₀	D ₁	D ₂	D ₃	(inch)	(mm)
Standard Pavement						
Section A (thin)	0.048	0.026	0.014	0.009	17.1	(434)
Section B (med)	0.027	0.020	0.014	0.010	23.3	(592)
Section C (thick)	0.018	0.015	0.012	0.009	27.0	(686)
Stabilize Subgrade						
Section A (thin)	0.036	0.020	0.013	0.009	18.5	(470)
Section B (med)	0.023	0.017	0.012	0.009	23.5	(597)
Section C (thick)	0.016	0.013	0.011	0.009	27.4	(696)
Asphalt Treated Base						
Section A (thin)	0.021	0.018	0.013	0.010	26.6	(676)
Section B (med)	0.014	0.012	0.010	0.009	28.7	(729)
Section C (thick)	0.012	0.011	0.009	0.008	30.0	(762)
Moisture Sensitivity						
Section A (thin)	0.053	0.026	0.014	0.009	16.1	(409)
Section B (med)	0.033	0.022	0.014	0.009	20.7	(526)
Section C (thick)	0.024	0.018	0.013	0.010	24.0	(610)

Table A-3. Trends of D₀ and Area Values

FWD Based Parameter		Generalized Conclusions *
Area	Maximum Surface Deflection (D ₀)	
Low	Low	Weak structure, strong subgrade
Low	High	Weak structure, weak subgrade
High	Low	Strong structure, strong subgrade
High	High	Strong structure, weak subgrade

* Naturally, exceptions can occur

Appendix B – Moduli Seasonal Variation

UNSTABILIZED MODULI

Based on FWD deflections obtained over a three-year period (1985 to 1987), the ratio of the moduli for the different seasons was estimated. These initial estimates are shown in Table C-1.

The data in Table C-1 suggest a greater variation in the base course (seasonally) than the subgrade. Clearly, this phenomenon can be quite site-specific. As such, the ratios are only, at best, "rules of thumb."

For dense graded base materials, numerous sources have suggested that moisture levels exceeding 85 percent of saturation can result in significant moduli reductions.

SEASONAL TEMPERATURES

Seasonal air temperatures are required inputs. These temperatures are used to adjust the AC moduli seasonally. These mean monthly air temperatures (MMAT) are converted to mean monthly pavement temperatures (MMPT) by use of the following equation:

$$\text{MMPT} = \text{MMAT} \left(1 + \left(\frac{1}{z + 4} \right) \right) - \left(\frac{34}{z + 4} \right) + 6$$

where MMPT = mean monthly pavement temperature (°F),
 MMAT = mean monthly air temperature (°F), and
 z = depth below pavement surface (inch).

For example, if the MMAT = 65 °F and z = 3 inch, then

$$\begin{aligned} &= (65) \left(1 + \left(\frac{1}{3 + 4} \right) \right) - \left(\frac{34}{3 + 4} \right) + 6 \\ &= 75.4 \text{ °F} \end{aligned}$$

Table C-1. Design Moduli Ratios for Western and Eastern Washington Base Course and Subgrade Materials¹

Region	Seasonal Period				
	Spring	Summer	Fall	Winter	
Western Washington	Climate:	Cool/Wet	Warm/Dry	Cool/Damp	Cool/Wet
	Months:	March April May	June July August September	October November	December January February
	Base	0.85	1.00	0.90	0.75
	Subgrade	0.85	1.00	0.90	0.85
Eastern Washington	Climate:	Thaw	Hot/Dry	Cool/Dry	Freeze
	Months:	February March April May	June July August September	October November December	January
	Base	0.65	1.00	0.90	1.10
	Subgrade	0.90	1.00	0.90	1.10

¹Design moduli ratios are appropriate for use if stress sensitive moduli relationships are not used. If stress sensitive moduli relationships are used (e.g., $E = k_1 \theta^{k_2}$), then use of these ratios may overestimate seasonal effects.