Falling Weight Deflectometer (FWD) Testing and Analysis Guidelines Volume I

Publication No. FHWA-FLH-07-001 February 2007

U.S. Department of Transportation
Federal Highway Administration

Federal Lands Highway
Commitment to Excellence

Federal Lands Highway Division
400 7th Street, Southwest, Room 6311
Washington, DC 20590

FOREWORD

The Federal Lands Highway (FLH) promotes development and deployment of applied research and technology applicable to solving transportation related issues on Federal Lands. The FLH provides technology delivery, innovative solutions, recommended best practices, and related information and knowledge sharing to Federal agencies, Tribal governments, and other offices within the FHWA.

The objective of this study was to produce a guide for project development and design personnel that clearly defined Falling Weight Deflectometer (FWD) testing requirements, data analysis approach and reporting requirements.

The study included a review of backcalculation computer programs, a review of prominent State DOT data collection and analysis procedures, as well as a review of the current FLH FWD testing and analysis approach. Based on the information collected and through consultation with a FLH technical working group (TWG), recommendations for a best practice FWD testing and analysis procedure were made. The guidelines developed will better assure that FLH collects quality FWD data and that the data is appropriately analyzed.

The contributions and cooperation of the CFLHD personnel is gratefully acknowledged.

Butch Wlaschin, P.E., Director of Program Delivery
Federal Highway Administration
Federal Lands Highway Division

Notice

Quality Assurance Statement

Technical Report Documentation Page

1. Report No. FHWA-FLH-07-001	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle *Falling Weight Deflectometer (FWD) Testing and Analysis Guidelines Volume I (U.S. Customary Units Version)*		5. Report Date February 2007 6. Performing Organization Code
7. Author(s) P.N. Schmalzer, G.R. Rada, J.S. Miller		8. Performing Organization Report No.
9. Performing Organization Name and Address MACTEC Engineering and Consulting, Inc. 1575 Delucchi Lane, Suite 201 Reno, NV, 89502		10. Work Unit No. (TRAIS) 11. Contract or Grant No. DTFH68-05-P-00118
12. Sponsoring Agency Name and Address Federal Highway Administration Federal Lands Highway Division 400 7th Street, Southwest, Room 6311 Washington, DC 20590		13. Type of Report and Period Covered Final Report, October 2005 – February 2007 14. Sponsoring Agency Code HFL-1

15. Supplementary Notes

COTR: Mike Voth, FHWA-FLH. Technical Working Group: Chris Chang, FHWA-EFLHD, Steve Deppmeir, FHWA-CFLHD, Gary Evans, FHWA-WFLHD. This project was funded as a FLH functional discipline leader (FDL) initiative.

16. Abstract

This report contains guidelines for the collection and analysis of FWD data. Background information is provided on the various types of FWD equipment and important components. Information on the various types of FWD analysis procedures is also provided, including: AASHTO 1993 Guide for the Design of Pavement Structures AC and PCC analysis procedures, layered-elastic backcalculation, non-linear backcalculation, load transfer efficiency, void detection, depth to hard bottom estimation and temperature correction techniques.

This report includes a field data collection procedure, with requirements for equipment capabilities, deflection sensor spacing, drop sequences and test point spacings. An optional procedure is provided for the collection of sub-surface temperature measurements. Recommendations are given for the use of field data QC checks. Guidelines are also included for the collection of layer thickness data.

This report includes an FWD data analysis procedure, using the MODTAG program. This procedure includes data QA checks, sub-sectioning and layered-elastic backcalculation. Analysis using the AASHTO 1993 Guide for the Design of Pavement Structures methods is discussed as an alternate procedure. Guidelines are provided for reporting analysis results.

17. Key Words **FALLING WEIGHT DEFLECTOMETER, MODTAG, BACKCALCUALTION, MODULUS, SURFACE DEFLECTIONS**	18. Distribution Statement No restriction. This document is available to the public from the sponsoring agency at the website http://www.cflhd.gov.		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 74	22. Price

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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List of Acronyms and Symbols

AASHTO	-	American Association of State Highway and Transportation Officials
AC	-	asphalt concrete
AGDPS	-	AAHSTO Guide for the Design of Pavement Structures, 1993 edition
ASTM	-	American Society for Testing and Materials
BST	-	bituminous surface treatment
C	-	subgrade resilient modulus correction factor
CRCP	-	continuously-reinforced concrete pavement
DOT	-	department of transportation
DMI	-	distance measurement instrument
ESAL	-	equivalent single axle load
E_p	-	effective pavement modulus
FDR	-	full depth reclamation
FHWA	-	Federal Highway Administration
FLH	-	Federal Lands Highway
FWD	-	falling weight deflectometer
GPR	-	ground penetrating radar
HWD	-	heavy weight deflectometer
JA	-	joint approach
JCP	-	jointed concrete pavement
JL	-	joint leave
k	-	subgrade support value
LTE	-	load transfer efficiency
LTPP	-	Long Term Pavement Performance Program
LVDT	-	linear variable displacement transducer
LWD	-	light weight deflectometer
MAAT	-	mean annual air temperature
MEPDG	-	mechanistic-empirical pavement design guide developed under NCHRP project 1-37A
ML	-	mid lane
M_r	-	Resilient Modulus
NCHRP	-	National Cooperative Highway Research Program
OWP	-	outer wheel path
PCC	-	portland cement concrete
PDDX	-	pavement deflection data exchange
RMSE	-	root mean squared error
SN_{eff}	-	effective structural number

1 INTRODUCTION

This report contains guidelines for the collection and analysis of Falling Weight Deflectometer (FWD) data for use on Federal Highway Administration (FHWA) Federal Lands Highway (FLH) projects. Its purpose is to ensure that the data and analysis results are consistent, high quality and responsive to the needs of FLH pavement engineers. In order to provide the context necessary to understand the guidelines, this document also contains background information on FWD equipment and the theory of FWD data analysis. Supporting documentation collected during the development of the guidelines is contained in Volume II.

These guidelines require the use of the MODTAG computer program. MODTAG was developed by the Virginia Department of Transportation (VDOT), and is available for free. It may be obtained from VDOT, Cornell University or FLH. MODTAG is distributed along with a User's Manual that contains screenshots and step-by-step instructions.

1.1 Pavement Deflection Testing

An FWD is a device designed to measure the deflection response of a pavement structure to an imposed load. This deflection response can be used for a variety of purposes, including the following:

- Determination of structural capacity of pavement
- Determination of pavement layer elastic moduli
- Void detection on Portland Cement Concrete (PCC) pavements
- Load transfer efficiency of PCC pavements
- Delineation of pavement sections into areas with consistent structural response
- Quality control/quality assurance of pavement construction

The information gained from the analysis of pavement deflection data can be used as an input to the pavement design process, a network-level pavement management system, or pavement research, such as calibration Mechanistic-Empirical Pavement Design Guide (MEPDG) developed under NCHRP 1-37A.

The load pulse generated by an FWD is intended to simulate the load pulse generated by a moving vehicle. An FWD generates this load pulse by dropping a large weight from a specified height. This load causes the pavement surface to deform, and the FWD measures this deformation at several discrete points. The load and deformation data collected by the FWD can be used to calculate the stiffness or stiffness-related parameters of the pavement structure. The deflection versus radial distance plot generated from FWD data is commonly known as a deflection bowl or deflection basin. An example of a deflection basin is shown in Figure 1.

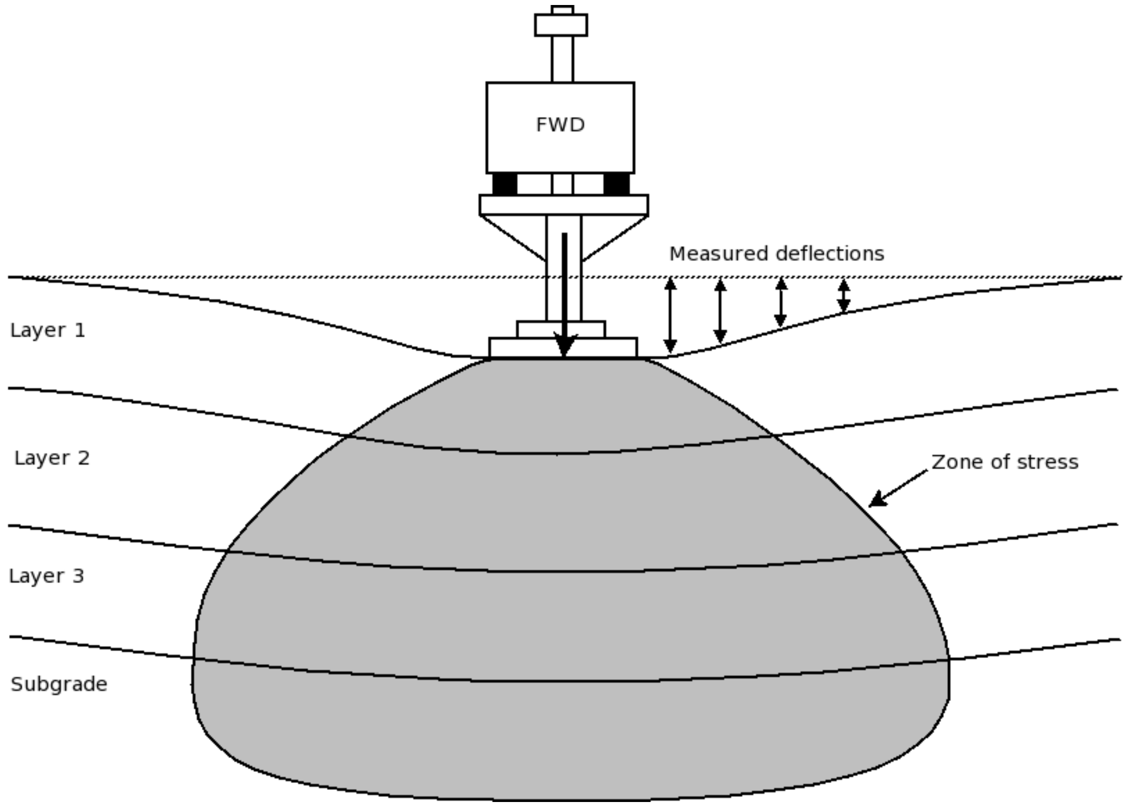

Figure 1. Schematic of FWD Test - Deflection Basin and Zone of Stress

Note that in this figure the full deflection basin is shown, while most FWDs just measure half of the deflection basin - either that portion in front of or behind the load plate.

FWDs are one of several types of pavement deflection testing equipment. The first type of deflection testing equipment in widespread use was the Benkleman Beam. The Benkleman Beam directly measures pavement deflections by use of a long lever arm. The pivot point of the lever is assumed to be outside the deflection bowl. Loading was provided by a heavy vehicle, typically a two-axle dump truck. Benkleman Beams have been almost entirely superceded in the United States by other types of deflection testing equipment, due in part to the high labor requirement and slow rate of data collection. However, several pavement design procedures based on Benkleman Beam data are still in use and correlation factors between Benkleman Beam data and FWD data have been developed.

Dynamic or vibratory deflectometers are another type of deflection testing equipment. The most common type of dynamic deflectometer is the Dynaflect. Most dynamic deflectometers have limited load ranges: Dynaflects produce a peak-to-peak load of 1000 pounds, while FWDs are typically capable of producing loads up to at least 20,000 lbs. There are some highly-specialized dynamic deflectometers built on heavy vehicle chassis that are capable of much higher loading.

However, the primary difference between dynamic deflectometers and FWDs is that the former imparts a sinusoidal load to the pavement while the latter imparts a single haversine-shaped load pulse. Figure 2 shows an idealized load vs. time plot for both a dynamic deflectometer (left) and an FWD (right).

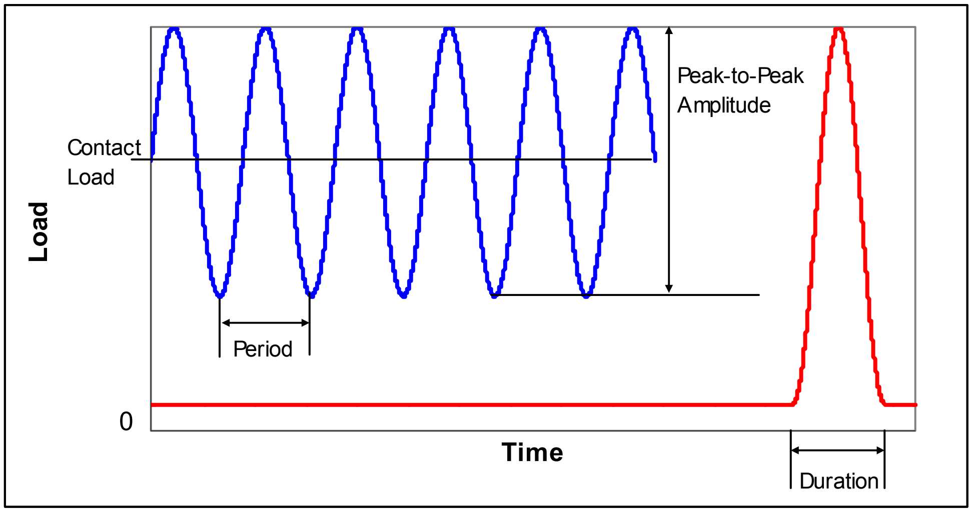

Figure 2. Load vs. Time Plot for a Dynamic Deflectometer and an FWD

As shown in Figure 2, the loading imparted by a dynamic deflectometer on the pavement can be characterized by a contact load, peak-to-peak amplitude and period, which is the inverse of frequency. As the dynamic deflectometer can only provide a downward force (i.e. it can not pull up on the pavement), the contact load is by necessity greater than one half the amplitude.

The loading imparted by an FWD is characterized by a contact load, peak load and duration. Unlike a dynamic deflectometer load, an FWD load pulse does not consist of a single frequency, as it is localized in the time domain. The magnitude of the contact load varies widely amongst FWD designs. FWDs do not typically report the contact load or the load duration, although the load duration can be computed from the raw time history data. The peak load reported by FWDs is relative to the contact load.

As the deflection response of most pavement materials is frequency-dependent, it is difficult to correlate the response of a pavement to loads with different frequency contents. In general, the deflection of a pavement system decreases as the loading frequency increases, resulting in a higher apparent stiffness. No FWD data analysis methodology in current production use in the US accounts for loading frequency, although there are several research-oriented dynamic backcalculation methods that do.

1.2 FWD Equipment

There are currently four major manufacturers of FWD equipment: Carl Bro, Dynatest, Foundation Mechanics Incorporated (sold under the JILS brand), and KUAB. The specifics of the equipment vary from manufacturer to manufacturer and model type to model type. Most FWDs are mounted on a trailer, but some are mounted directly on a vehicle. Some of the most common types of FWD in use in the United States are shown in Figures 3 through 6.

Figure 3. Carl Bro PRI 2100 FWD

Figure 4. Dynatest Model 8002 FWD

Figure 5. JILS Truck-Mounted FWD

Figure 6. Kuab 2m FWD

There are two major classes of FWDs based on load ranges. The first class, simply known as FWD, is capable of producing loads of at least 16,000 lbs. The second class, typically known as a heavy-weight deflectometer or HWD, is capable of producing loads in excess of 50,000 lbs. The higher loads produced by HWDs are useful for testing very stiff pavements such as those seen at major airfields; however, most HWDs are also capable of testing at the lower load levels typically used for highway pavements.

There is another class of equipment known as Lightweight FWDs (LWDs) or Portable FWDs that work on a similar principal to FWDs, but are hand-operated and restricted to very low load levels.

General features common to all FWDs are shown in Figure 7. The numbered components are further identified in the paragraphs following the figure.

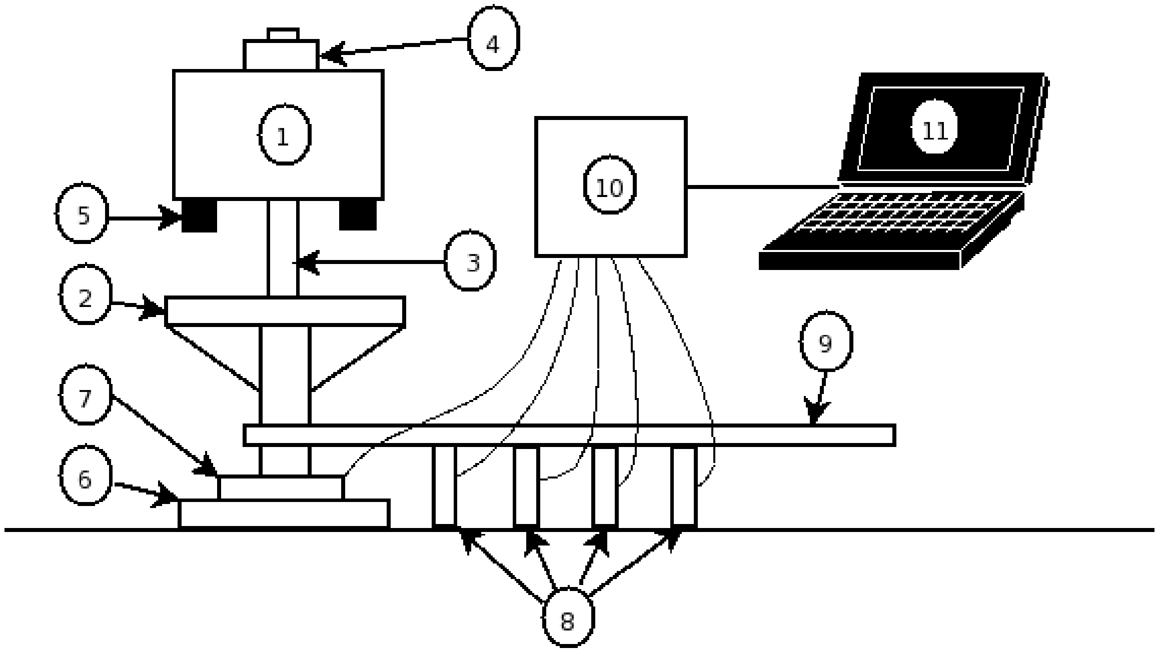

Figure 7. Generic Diagram of an FWD

1 - Weight Package: The weight package is a large mass that is raised and dropped to generate the load. The mass of the weight package can be adjusted by adding or removing steel blocks or plates.

2 - Strike Plate: The strike plate is a plate that arrests the weight package.

3 - Raise Weight Cylinder: The raise weight cylinder is a hydraulic cylinder that lifts the weight package. It lifts the weight package up from the strike plate to a certain height and then releases it. On Dynatest and Kuab FWDs, the height is determined by the location of a limited number of adjustable switches. On JILS FWDs, the height is determined indirectly by the time of the lift sequence. On Carl Bro FWDs, the height is measured directly.

4 - Catch: The catch attaches the raise weight cylinder to the weight package. It locks on to the weight package at the beginning of the raise weight sequence and releases the weight package at the end of the sequence. Carl Bro and Kuab FWDs use an electromagnetic catch. Dynatest FWDs use a mechanical catch. JILS FWDs do not have a catch; the raise weight cylinder and weight package are always coupled, and the drop is accomplished by opening a large dump valve in the raise weight cylinder.

5 - Buffers: Buffers are rubber springs that are affixed either to the bottom of the weight package or the top of the strike plate. These buffers modify the shape of the load pulse. For the same mass and drop height, a softer buffer will result in a longer duration load pulse with lower amplitude than a stiffer buffer. On most FWDs the number of buffers and buffer type can be modified. The stiffness of rubber buffers may change over time: The stiffness will increase with age due to oxidation, but will decrease during testing due to temperature and load history effects.

6 - Load Plate: The load plate is a circular plate that contacts the pavement surface and transmits the load pulse into the pavement. The load plate may be solid, or split into two or more segments that can rotate relative to each other. Segmented load plates can conform better to the pavement surface (especially a severely rutted surface) and provide a more uniform pressure distribution. The standard load plate on Carl Bro, Dynatest and KUAB FWDs is 11.8 inches (300 mm) in diameter, while JILS units have a 12.0 inch (305 mm) diameter load plate.

7 - Load Cell: The load cell is located between the strike plate and the load plate, and measures the load imparted to the pavement.

8 - Deflection Sensor: A deflection sensor is a transducer that is used to measure the deflection of the pavement surface in response to the applied load. On most FWDs the deflection sensors are geophones, but some KUAB FWDs use seismometers.

Geophones used on FWDs consist of a coil suspended around a cylindrical magnet. Motion of the coil relative to the magnet induces an electrical current in the coil proportional to its relative velocity. For this reason, geophones are sometimes called velocity transducers. Displacement can be determined from velocity through integration.

Seismometers have an inertial mass suspended within the housing. Motion of the inertial mass relative to the housing is directly measured using a linear variable displacement transducer (LVDT).

9 - Sensor bar: The sensor bar is a long bar that provides an attachment point for the deflection sensors. The sensor bar runs along a radial line from the load plate. On most FWDs this line runs from the load plate towards the front of the vehicle. On some KUAB FWDs and JILS truck-mounted FWDs, the sensor bar runs from the load plate towards the rear of the vehicle.

10 - Signal Processor: The signal processor is an electronic device that conditions, amplifies and digitizes the output from the FWD-mounted transducers, including the load cell and the deflection sensors. On most FWDs the signal processor is located in the tow vehicle, but in some cases it is located in the trailer.

11 - Data Collection Computer: The data collection computer is the computer that operates the FWD and collects, displays and stores data from the transducers.

1.3 FWD Data Analysis

The primary use of FWD data is to determine the stiffness or stiffness-related parameters of a pavement system. There have been many analysis procedures developed over the years, however these guidelines are limited to the procedure used in the American Association of State Highway and Transportation Officials (AASHTO) 1993 "Guide for Design of Pavement Structures" (AGDPS) and layered-elastic backcalculation as performed by the MODTAG computer program.[1,2]

Both procedures express the stiffness of pavement layers in units of pressure, typically as pounds per square inch (psi) in the US customary system or Pascals (pa) in the SI unit system. The stiffness of unbound pavement materials is typically referred to as the "resilient modulus" (M_r), while the stiffness of bound pavement materials is typical referred to as the "elastic modulus." In practice these terms are often used interchangeably.

Other uses of FWD data include load transfer efficiency between PCC slabs, detection of voids under PCC slabs, and estimation of the depth to hard bottom.

1.3.1 AGDPS Procedure

Deflection test data within the AGDPS is used almost exclusively for the rehabilitation of existing pavement structures. More specifically, deflection test data are used to characterize the effective structural capacity of the existing pavement structure for purposes of determining the required overlay thickness.

Although other options for characterizing the effective structural capacity of existing pavements are provided in the guide, such as visual surveys and remaining life, deflection testing is the preferred option. Furthermore, impulse-type deflection devices such as the FWD are recommended for purposes of generating the necessary deflection test data.

The specific procedure used to characterize the structural capacity of an existing pavement depends on the pavement type. For asphalt concrete (AC) pavements, the key outputs from the analysis of the deflection data are the design resilient modulus (M_R) of the subgrade and the effective structural number (SN_{eff}) of the pavement structure. For PCC pavements, the key analysis outputs are the effective static k-value of the foundation support, the elastic modulus (E) of the PCC slab and the joint load transfer coefficient (J). Composite pavements (AC overlay of PCC pavement) are treated the same as PCC pavements, but with additional steps to account for the presence and influence of the AC overlay.

A summary of the analysis procedure used for the design of AC overlays according to pavement type is provided next. Before this analysis procedure is discussed, it is important to emphasize some important issues relative to the analysis of deflection data within the AGDPS. First, the AGPDS assumes that the deflection data analyses are performed on uniform sections; i.e., lengths of pavements having similar subgrade soil, structure (layer types and thicknesses), traffic (loads and volumes), climate (moisture and temperature conditions) and conditions (distress and roughness), and therefore similar performance characteristics. Second, the various analyses are performed on the individual deflection test points and the average of the individual results is then used for determination of the required overlay thickness. And third, the analysis requires or assumes accurate pavement layer thickness data and, in the case of AC pavements, the temperature of the AC mix during deflection testing.

1.3.1.1 AC Pavements

The analysis procedure for AC pavements is based on a simplified version of the Boussinesq equation for deflection in an elastic half-space (Equation 1), as well as an assumption that the pavement system can be represented as two layers: a subgrade of infinite depth and a pavement having a total thickness D and an effective modulus (E_p) as illustrated in Figure 8. To simplify the Boussineq equation, it is further assumed that the Poisson's ratio for both the subgrade and pavement materials is 0.5.

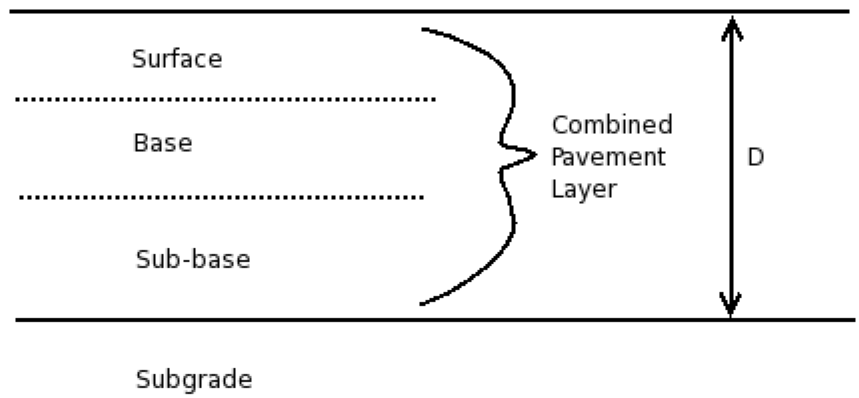

Figure 8. AGDPS Flexible Pavement Model

The first step in the analysis procedure is the backcalculation of the subgrade M_R value using Equation 1.

$$M_R = \left(\frac{0.24P}{d_r r} \right)$$

Figure 9. Equation 1.

where: M_R = backcalculated subgrade resilient modulus, psi
P = applied load, pounds
d_r = measured deflection at radial distance r, inches
r = radial distance at which the deflection is measured, inches

This equation for backcalculating the subgrade M_R is based on the observation that, at points sufficiently distant from the load center, the measured deflection is almost entirely due to deformation of the subgrade, and is also independent of the load radius; see Figure 1. The deflection used must be measured far enough away that it provides a good estimate of the subgrade M_R, but also close enough so that it is not too small to measure accurately. The minimum distance may be determined from Equation 2.

$$r \geq 0.7\sqrt{a^2 + \left(D\sqrt[3]{\frac{E_p}{M_R}}\right)^2}$$

Figure 10. Equation 2.

where:
- r = minimum sensor radius, inches
- a = load plate radius, inches
- D = total thickness of pavement layers above the subgrade, inches
- E_p = effective modulus of all pavement layers above subgrade, psi
- M_R = subgrade resilient modulus, psi

To arrive at the design M_R value, the backcalculated subgrade M_R from Equation 1 must be adjusted in order to make the resulting value consistent with value used to represent the AASHO road test subgrade. This is accomplished with Equation 3.

$$M_{R,design} = CM_R$$

Figure 11. Equation 3.

where:

- $M_{R,design}$ = design subgrade M_R value
- C = adjustment factor
- M_R = calculated subgrade M_R value (from Equation 1)

A value of C equal to 0.33 is recommended by the AGDPS unless there is the presence of a very stiff layer (e.g., bedrock) within about 15 feet of the top of the subgrade that may cause the backcalculated subgrade M_R value to be high. When such condition exists, a value less than 0.33 for C is warranted, but no guidance is provided in the AGDPS as to the value that should be used. The AGDPS recommends against using a value of C greater than 0.33.

In addition, the design subgrade M_R value must be representative of the effects of seasonal variations. Accordingly, a seasonal adjustment may be also made, when needed, in accordance with the procedures described in Part II, Section 2.3.1 of the AGDPS.

Once the backcalculated and design subgrade M_R values have been established, the next step in the analysis procedure is to estimate the effective structural number (SN_{eff}) of the pavement structure. Since both the maximum deflection and backcalculated (not design) subgrade M_R value have been computed, this is accomplished using a version of the

Boussineq deflection equation that has been tailored to the AGDPS design procedure, as shown in Equation 4.

$$d_0 = 1.5pa\left(\frac{1}{M_R\sqrt{1+\left(\frac{D}{a}\sqrt[3]{\frac{E_p}{M_R}}\right)^2}} + \frac{1-\frac{1}{\sqrt{1+\left(\frac{D}{a}\right)^2}}}{E_p}\right)$$

Figure 12. Equation 4.

where:
- d_o = deflection measured at the center of the load plate, inches
- p = load plate pressure, psi
- a = load plate radius, inches
- D = total thickness of pavement layers above the subgrade, inches
- M_R = backcalculated subgrade resilient modulus, psi (from Equation 1, without adjustment factor C or seasonal adjustments)
- E_p = effective modulus of all pavement layers above subgrade, psi.

Prior to using the above equation, it is important to remember that the measured maximum deflection (at the center of the load plate) must be adjusted to a standard temperature of 68°F. This is completed by means of a temperature adjustment factor, which is a function of the temperature of the AC mix during deflection testing and the total asphalt thickness. Two figures are provided in the AGDPS (on pages III-99 and III-100) for determining the temperature adjustment factor; the first one for AC pavements with granular or asphalt-treated bases and the other for AC pavements with cement- or pozzolanic-treated bases.

The final step in the analysis procedure is to determine the effective structural number (SN_{eff}) of the existing pavement, which is done using Equation 5.

$$SN_{eff} = 0.0045D \times \sqrt[3]{E_p}$$

Figure 13. Equation 5.

where:
- SN_{eff} = effective structural number of existing pavement
- D = total thickness of pavement layers above the subgrade, inches
- E_p = effective modulus of all pavement layers above subgrade, psi.

A figure is also provided in the AGDPS (on page L-25), which allows the user to determine the effective structural number (SN_{eff}) based on the total thickness of the pavement (D) and effective modulus of all pavement layers (E_p).

1.3.1.2 PCC Pavements

The analysis procedure for PCC pavements requires the characterization of the subgrade and base layers supporting the PCC slab by an effective k-value, the PCC slab in terms of its elastic modulus (E), and the joint load transfer coefficient (J). To accomplish this, Westergaard's deflection equation for a slab on a spring (dense liquid) has been adapted to the guide, as illustrated in Figure 14.

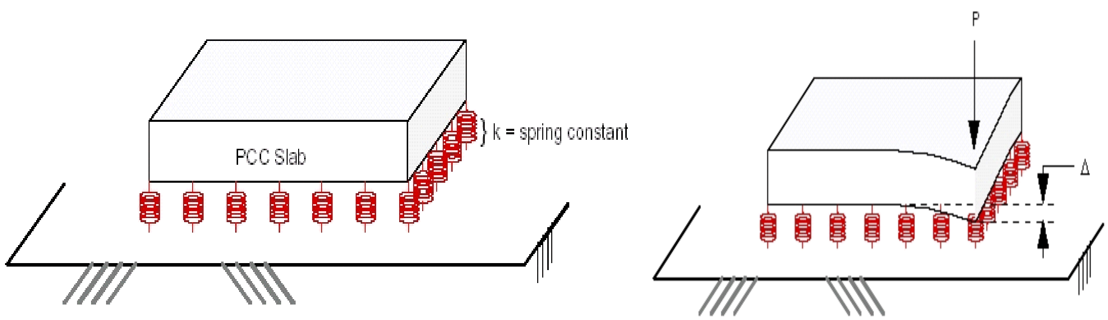

Figure 14. Relation of Load (P), Deflection (Δ) and Modulus of Subgrade Reaction (k) in Westergaard's Slab on Spring Model

Estimation of the effective k-value is accomplished by means of a direct calculation using the empirical AREA concept, which characterizes the measured deflection basin using either Equation 6 or 7.

$$AREA = 6\left(1 + 2\frac{d_{12}}{d_0} + 2\frac{d_{24}}{d_0} + \frac{d_{36}}{d_0}\right)$$

Figure 15. Equation 6.

$$AREA = 4 + 6\frac{d_8}{d_0} + 5\frac{d_{12}}{d_0} + 6\frac{d_{18}}{d_0} + 9\frac{d_{24}}{d_0} + 6\frac{d_{36}}{d_0}$$

Figure 16. Equation 7.

where:
- d_0 = deflection at center of load plate, inches
- d_8 = deflection at 8 inches from center of load plate, inches
- d_{12} = deflection at 12 inches from center of load plate, inches
- d_{18} = deflection at 18 inches from center of load plate, inches
- d_{24} = deflection at 24 inches from center of load plate, inches
- d_{36} = deflection at 36 inches from center of load plate, inches

Equation 6 is the original form of the AREA equation, and was developed when most FWDs only mounted seven deflection sensors. Equation 7 was developed to take advantage of the additional sensor data available on modern FWDs. AREA has a unit of length, rather than area, since each of the deflections is normalized with respect to d_0 (in order to remove the effects of different load levels and to restrict the range of values obtained), and typically ranges between 29 and 32 for sound PCC.

Using the measured maximum deflection (d_0) and the computed AREA, the effective dynamic k-value and the dense liquid radius of relative stiffness (ℓ_k) may be obtained using Westergaard's deflection equation as adapted by the AGDPS, as shown in Equations 8, 9 and 10.

$$\ell_k = \left[\frac{\ln\left(\frac{36 - AREA}{1812.279133}\right)}{-2.559340}\right]^{4.387009}$$

Figure 17. Equation 8.

$$k_d = \left(\frac{P}{8 d_0 \ell_k^2}\right)\left\{1 + \left(\frac{1}{2\pi}\right)\left[\ln\left(\frac{a}{2\ell_k}\right) + \gamma - 1.25\right]\left(\frac{a}{\ell_k}\right)^2\right\}$$

Figure 18. Equation 9.

$$\ell_k = \sqrt[4]{\frac{E_{pcc} D_{pcc}^3}{12(1 - \mu_{pcc}^3) k_d}}$$

Figure 19. Equation 10.

where:

- ℓ_k = dense liquid radius of relative stiffness, inches
- AREA = AREA calculated from measured deflections (equation 5)
- P = load, pounds
- d_0 = deflection at center of load plate, inches
- a = load plate radius, inches
- γ = Euler's constant, 0.57721566490
- E_{PCC} = PCC elastic modulus, psi
- D_{PCC} = PCC slab thickness, inches
- μ_{PCC} = PCC Poisson's ratio
- k_d = effective dynamic k-value, psi/inch

The AGDPS also provides alternative graphical solutions for these equations on pages L-15 through L-17.

As the rehabilitation procedure contained in the AGDPS is based on the static k-value, the effective dynamic k-value obtained from the deflection measurements must be converted as shown in Equation 11.

$$k_s = \frac{k_d}{2}$$

Figure 20. Equation 11.

where: k_s = effective static k-value
k_d = effective dynamic k-value

In addition, the effective static k-value must be representative of the effects of seasonal variations. Accordingly, a seasonal adjustment also may be made, when needed, in accordance with the procedures described in Part II, Section 2.3.1 of the AGPDS.

1.3.1.3 Composite Pavements

As indicated earlier, the analysis procedure for composite pavements (AC overlay on PCC pavement) is the same as that for PCC pavements, but the procedure includes additional steps to account for the presence and influence of the AC overlay.

Two methods for determining the elastic modulus of the AC overlay as a function of mix temperature are provided in the AGDPS. The first one makes use of the Asphalt Institute's AC modulus predictive equation, which is a function of the AC mix parameters, mix temperature and loading frequency; see Equations 4.5 and 4.6 on page L-18 of the AASHTO 1993 Guide. (Note: significant improvements to these Asphalt Institute equations have been made over the past decade based on new laboratory test results; the most recent version of this equation is contained in the MEPDG). The second method relies on laboratory repeated load indirect tension testing (ASTM D4123) of AC cores taken from the in-service composite pavement, which must be adjusted to the load frequency and temperature corresponding to the deflection test data.

Next, the compression of the AC overlay at the center of the load plate ($d_{0,\ compression}$) is estimated as a function of the existing AC overlay thickness and modulus; see Equation 4.8 on page L-18 of the AGDPS. The constants in this equation are a function of the bonding conditions between the AC overlay and PCC slab; i.e., bonded or un-bonded.

Finally, the estimated compression of the AC overlay ($d_{0,\ compression}$) is subtracted from the deflection under the load plate center (i.e., maximum deflection), and the resulting value ($d_{0,\ PCC}$) is then used as the d_0 value within the analysis procedure described earlier for PCC pavements. No corrections are made to the deflections measured at 12, 24 and 36 inches as the effects of the AC overlay on these measurements have been determined to be close to zero.

1.3.2 Layered-Elastic Backcalculation

The deflection data analysis procedures contained within the AGDPS and summarized in the previous section have been the most widely used procedures over the last decade. They are still widely used, but layered-elastic backcalculation techniques are being used more and more frequently to analyze deflection data. Furthermore, the usage of these techniques is expected to increase in the coming years as highway agencies throughout the country begin the calibration, validation and implementation of the MEPDG, which relies heavily on FWD deflection data for pavement rehabilitation designs.

The principal outcome from the layered-elastic backcalculation analysis is the elastic modulus of each layer in the pavement structure and subgrade soil, which is then used as input into the pavement evaluation or rehabilitation design process. Layered-elastic techniques, as implied by the name, are based on layered-elastic theory. As shown in Figure 21, the pavement system is modeled as a set of layers having a given elastic modulus (E), Poisson's ratio (μ) and thickness (t), except for the subgrade, which is assumed to have an infinite depth. All layers in the system are assumed to be homogeneous, isotropic and of infinite extent in the horizontal directions. In addition, the pavement deflections are considered to be independent of loading rate.

Clearly, these assumptions are violated in actual pavement structures, but that generally does not prevent the generation of reasonable results for use in pavement evaluation and rehabilitation design. This is especially true for AC surfaced pavements that have layers with decreasing strength and increasing thickness with depth.

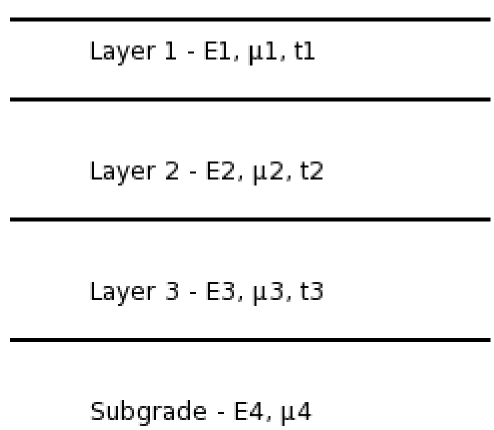

Figure 21. Layered-elastic Pavement Model

There is no accepted closed-form solution for computing individual layer moduli in a multi-layer system based on surface deflections. Instead, the analyst must first estimate the layer moduli. These estimated moduli are typically known as "seed moduli". Using these seed moduli, the surface deflections for the pavement structure can be computed using a layered-elastic analysis program. Then, the computed deflections and the measured deflections are compared and the moduli are adjusted based on that comparison. The process of adjusting moduli based on the comparison of measured to computed deflections is performed iteratively until some criteria are satisfied.

The choice of seed moduli can impact the backcalculation process in two ways. First of all, the closer the seed moduli are to the actual moduli, the fewer iterations are required to converge on a solution, and therefore processing time will be reduced. In addition, there may be more than one combination of layer moduli that results in a computed deflection basin similar to the measured deflection basin. Starting with seed moduli that are reasonable for the materials the layers are composed of makes it more likely that the solution found is the one that is wanted.

It is important to emphasize three **very critical points** with regards to the results generated by the layered-elastic backcalculation programs:

- The backcalculated layer moduli represent the "effective" or "equivalent" elastic modulus of the layers, which account for differences in stress states as well as discontinuities or anomalies such as variations in layer thickness, slippage between adjacent layers, cracks and the combination of similar materials into a single layer.

- The backcalculated results represent the "effective" or "equivalent" layer moduli at a very specific point in time, associated with certain temperature and moisture conditions. If the layer moduli are calculated based on deflection measurements taken a few hours or days later, those values are quite likely to be different as moisture contents and temperatures within the pavement may not be the same, hence layer characteristics and their response will change. The water table level, for example, may change throughout the year, and frost penetration and spring thaw will affect the deflection data and hence analysis results.

- There is not a unique solution. One of the most difficult questions to be answered is "how accurate are the layer moduli backcalculated from measured deflection basins?" This is an impossible question to answer conclusively for real deflection basins, but the reasonableness of the results can and should be established using engineering judgment, based on prior experience with similar materials.

In addition, it should be noted that the backcalculation process is highly sensitive to errors in the measured deflections and layer thicknesses. Irwin et al. evaluated the impact of these errors using a Monte Carlo approach.[3] The pavement structure used in their analysis is shown in Table 1.

Table 1. Pavement Structure Used for Error Analysis

Layer	Type	Modulus, psi	Poisson's Ratio	Thickness, inches
1	Asphalt Concrete	300,000	0.35	3
2	Base	45,000	0.40	6
3	Subbase	21,000	0.40	12
4	Subgrade	7,500	0.45	infinite

The deflection of this pavement structure due to a 10,000 pound load was computed using the CHEVRON layered-elastic computer program. Then 30 deflection basins with added random errors with a standard deviation of ±0.0768 mils were generated based on the "true" deflection basin. These deflection basins were then backcalculated using MODCOMP 2. The results are summarized in Table 2.

Table 2. Effect of Random Deflection Measurement Errors on Backcalculated Moduli

Layer	Backcalculated modulus, psi			
	Mean	**Maximum**	**Minimum**	**Standard Deviation**
1	306,000	426,000	196,000	50,000
2	44,600	59,900	32,300	5,900
3	21,300	25,000	18,00	1,400
4	7,490	7,670	7,390	90

Irwin et al. also performed backcalculation using the "true" deflection basin, but varying the layer thicknesses randomly. In this analysis, the standard deviation of the thickness Layer 1 was ±0.25 inches, that of Layer 2 was ±1 inches and that of Layer 3 was ±1.5 inches. The results for 30 trials with MODCOMP 2 are shown in Table 3.

Table 3. Effect of Random Layer Thickness Measurement Errors on Backcalculated Moduli

Layer	Backcalculated modulus, psi			
	Mean	**Maximum**	**Minimum**	**Standard Deviation**
1	311,000	410,000	236,000	38,000
2	46,000	53,700	39,800	3,700
3	20,900	26,400	15,800	7,350
4	7,500	7,670	7,350	70

Note that the effect of errors in both deflections and layer thicknesses decreases with increasing depth in the pavement structure.

These guidelines require the use of the MODTAG computer program, which was developed by the Virginia Department of Transportation, for FWD data analysis. MODTAG uses the MODCOMP computer program, which was developed by Cornell University, to perform backcalculation. MODCOMP uses CHEVLAY2, which was originally developed by the Chevron Corporation and modified by Cornell University, to perform layered-elastic calculations.

To perform backcalculation, the user inputs information about the pavement structure including thickness, moduli and Poisson's ratio for each layer into MODTAG. Then, MODTAG automatically sends that information along with the FWD data to MODCOMP to perform the actual analysis.

MODCOMP first sends the FWD load, layer thickness, seed moduli and Poisson's ratio information to the CHEVLAY2 layered-elastic program which returns the computed deflection basin. MODCOMP automatically adjusts the layer moduli based on the difference between the computed and measured deflections until one of three criteria are satisfied:

- The maximum number of iterations is exceeded. By default this is set to 15, but it is adjustable from within MODTAG.
- The rate of convergence of all moduli is less than 1.5%. This criterion is satisfied if the difference between all moduli computed in iteration *i* and iteration *i + 1* is less than 1.5%. This criterion is not adjustable from within MODTAG
- The deflection fit tolerance is less than 1%. This criterion is satisfied if the difference between the measured and computed deflections is less than 1% for all sensors. This criterion is not adjustable from within MODTAG.

For each deflection basin processed, MODTAG will report the computed layer moduli, root-mean-square error (RMSE) and any error codes. The RMSE is computed as shown in Equation 12.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{d_{i,c} - d_{i,m}}{d_{i,m}}\right)^2} \times 100$$

Figure 22. Equation 12.

where: RMSE = root mean squared error
n = number of deflection sensors
$d_{i,m}$ = measured deflection at location i
$d_{i,c}$ = computed deflection at location i

MODTAG is also capable of performing non-linear backcalculation. As with linear-elastic backcalculation, non-linear backcalculation is performed using MODCOMP, which in turn uses CHEVLAY2 as the layered elastic calculation engine.

Linear elastic models assume that the modulus of a material is independent of its stress level. Non-linear elastic models express modulus as a function of the material's stress state. MODCOMP includes nine different stress-dependency models each of which includes one or more stress parameters and one or more constants. The purpose of non-linear backcalculation is to determine the value of those constants.

Performing non-linear backcalculation using MODTAG requires deflection data for four different load levels at each location.

1.3.3 Non-Linear Backcalculation

The resilient modulus of unbound materials is dependent on their stress state. Figures 23 and 24 are example resilient modulus versus stress state plots for a fine grained and a coarse grained material. The data for these plots was collected from laboratory repeated load triaxial testing, using the LTPP P46 test protocol.

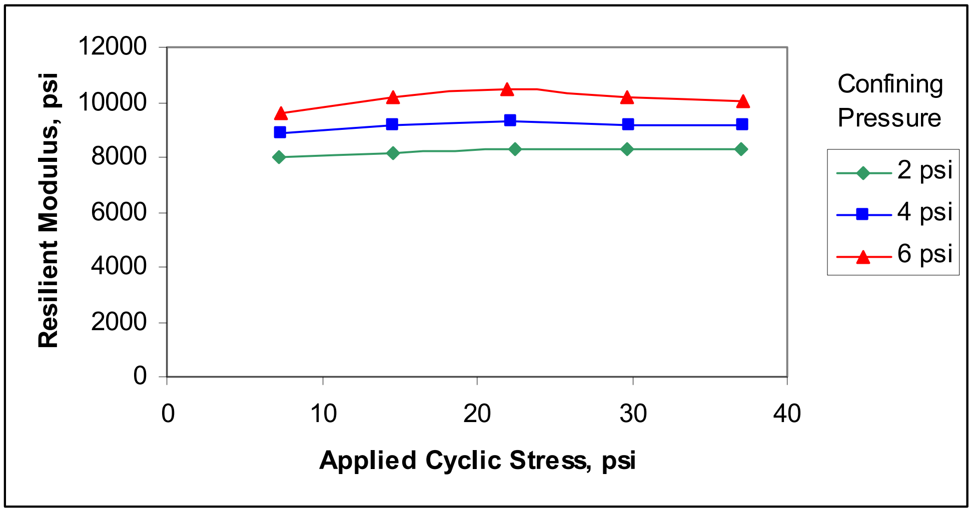

Figure 23. Resilient Modulus vs. Cyclic Stress for a Fine Grained Material

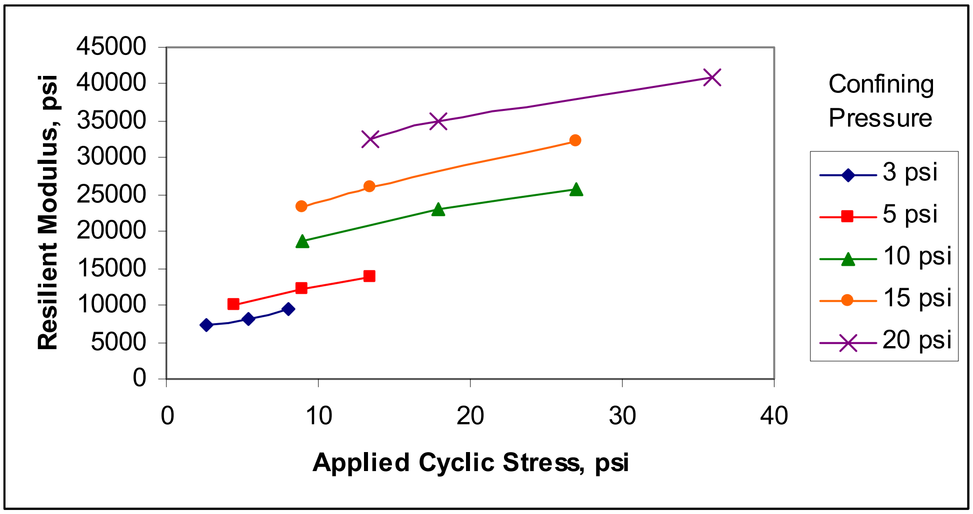

Figure 24. Resilient Modulus vs. Cyclic Stress for a Coarse Grained Material

The resilient modulus backcalculated from FWD test data is specific to the stress state of the material at the time of the test. That stress state is a combination of the dynamic stresses generated by the FWD test and the static, in-situ stresses due to overburden and load history. Therefore, a backcalculated resilient modulus may not be representative of the behavior of that material in response to a different load level.

In the AGDPS, traffic loading is normalized to 18 kip equivalent single axle loads (ESALs). Therefore, the resilient modulus due to a 9 kip FWD load (i.e. half an ESAL) is typically used with the AGDPS and non-linear material response is ignored. For pavement design procedures such as the MEPDG that do not normalize traffic loads a different approach is required.

The stress sensitivity of a material can be characterized by a constitutive equation that expresses the resilient modulus as a function of one or more stress parameters. The bulk stress model shown in Equation 13 has been commonly used for coarse-grained materials.[4]

$$M_r = k_1 \theta^{k_2}$$

Figure 25. Equation 13.

where: M_r = resilient modulus, psi
θ = bulk stress (the sum of the principal stresses), psi
k_1, k_2 = regression parameters.

Fine-grained materials are often characterized using the deviator stress model shown in Equation 14.[4]

$$M_r = k_1 \sigma_d^{\,k_2}$$

Figure 26. Equation 14.

where: M_r = resilient modulus, psi
σ_d = deviator stress, psi
k_1, k_2 = regression parameters.

The MEPDG uses a single constitutive model for both fine-grained and coarse-grained materials as shown in Equation 15.[5]

$$M_r = k_1 p_a \left(\frac{\theta}{p_a} \right)^{k_2} \left(\frac{\tau_{oct}}{p_a} + 1 \right)^{k_3}$$

Figure 27. Equation 15.

where: M_r = resilient modulus, psi
p_a = atmospheric pressure, psi
θ = bulk stress, psi
τ_{oct} = octahedral shear stress, psi
k_1, k_2, k_3 = regression parameters

In this equation atmospheric pressure is used to nondimensionalize the exponentiated quantities. This allows k_1, k_2, k_3 to be independent of the unit system chosen.

Non-linear backcalculation is the process of backcalculating the regression parameters in a constitutive model. In linear backcalculation the resilient modulus is the only unknown value for each layer. In non-linear backcalculation there are three or more unknowns per layer, including at least two regression coefficients as well as the appropriate stress parameter. In addition, the overburden stress on each layer and the at-rest ratio of horizontal to vertical stress must be input as known quantities.

MODTAG can perform non-linear backcalculation provided that at FWD data has been collected with at least four load levels per location. Backcalculation is performed for each load level as with the linear method, except that CHEVLAY2 also reports the relevant stress parameters for the final iteration. Knowing the modulus value and stress parameters at each of four load levels, the constants in the stress-dependency model are computed through regression.

MODTAG, through MODCOMP, includes nine constitutive models; however, none are in the exact form of the models presented in Equations 13, 14 and 15. The nearest equivalents are shown in Equations 16, 17 and 18.

$$M_r = k_1 \times EXP(k_2\theta)$$

Figure 28. Equation 16.

$$M_r = k_1 \times EXP(k_2\sigma_d)$$

Figure 29. Equation 17.

$$M_r = k_1\theta^{k_2}\tau_{oct}^{k_3}$$

Figure 30. Equation 18.

Equations 16 and 17 are semi-log versions of Equations 13 and 14, respectively. Equation 18 is a non-normalized version of Equation 15. While these equations are similar, the regression coefficients are not directly comparable. Further information on non-linear backcalculation in MODCOMP, including constitutive models not discussed here, can be found in the MODCOMP user's manual, which is distributed with MODTAG.

1.3.4 Load Transfer Efficiency

Load transfer efficiency (LTE) is a measure of how well a joint between two PCC slabs transmits shear. It is measured by placing the FWD load plate tangent to the joint and measuring the deflections on either side of the joint in response to a load pulse. An excellent joint will have no difference in deflections on either side of the joint, as shown in Figure 31. Poorly performing joints will show a large difference in deflection, as shown in Figure 32.

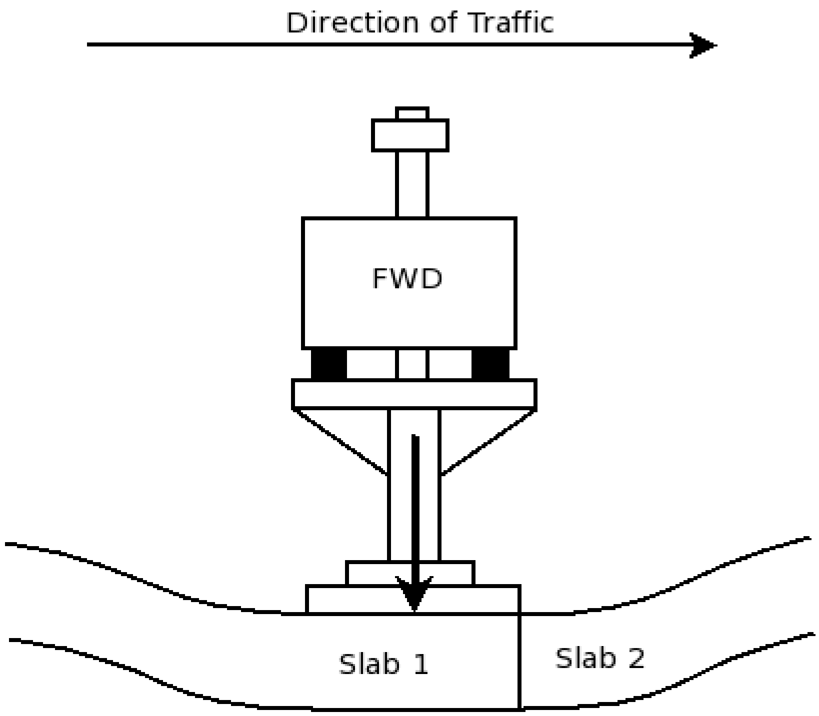

Figure 31. Example of Good Load Transfer

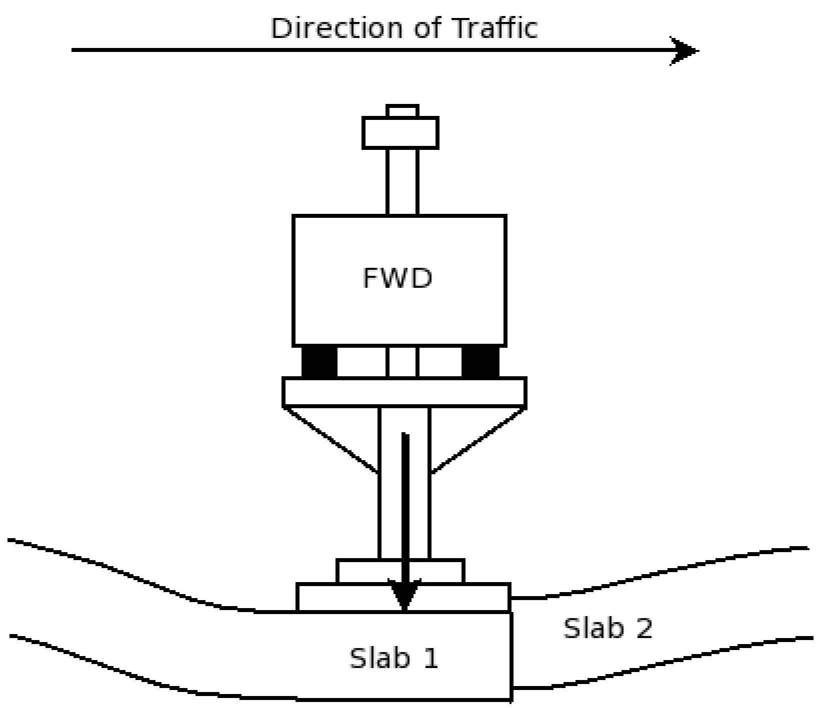

Figure 32. Example of Poor Load Transfer

In contrast to backcalculation, LTE is easy to calculate. LTE can be calculated using Equation 19.

$$LTE = B\frac{d_{ul}}{d_l} \times 100$$

Figure 33. Equation 19.

where:
LTE = deflection load transfer, percent
d_{ul} = unloaded side deflection, inches
d_l = loaded side deflection, inches
B = slab bending correction factor

For FWD testing, d_l is the center deflection sensor and d_{ul} may be the sensor at either 12 inches or -12 inches depending on the geometry of the FWD and which side of the joint the test was performed on. Relative to a joint, the approach slab is the one in the upstream direction of traffic. The leave slab is the one in the downstream direction of traffic. In Figures 31 and 32, slab 1 is the approach slab and slab 2 is the leave slab. A joint approach (JA) test is performed with the load plate located on the approach slab. A joint leave (JL) test is performed with the load plate located on the leave slab.

The slab correction factor (B) is necessary because the deflection d_0 and d_{12}, measured 12 inches part, would not be equal even if measured in the interior of the slab. Typical B values range from 1.05 to 1.15. B can be calculated from the ratio of d_0 and d_{12} measured at a mid-slab location, using Equation 20 B values should be calculated based on data collected as close to the joint as possible, preferably on the same slab.

$$B = \frac{d_0}{d_{12}}$$

Figure 34. Equation 20.

where:
B = slab bending correction factor
d_0 = deflection at the center of the load plate, inches
d_{12} = deflection at 12 inches from the load plate, inches

1.3.5 Void Detection

FWD data may also be used to detect voids under the corner of a PCC slab. The void detection procedure used by MODTAG is based on the premise that a load vs. deflection plot for a single location should be roughly linear with an x-intercept of zero. If the intercept is significantly different from zero, that is an indication that a void may be present. An example plot is shown in Figure 35.

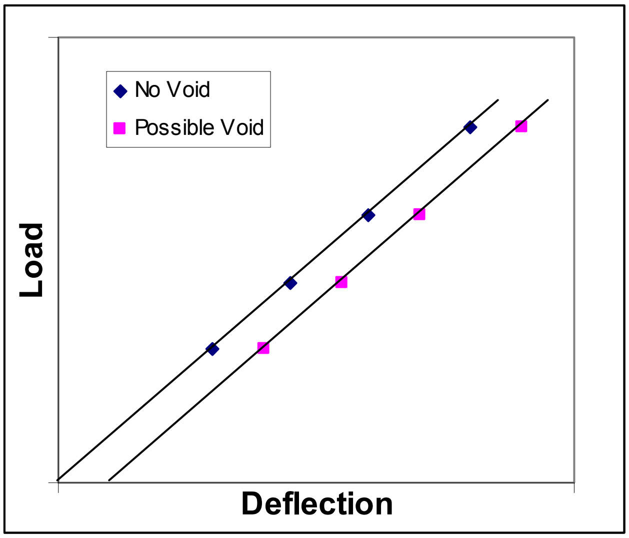

Figure 35: Void Detection Plot

MODTAG uses an x-intercept threshold of 2 mils for void detection. If the x-intercept is greater than 2 mils there is a high probability there is a void under the corner of the tested slab.

1.3.6 Depth to Hard Bottom Estimation

FWD data can be used to estimate the depth from the surface to bedrock or some other stiff layer. This estimation can then be used when modeling the pavement structure during backcalculation.

The procedure used by MODTAG is to plot measured deflection versus the inverse of deflection sensor offset (1/r). This plot typically has a linear section followed by a non-linear concave-down section at high values of 1/r. Sometimes there is also a non-linear concave-up section to the plot at low values of 1/r. The linear portion of the plot is extrapolated down to the X-axis, and the inverse of this intercept, multiplied by 1.2, is taken as an estimate of the depth to the hard bottom. An example plot is shown in Figure 36. This method requires at least three and preferably four deflection sensors located at distances greater than or equal to 36 inches from the load plate.

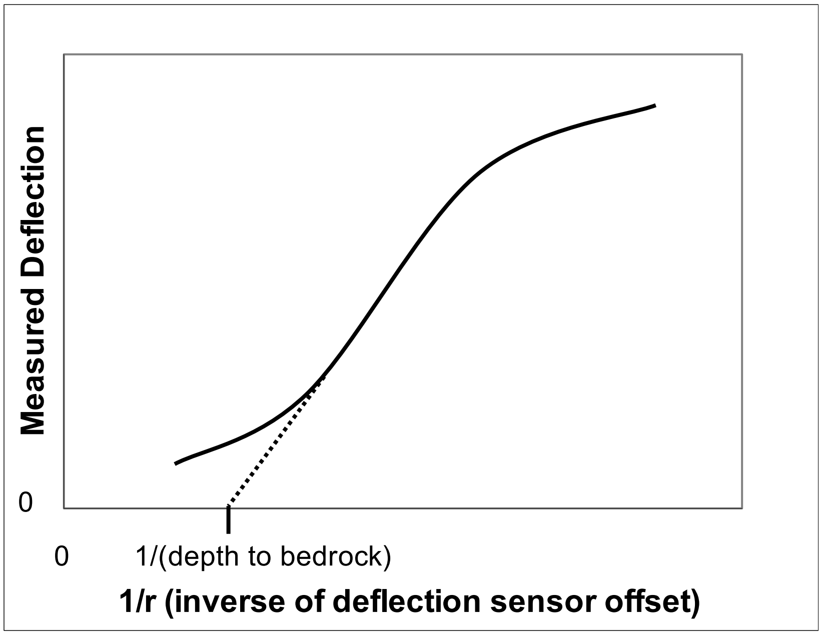

Figure 36: Depth to Hard Bottom Plot

This method has not been rigorously tested with real-world data. It is considered by the developers of MODTAG to be sufficiently accurate for backcalcualtion purposes because, as discussed in Section 1.3.2, the deeper a layer is within the pavement structure, the smaller the modeling errors associated with inaccuracies in its position. Direct measurements of the depth to hard-bottom from GPR or soil borings, if available, should be used in preference to this procedure. This procedure should not be considered sufficiently accurate for backcalculation purposes in cases where the depth to hard bottom is very small, or when the subgrade response is strongly non-linear.

1.3.7 Temperature Correction of AC Moduli

The elastic modulus of asphalt concrete is very sensitive to temperature. Figure 37 is a modulus versus temperature graph derived from backcalculation of data collected by the Long Term Pavement Performance Program (LTPP).

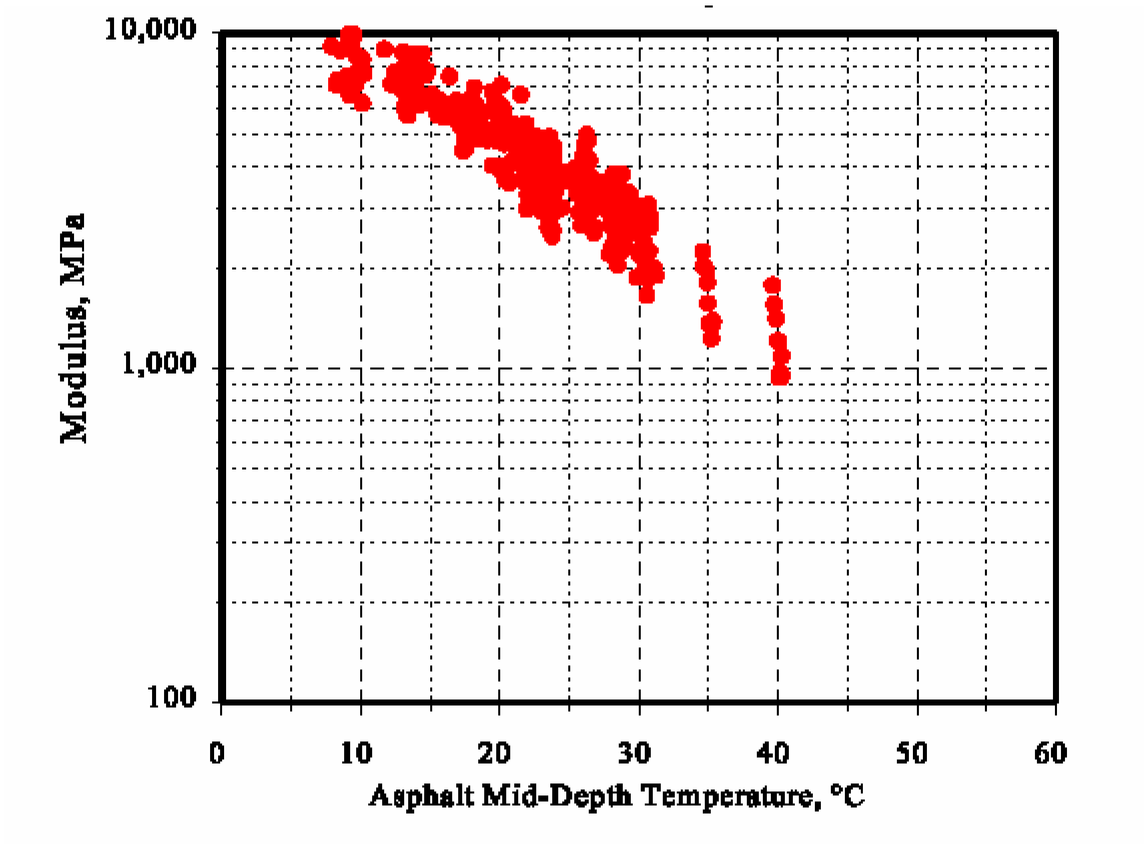

Figure 37. Backcalculated AC Modulus vs. Temperature[6]

As the temperature of an in-place AC layer cannot be controlled, the backcalculated moduli should be corrected for temperature effects. MODTAG uses Equation 21 to adjust backcalculated moduli to a reference temperature.

$$E_{ref} = E_{calc} \times 10^{k(T_{ref} - T_{calc})}$$

Figure 38. Equation 21

where:

	E_{ref}	= Modulus at the reference temperature
	E_{calc}	= Backcalculated modulus
	k	= -0.0195 for testing in the wheel path, -0.021 for mid-lane
	T_{ref}	= Reference temperature, ºC
	T_{calc}	= Mid-depth temperature at the time of testing, ºC

Equation 14 requires the mid-depth temperature of the AC layer at the time of testing. This can be directly measured by means of drilling a hole from the pavement surface to the middle of the layer; however, this process takes much more time than a typical FWD test. MODTAG includes the BELLS3 predictive equation to estimate the mid-depth temperature based on the pavement surface temperatures at the time of the test, and the average air temperature during the previous day. The BELLS3 equation is shown in Equation 22.

$$T_d = 0.95 + 0.892T_{surf} + [\log(d) - 1.25][-0.448T_{surf} + 0.621T_{air} + 1.83H1] + 0.042T_{surf}(H2)$$

Figure 39. Equation 22.

where:

T_d = Pavement temperature at depth d, ºC
d = Depth from the surface, mm
T_{surf} = Pavement surface temperature, ºC
T_{air} = Average air temperature during the day prior to testing, ºC
H1 = -1 for test times between 0500 and 1100; otherwise, $\sin\left(\frac{2\pi(HD1-15.5)}{18}\right)$
H2 = -1 for test times between 0300 and 0900; otherwise, $\sin\left(\frac{2\pi(HD2-13.5)}{18}\right)$
HD1 = Time of day in decimal hours. For times before 0500, add 24 hours.
HD2 = Time of day in decimal hours. For times before 0300, add 24 hours.

1.4 Problems Inherent to FWD Testing and Analysis

There are several situations for which FWD data is not likely to yield useful analysis results. Four situations were identified and are discussed in the following sections.

1.4.1 Thin Layers

The moduli of thin layers are often difficult to backcalculate because these layers do not contribute significantly to the stiffness of the entire pavement structure, regardless of their modulus. The modulus of a thin layer can vary greatly and still not have much effect on surface deflections. Because the sensitivity of surface deflections to the modulus of that layer is small, the effect of that layer on deflection measurements can be totally eclipsed by errors such as random error in the deflection measurements or the estimated thickness of other layers.

There is no set definition for what constitutes a thin layer. A 2-inch AC layer over an aggregate base will probably not exhibit this problem, while a 2-inch AC layer over 12 inches of PCC will almost certainly exhibit it. Bituminous surface treatments (BSTs) are almost always too thin to backcalculate regardless of the remaining pavement structure.

Backcalculated moduli for thin layers are often unreasonably high or low. One solution to this problem is to combine the thin layer with an adjacent layer of the same type, if possible. For example, a BST could be combined with the AC layer below it. In this case the backcalculated modulus for the combined layer will be a composite modulus of the two layers. If there is no adjacent layer of similar enough type, MODTAG allows the modulus of that layer to be set as “known”. In that case, the seed modulus of that layer will not be adjusted during backcalculation. If the layer is thin, there will be no significant influence on the moduli of the remaining layers in the system.

1.4.2 Non-decreasing Stiffness with Depth

Most pavements are built such that the moduli of the layers decrease with increasing depth. There are a few pavements, most notably composite pavements consisting of an AC overlay over PCC for which this is not the case.

As with thin layers, problems with strongly non-decreasing stiffness with depth may show up as unreasonable values for the moduli of the layers above the stiff layer. In these cases the only solution is to set the moduli of the upper layers as known. Some backcalculation programs have a built-in assumption that layer modulus will decrease with depth, so even slight increases in stiffness with depth may cause problems. MODTAG does not have this problem.

1.4.3 Seasonal Variation of Unbound Layer Properties

The moduli of unbound layers are sensitive to moisture content and freeze state. A single FWD test provides the answer to what the subgrade modulus was at the time of the test. That modulus value may or may not be one that is representative of the effective modulus over the pavement's lifetime. Figures 40 and 41 are provided as published examples of the variation of subgrade modulus over the course of a year for wet-freeze and wet-no freeze zones.

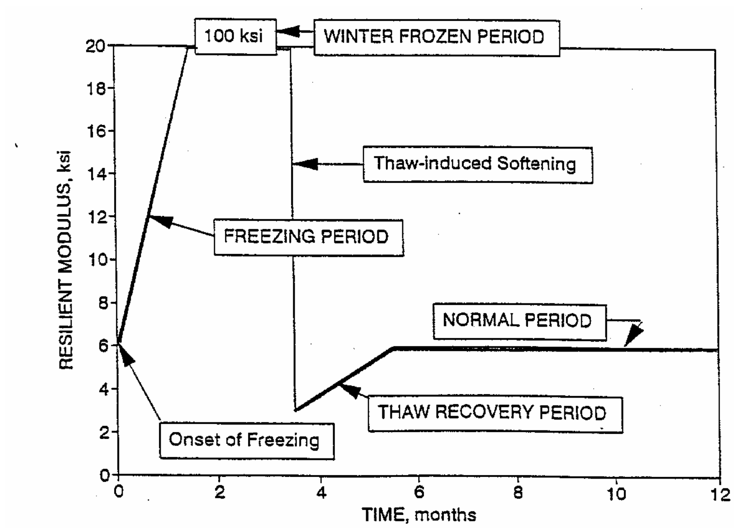

Figure 40. Winter-Freeze, Spring-Thaw Model[7]

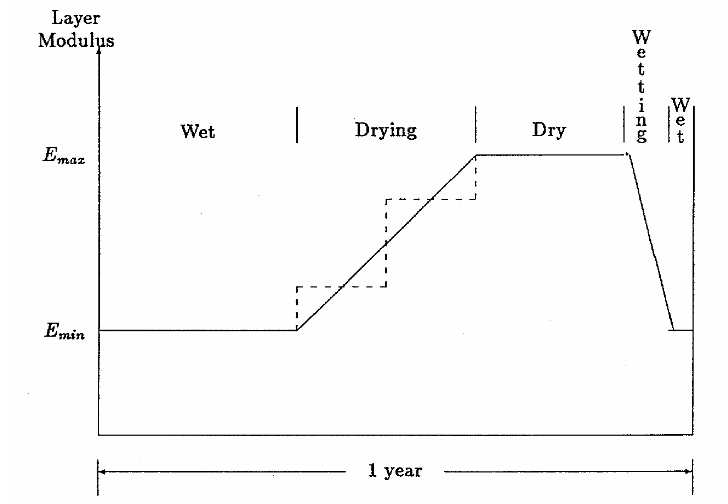

Figure 41. Wet-Dry Seasonal Model[8]

The Asphalt Institute (AI) flexible pavement design method documented in MS-1 accounts for freeze-thaw related variations in subgrade and base layer moduli.[9] This methodology considers three climate regimes, based on the mean annual air temperature (MAAT). The values of MAAT considered are 45° F, 60° F and 75° F. Moduli in areas with a MAAT of 75° F are assumed to not vary with respect to date. The variation of the moduli for the remaining two regimes is modeled as shown in Tables 4 and 5. Note that MS-1 uses the bulk stress model ($Mr = k_1\theta^{k2}$) described in Section 1.2.3 to characterize the base layer.

Table 4. Subgrade modulus variation used in MS-1

MAAT	Normal Modulus, ksi	Subgrade Modulus by Month, ksi											
		Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
45° F	4.5	4.5	15.9	27.3	38.7	50.0	0.9	1.62	2.34	3.06	3.78	4.5	4.5
	12	12.0	21.5	31.0	40.5	50.0	6.0	7.2	8.4	9.6	10.8	12.0	12.0
	22.5	22.5	29.4	36.3	43.1	50.0	15.8	17.1	18.5	19.8	21.2	22.5	22.5
60° F	4.5	4.5	4.5	27.3	50.0	1.35	2.14	2.93	3.71	4.5	4.5	4.5	4.5
	12	12.0	12.0	31.0	50.0	7.2	8.4	9.6	10.8	12.0	12.0	12.0	12.0
	22.5	22.5	22.5	38.3	50.0	18.0	19.1	20.3	21.4	22.5	22.5	22.5	22.5

Table 5. Granular base modulus variation used in MS-1

MAAT	Normal K_1, ksi	K_1 by Month, ksi											
		Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
45° F	8	8.0	12.0	16.0	20.0	24.0	2.0	3.2	4.4	5.6	6.8	8.0	8.0
	12	12.0	18.0	24.0	30.0	36.0	3.0	4.8	6.6	8.4	10.2	12.0	12.0
60° F	8	8.0	8.0	16.0	24.0	2.0	3.5	5.0	6.5	8.0	8.0	8.0	8.0
	12	12.0	12.0	24.0	36.0	3.0	5.25	7.5	9.75	12.0	12.0	12.0	12.0

In the model used in MS-1 the "normal modulus" is the modulus in the month of December. The frozen modulus is set at 50 ksi for subgrade materials, and three times the normal modulus for aggregate base materials. The minimum modulus varies according to material type and climate regime.

The MEPDG includes a mechanistic model to correct a measured resilient modulus value to a reference moisture content. The MEPDG uses proctor optimum moisture content as the reference value. This model is shown in Equation 23.[4]

$$\log \frac{M_r}{M_{r,ref}} = a + \frac{b-a}{1 + EXP\left(\ln \frac{-b}{a} + k_m \left(S - S_{ref} \right) \right)}$$

Figure 42. Equation 23.

where:
- M_r = resilient modulus, psi
- $M_{r,ref}$ = resilient modulus at reference moisture content, psi
- S = degree of saturation, expressed as decimal
- S_{ref} = reference degree of saturation, expressed as decimal
- a = regression parameter
- b = regression parameter
- k_m = regression parameter

The MEPDG uses the values shown in Table 6 for the regression parameters a, b and k_m.

Table 6. Values of a, b, k_m for coarse-grained and fine-grained materials

Parameter	Coarse-Grained Materials	Fine-Grained Materials	Comment
a	-0.3132	-0.5934	Regression parameter
b	0.3	0.4	Conservatively assumed, based on modulus ratios of 2 and 2.5, respectively
k_m	6.8157	6.1324	Regression parameter

The MEPDG assumes that the resilient modulus of frozen coarse-grained materials (0% passing the #200 sieve or a plasticity index of 0) is 2,500 ksi and the resilient modulus of frozen fine grained materials is 1,000 ksi. The freeze state and degree of saturation of unbound materials is computed using the enhanced integrated climactic model (EICM).

The MEPDG can directly account for annual variability in resilient moduli in its design calculations. For designs performed with the AGDPS, however, a single effective resilient modulus must be used. The AGDPS recommends that the effective modulus be calculated from the seasonal moduli using the effective damage concept, using Equation 24.

$$u_f = 1.18 \times 10^8 \left(M_R\right)^{-2.32}$$

Figure 43. Equation 24.

where: u_f = relative damage factor
M_r = resilient modulus, psi

In this method, the seasonal resilient moduli are first converted to relative damage factors. Then the time-weighted average relative damage factor is computed, and converted back to the resilient modulus. Example calculations are shown in Table 7.

Table 7. Example Effective Resilient Modulus Calculation

Month	Subgrade Resilient Modulus, M_r (psi)	Relative Damage, u_f
January	21,500	0.010
February	31,000	0.004
March	40,500	0.002
April	50,000	0.001
May	6,000	0.203
June	7,200	0.133
July	8,400	0.093
August	9,600	0.068
September	10,800	0.052
October	12,000	0.041
November	12,000	0.041
December	12,000	0.041
	Average u_f	0.057
	Effective Subgrade Resilient Modulus (psi)	10,300

Until the MEPDG or some other comprehensive seasonal correction procedure is implemented, analysts must use engineering judgment in evaluating the seasonal variability of resilient moduli.

1.4.4 Distressed Areas

Highly distressed pavements violate the assumption inherent in layered-elastic theory that the layers are homogenous. Deflection tests on highly distressed pavements may not produce the smooth basin predicted by layered-elastic theory. Rather, the basin may be non-continuous when it crosses cracks. The effect of these discontinuities on the backcalculated results is highly variable.

In general backcalculation of data collected on pavements with moderate or severe distress in the area between the load plate and the outermost deflection sensor is problematic. Even if the distress is limited to the surface layers, with layered elastic backcalculation, errors in modeling specific pavement layers are not separable from the remaining pavement layers. Despite this, simpler analysis methods, such as one layer Boussinesq method used by the AGDPS and discussed in Section 1.2.1.1, can be used to determine the subgrade resilient modulus.

2 FWD OPERATIONS

2.1 Equipment Requirements

This section includes specific requirements of the FWD equipment to be used on FLH projects. FWDs that do not meet these requirements should not be used to collect data on FLH projects.

2.1.1 Load Plate

The load plate shall be either 12 inches or 11.8 inches (300 mm) in diameter. For testing on unbound surfaces the FLH pavement engineer may request that an 18 inch or 17.7 inch (450 mm) diameter plate be used.

2.1.2 Loads

The FWD shall be capable of producing any specified load between 6,000 lbs. and 16,000 lbs. to within 10% of the specified level. The load pulse duration shall be between 20 milliseconds and 35 milliseconds for a 9,000 pound load. The load pulse duration can be determined from a plot of load versus time, also known as a time history plot. On some FWDs, the load pulse duration can be adjusted by changing the number or type of buffers.

2.1.3 Deflection Sensors

The FWD shall mount at least nine deflection sensors. The FWD shall be capable of positioning these sensors at the following offsets from the center of the load plate: 0, 8, 12, 18, 24, 36, 48, 60 and 72 inches. If the project requires load transfer testing, the FWD must be additionally capable of positioning a sensor at an offset of -12 inches.

The FWD operator shall verify that the deflection sensors are in the specified positions, within a tolerance of ± 0.1 inches, prior to testing. Sensor positions shall be verified using a steel tape measure with graduations of at least 0.1 inch. All sensor position measurements shall be referenced to the center of the load plate in order to avoid accumulating error.

2.1.4 Temperature Sensors

Air and pavement surface temperature measurements shall be collected at each FWD test points. These sensors should be mounted on the FWD, and the FWD data collection computer should be capable of collecting data from these sensors and reporting them in the data file. Alternatively, these measurements may be collected using hand-held instruments and manually entered into the data collection computer. Temperature readings should be accurate to ± 5º Fahrenheit.

2.1.5 Distance Measurement Instrument

Every FWD test point shall be referenced to a longitudinal position along the pavement centerline that is consistent throughout the test section. To accomplish this, the FWD should have a distance measurement instrument (DMI), and the FWD data collection computer should be capable of automatically collecting data from the DMI and reporting it in the data file. Alternatively, distance measurements may be collected using a separate instrument and manually entered into the data collection computer. Distance measurements should be collected with a resolution of one foot.

2.1.6 Calibration

The FWD shall have undergone reference calibration according to the "SHRP/LTPP FWD Calibration Protocol" dated March 1994, or the most current nationally accepted protocol.

The FWD shall have undergone relative calibration according to the "SHRP/LTPP FWD Calibration Protocol" dated March 1994, or the most current nationally accepted protocol, within the previous month.

Documentation showing that these calibrations were performed successfully, including gain values for each sensor calibrated shall be kept with the FWD. The gain values entered in the FWD data collection software shall be consistent with these calibrations.

2.1.7 Data File Format

The data file format shall be compatible with the MODTAG data analysis software. Stations shall be recorded in feet. Version 4.0.3 of MODTAG is compatible with the Dynatest F20 and F25 formats and the AASHTO PDDX format.

2.2 Equipment Setup

This section describes how the FWD should be setup to collect data on FLH projects. The specific setup for a project will be determined by the FLH Pavement Engineer in keeping with these guidelines.

2.2.1 Drop Sequences

A buffer warm-up sequence should be performed prior to collecting data. This sequence should be performed just prior to the start of testing and again if the FWD is idle for more than 60 minutes during testing. This sequence helps ensure that the load pulse generated by the FWD does not change substantially during testing. The required buffer warm-up sequence is:

Buffer Warm-up: (6, 9, 12, 16, 16, 16 and16 kips) repeated eight times (56 drops total)

The drop sequences used during testing shall be as shown in Table 8.

Table 8. Drop Sequences

Drop Sequence	Drop Load, kips				
	Seating	Drop 1	Drop 2	Drop 3	Drop 4
Standard	9	9	9	12	12
Stiff	9	9	9	16	16
Soft	9	6	6	9	9
Void Detection / Nonlinear	9	6	9	12	16

The actual load shall be within 10% of the specified load for all testing. If the actual loads fall outside this range during testing, data collection shall be halted and the FWD shall be adjusted to produce satisfactory loads before data collection is restarted. Data collected prior to the adjustments but which is within the acceptable range should not be discarded or re-collected. As the loads produced by many FWDs decrease slightly during testing, it is often a good idea to begin testing with the actual loads set slightly higher than the specified load.

The standard drop sequence should be specified for most pavements. For pavements with more than 8 inches of AC or pavements with a PCC layer, the “stiff” pavement drop sequence should be specified. For pavements without a bound layer, or for which the only bound layer is a surface treatment such as a chip seal, the “soft” pavement drop sequence shall be used. In rare cases a pavement may be so weak that some deflections are beyond the range of the FWD deflection sensors even at the 9,000 pound load level. In these cases, the “soft” pavement drop sequence shall be used, but drops 3 and 4 may be eliminated.

If the standard drop sequence is specified and at the start of testing more than 40 mils of deflection at the center of the load plate are recorded at the 12 kip load, then the soft pavement drop sequence should be used. If the standard drop sequence is specified and at the start of testing less than 12 mils of deflection at the center of the load plate are recorded at the 12 kip load, then the stiff pavement drop sequence should be used.

Drop sequences shall not be changed during testing. Data files that contain FWD data collected under more than one drop sequence are not compatible with MODTAG.

2.2.2 Deflection Sensor Spacing

The required deflection sensor positions are shown in Table 9.

Table 9. Deflection Sensor Positions

	Deflection Sensor Offsets, inches								
	D1	**D2**	**D3**	**D4**	**D5**	**D6**	**D7**	**D8**	**D9**
Standard	0	8	12	18	24	36	48	60	72
Load Transfer	0	-12	12	18	24	36	48	60	72

The "standard" deflection sensor positions shall be used for all testing except on sections where load transfer testing is required. If any load transfer testing is to be performed on a section, then the "load transfer" deflection sensor positions shall be used for both load transfer and basin testing.

2.3 Test Point Spacing

The test point spacing shall be established by the FLH Pavement Engineer prior to testing. The following guidelines are provided to assist the Pavement Engineer in determining the appropriate test point spacing. These guidelines are intended for project-level FWD testing as an input to the pavement design process. Network level testing and testing for research or forensic purposes will require different testing intervals.

If construction history, coring or other available information indicates that the pavement structure varies within the project limits, the project should be broken into sections with approximately equivalent structure.

There should be at least fifteen evenly spaced test points per direction in each section. For roads with more than two lanes (i.e. more than one lane per direction) only the outside lanes should be tested. Test sections should be continuous, and intersecting roads, spur roads, access roads, ramps or parking lots should be treated as separate sections to avoid any confusion over the test location. The limits of each section should be clearly communicated to the FWD operator.

The test point interval should be no more than 1000 feet and no less than 100 feet except for sections less than 1500 feet long. Intervals should be specified in round numbers to avoid operator confusion. Table 10 includes example project lengths and test point spacings that are consistent with these requirements.

Table 10. Example Section Lengths and Test Point Spacings

Section Length, feet	Test Point Spacing, feet	Number of Test Points per direction
1000	50	21
1500	100	16
2000	125	17
5000	250	21
10000	500	21

These spacing requirements apply to both flexible and rigid pavements. On rigid pavements, load transfer tests and basin tests shall be performed at the same nominal spacing; however, they will be offset by half the effective slab width, as discussed in Section 2.5.3.2.

Based on previous FLH projects and State DOT experience, production rates of between 100 and 200 test points per day are typical, provided the FWD is in good working condition. Note that rigid pavements will require three times as many tests as flexible pavements, given the same test point spacing, due to the load transfer tests.

Void detection testing on rigid pavements is not an input to standard pavement design processes. Test point spacing should be determined by the FLH pavement engineer on a project-by-project basis depending on the purpose of the testing. As void detection testing is not performed at the same transverse location as basin and load transfer testing, it should be performed in a separate test pass.

2.4 Weather and Temperature Considerations

FWD testing should only be performed when the air temperature is above 40º F, unless otherwise authorized by the FLH Pavement Engineer. Further, FWD testing should not be conducted if there is any indication that frozen layers exist within the pavement structure, or there is excessive moisture in the unbound layers due to spring thaw or other transient events, unless the testing is being performed for research purposes.

Load transfer testing shall only be performed when the pavement surface temperature is below 85º F. At higher temperatures the expansion of pavement slabs may lead to “joint lock-up” which would invalidate the load transfer measurements. Depending on the project location and time of year, it may be prudent to schedule load transfer testing at night or early morning for this reason.

Testing at night and in the rain or other inclement weather is permissible from a data quality viewpoint, but may be inappropriate due to safety concerns. These guidelines do not address safety issues associated with FWD testing.

2.5 Test Procedure

This section describes the test procedure to be followed by the FWD operator.

2.5.1 Before Operations

Before the start of testing the FWD operator shall perform a buffer warm-up sequence on the shoulder or another area outside the section limits. The section limit shall be clearly identified.

2.5.2 Transverse Test Location

All FWD testing shall be performed in the outer wheel path (OWP), with the exception of void detection testing. If the position of the OWP is not readily apparent, then it shall be considered to be 30 inches from the outer lane edge. If the FWD cannot be practically positioned at this location due to the condition of the shoulder or safety considerations, then the FWD should be positioned as close to the outer lane edge as possible.

If there is a great extent of high severity distress in the OWP such that collecting good-quality data in the OWP is difficult, and the mid-lane (ML) is less distressed, then the FWD may be positioned in the ML. A comment on this situation shall be placed in the data file.

Void detection tests should be performed at the outside corner of the concrete slab.

2.5.3 Longitudinal Test Locations

Unless otherwise specified by the FLH Pavement Engineer, the FWD operator shall designate the section limit at which testing starts as station 0. All other test locations at that section shall be referenced to that zero point. The first test location shall be at station 0. Subsequent test locations shall be at the specified offsets. A test shall be performed at the section end limit regardless of the interval from the previous test location.

After completing testing in the first direction, the FWD shall be repositioned so that the load plate is at the section end limit in the second direction. The FWD distance measurement instrument (DMI) shall be set to the DMI reading recorded at the last test point in the first direction. The DMI should be set for decreasing stations.

The first test point in the second direction shall be at the section end limit. The second test point shall be referenced to the location of the next-to-last test point in the first direction. If the station of the next-to-last test point in the first direction is less than half the specified test interval from the section end limit, then the second test point in the second direction shall be at the location of the next-to-last test point in the first direction minus one-half of the test interval.

If the station of the next-to-last test point in the first direction is more than half the specified test interval from the section end limit, then the second test point in the second direction shall be at the location of the next-to-last test point in the first direction plus one-half of the test interval. Subsequent test points shall be at the specified offset, starting from the second test point.

Example 1:

Test interval: 250 ft
Section end limit: 2890 ft

First direction:
    Second-to-last test point: 2750 ft
    Last test point: 2890 ft

Second direction:
    First test point: 2890 ft
    Second test point: 2875 ft
    Third test point: 2625 ft

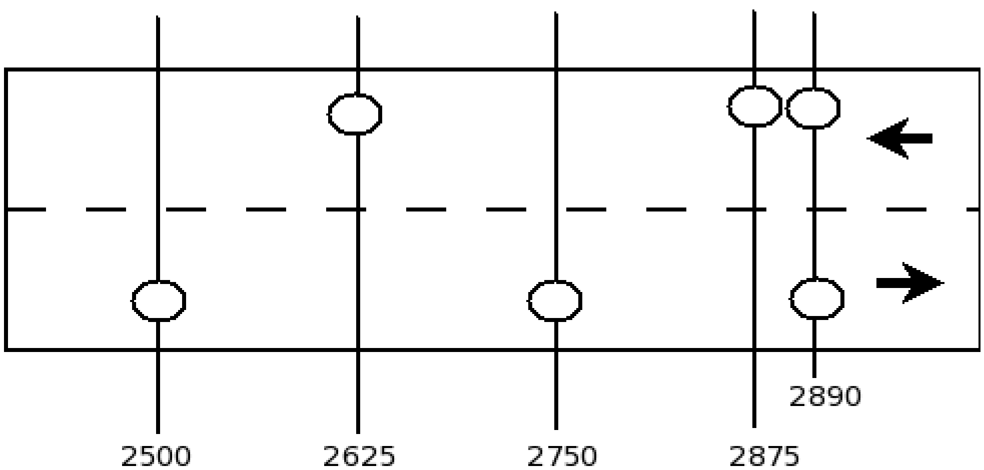

Figure 44. Diagram of Test Pattern from Example 1

Example 2:

Test interval: 250 ft
Section end limit: 2792 ft

First direction:
    Second-to-last test point: 2750 ft
    Last test point: 2792 ft

Second direction:
    First test point: 2792 ft
    Second test point: 2625 ft
    Third test point: 2375 ft

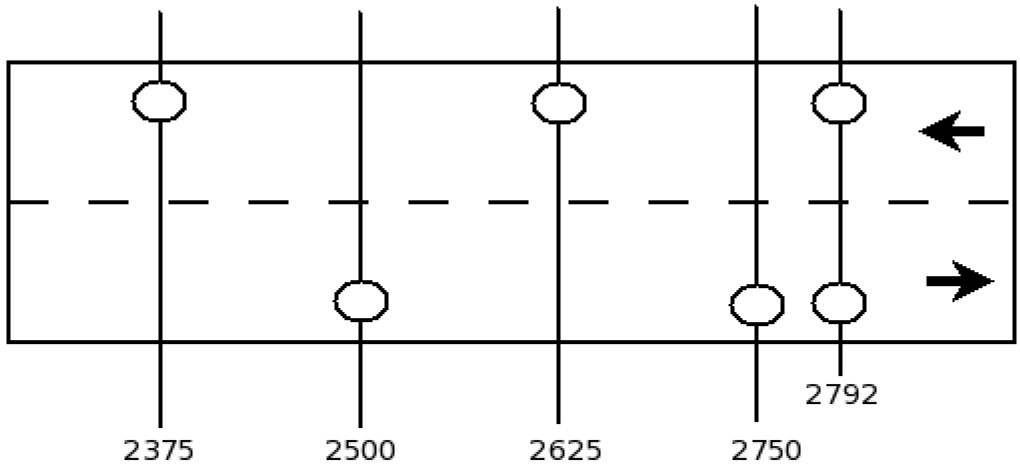

Figure 45. Diagram of Test Pattern from Example 2

An additional test shall be performed at the location of any core hole. For FWDs with the sensor bar mounted in front of the load plate, the load plate should be positioned 5 feet beyond. For FWDs with the sensor bar mounted behind the load plate, the load plate should be positioned 5 feet before the core hole.

2.5.3.1 Distressed Areas

If the pavement surface at the specified test location is distressed the operator may move the FWD either forward or backward up to 10% of the specified test interval to find an area that is relatively free of distress. The FWD operator should attempt to find a position in which there is no significant distress in the area from one foot behind the load plate to one foot in front of the outermost deflection sensor. If the operator cannot locate such a position within 10% of the specified test interval, the operator shall test at the specified test interval. In that case the operator should place a comment in the FWD data file stating that a distress-free area could not be found, and the nature of the distress.

2.5.3.2 Rigid Pavements

Rigid pavements consist of individual slabs. These slabs may be bounded by contraction and construction joints such as those on jointed concrete pavements (JCP), or full-width transverse cracks. A slab that is bounded on at least one side by transverse cracks is known as an "effective slab". All slabs on non-jointed rigid pavements such as continuously-reinforced concrete pavements (CRCP) are effective slabs. Slabs on JCP may be as-constructed slabs or effective slabs due to deterioration.

Test locations on a rigid pavement should be referenced to the slab at located at the specified test interval. Basin tests should be performed at the center of the slab. Joint approach tests should be performed with the FWD load plate located on the effective slab immediately prior to the selected effective slab. Joint leave tests should be performed with the FWD load plate on the selected slab. In both types of joint tests, the FWD load plate shall be no more than two inches from the joint or crack. Under no circumstances should the load plate bridge the joint or crack.

Void detection testing shall be performed on the outside corner of the selected slab. The FWD load plate should be tangent to both the longitudinal and transverse cracks or joints that define the slab. The edges of the load plate should be no more than two inches from either crack or joint, and shall not bridge them.

The location of the joint approach, joint leave and corner test locations relative to the test slab are shown in Figure 46 for jointed pavements and Figure 47 for un-jointed pavements. Figures 48 and 49 show the location of the FWD load plate relative to the joint for joint approach and joint leave testing.

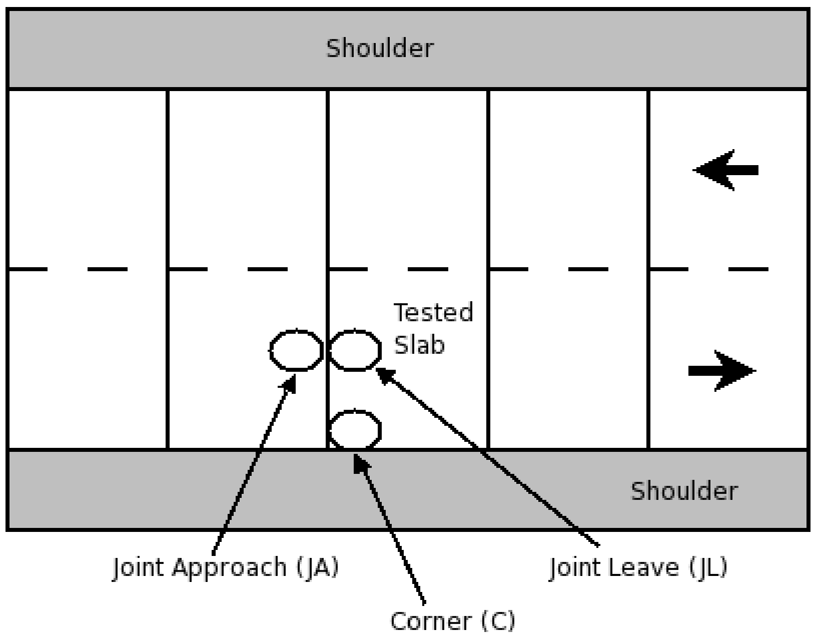

Figure 46. Test Locations on a Jointed PCC Pavement

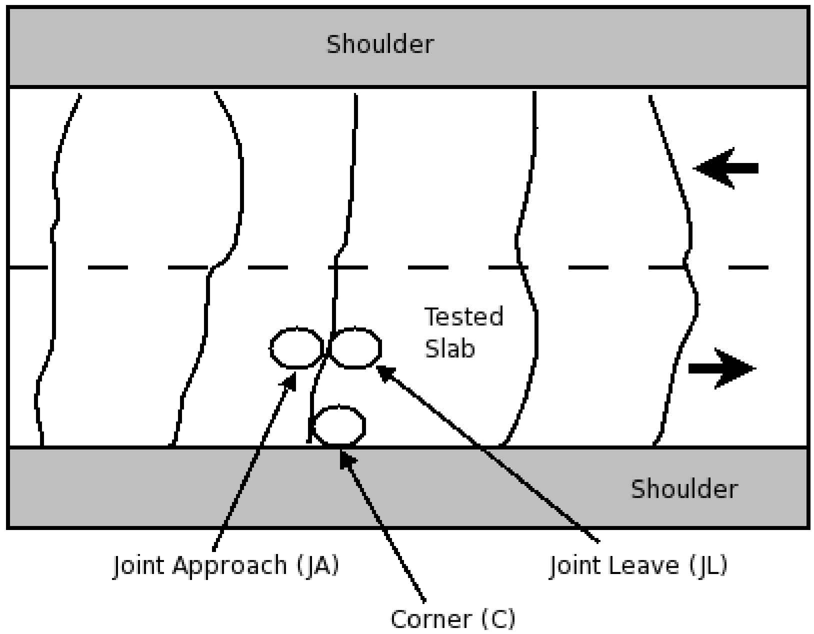

Figure 47. Test Locations on an Un-jointed PCC Pavement

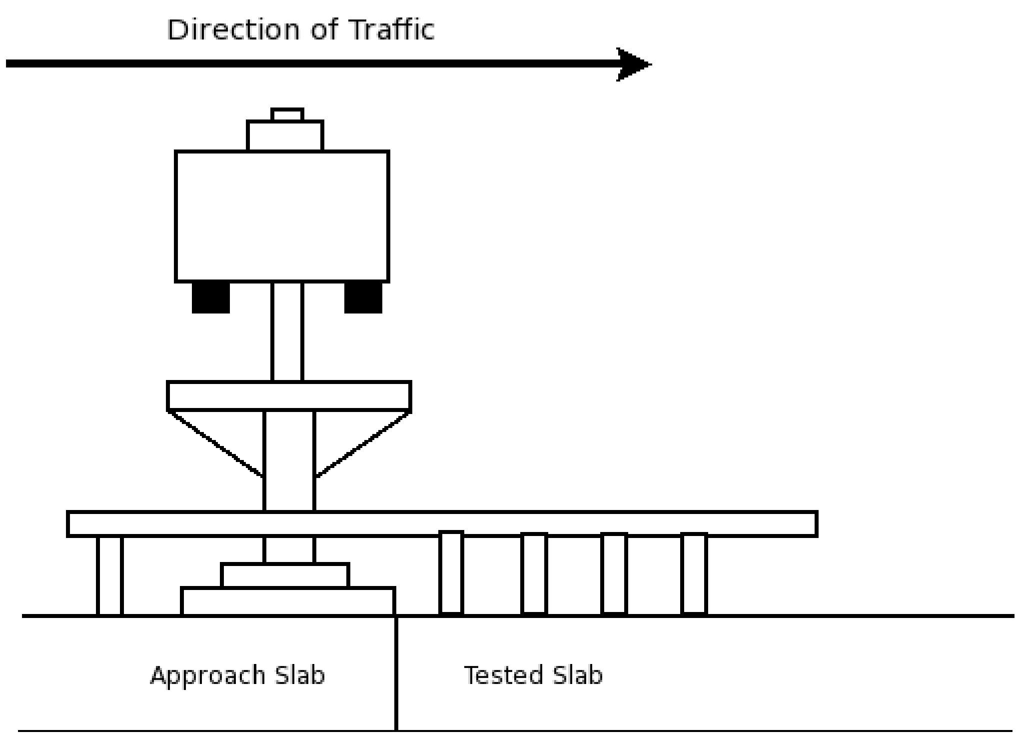

Figure 48. Load Plate Position for Joint Approach Test

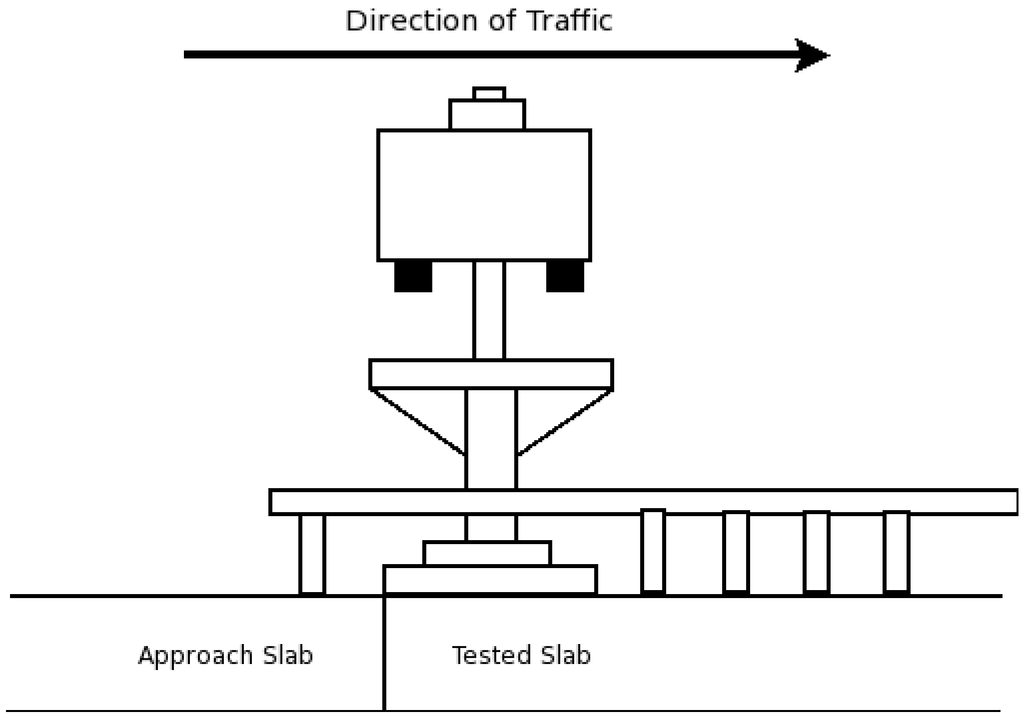

Figure 49. Load Plate Position for Joint Leave Test

The FWD operator should take care that basin, joint approach, joint leave and corner tests are appropriately labeled "B", "JA", "JL" or "C" in the FWD data file, in such a way that they can be automatically identified by MODTAG. In general this information is read out of the first two characters of the "Comments" field; however it is recommended that operators test their FWD data collection software with MODTAG in this regard prior to collecting data. These labels may also be set manually within the MODTAG software, but it is generally easier and less error-prone to set them in the field.

2.5.4 Associated Data

2.5.4.1 Test Comments

The FWD operator should note any conditions that may be of interest to the data analyst. These conditions include weather events (e.g. onset of rain) and distresses in the vicinity of the test point. The operator should also periodically comment on the station of intersecting roads, mile-markers and other landmarks that may help verify the proper operation of the DMI.

2.5.4.2 Temperature measurements

An air and pavement surface temperature measurement shall be taken at each test point. If these measurements are not taken automatically, they should be manually entered into the data collection software.

The FLH Pavement Engineer may request sub-surface temperature measurements. The FLH Pavement Engineer will specify the depth at which the measurements are to be taken, and the time interval at which the temperatures are to be recorded. If only one sub-surface temperature measurement is to be taken, the depth should be set to one-half the thickness of the bound layers in the pavement. If three measurements are to be taken, the depths should be set to one-quarter, one-half and three quarters of the bound layer thickness. In general, temperature measurements should be taken at a 30 minute interval. Direct sub-surface temperature measurements are more accurate than estimation using the BELLS3 equation, but take much more time than an FWD test and are typically only used for research-quality data collection.

If sub-surface temperature measurements are required, temperature holes shall be drilled using a 0.5-inch diameter drill bit. After the hole is drilled to the required depth, it shall be cleared of debris and dust by blowing through a short piece of plastic tubing or other suitable device. The hole shall then be filled with mineral oil to a depth of 0.5 inch to provide thermal conductivity between the pavement and the temperature hole. Finally, the hole shall be covered with tape (such as duct tape) which is slit to allow the probe to be inserted. After these activities are complete, wait at least 15 minutes before taking the first measurement.

2.5.5 Field Data Checks

Most modern FWD data collection software includes automated data quality checks. Use of these checks helps prevent the collection of bad data which must be discarded. MODTAG can also perform many of these checks on stored data; however it can only perform them once data collection is complete. Use of field data checks will alert the operator to data problems during collection, thus reducing the need to discard and re-collect data.

2.5.5.1 Non-Decreasing Deflections

Pavement deflections should decrease with increasing distance from the load plate. If they do not decrease, then it is likely that there is a problem with the data.

One possible cause of this problem is if there is a crack or other discontinuity in the pavement between two sensors. If this is the case, the FWD should be re-positioned in accordance with Section 2.5.3.1.

Another possible cause of this problem is if the deflection sensors are not properly seated on the pavement. Check that the flagged sensors are well-seated in their holders and that the holder has good contact with the pavement surface. Raising and lowering the sensor bar may help clear this error.

If the deflections are very low (less than 0.3 mils) this error may be due to the random error inherent in the measurement device. Errors of this sort are not correctable;

however, this may be an indication that the drop loads should be increased in accordance with Section 2.2.1.

2.5.5.2 Roll-off

A roll-off error is triggered when the measured deflection of the pavement surface does not return to zero after the deflection wave passes.

This error generally occurs when the deflection sensor does not have good contact with the pavement surface, and is most commonly seen on surfaces that are rough or have debris such as sand or gravel. For example, the deflection sensor may be resting on a loose pebble which moves during the test. This error might not re-occur in a repeat test. If it does, raising and lowering the sensor bar or repositioning the FWD in accordance with Section 2.5.3.1 may clear the error. If there is a large amount of loose debris in the test area, the area underneath the FWD should be swept.

The roll-off error may also occur on very weak pavements that are permanently deformed by the FWD test. In these cases the drop loads should be decreased in accordance with Section 2.2.1.

2.5.5.3 Overflow

An overflow error is triggered when the pavement surface deflection is beyond the measurement range of the deflection sensors. Different makes and models of FWDs have different measurement ranges.

Overflow errors on pavement surfaces that are not severely distressed are uncommon. In these cases, it is likely that there is an equipment problem, such as a deflection sensor that is not securely fastened to its holder. If the problem occurs in a localized area of severe distress, the FWD should be repositioned in accordance with Section 2.5.3.1. If this error occurs on very thin pavements, the drop loads should be decreased in accordance with Section 2.2.1.

2.5.5.4 Excess Variation

An excess variation error is triggered when the normalized deflections measured in successive drops varies by more than some set amount. This amount can be adjusted by the operator. Normalized deflection is calculated by dividing the measured deflection by the peak load and multiplying by 9000 lbs.

This error usually indicates that one or more deflection sensors do not have good contact with the pavement surface. In these cases, the error may be cleared by raising and lowering the sensor bar. On very thin or highly distressed pavements, it may indicate that the pavement properties are being modified by the testing process itself. In such cases the FWD should be repositioned in accordance with Section 2.5.3.1

2.5.6 Data Files

Each data file shall contain data corresponding to only one direction on one test section. All data in the data file should be collected using the same drop sequence. MODTAG cannot analyze data files containing multiple sections, directions of travel or drop sequences. Data from a single test section may be contained in multiple files. Data files shall be compatible with MODTAG. It is recommended that FWD operators test their data files for compatibility with MODTAG prior to data collection. It is also recommended that FWD files be backed up on removable media such as a flash drive immediately after collection.

3 LAYER THICKNESS INFORMATION

Analysis and interpretation of pavement deflection response relies on knowledge or assumptions about the pavement structure; number of layers, materials making up each layer, layer thickness, and depth to rigid layer. This section describes ways pavement layer thickness and material type may be determined from field investigation. Investigation techniques include records review, pavement coring and soil boring, and ground penetrating radar (GPR) surveys. The following information is intended to supplement guidance provided in Chapters 6 and 11 of the FLH Project Development and Design Manual.

Information gathered during project planning may provide expected pavement structure. However, variability in construction, construction history, and undocumented construction and maintenance activities require some level of field verification. Because deflection analysis relies on knowledge of pavement structure for modeling and interpretation, layer thickness is a critical piece of information.

The influence of errors in layer thickness has been evaluated on many occasions. ASTM D-5858 “Standard Guide for Calculating In Situ Equivalent Elastic Moduli of Pavement Materials Using Layered Elastic Theory” suggests tolerances for layer thickness of ± 0.2 inches for bound layers (AC, PCC) and ± 1.0 inches for unbound layers.[10] These tolerances suggest that project investigations should seek to define subsections within the project where the pavement layers may be averaged within these limits.

As a general rule, all material types and layer thicknesses recovered from as-built construction plans should be verified using field cores or borings, or both, if at all possible. The specific number of cores required per analysis section or project is not a part of this guide. Engineering judgment informed by statistical methods applied to the deflection data may be utilized to determine the locations of cores required to estimate layer thicknesses to a desired level of precision and degree of confidence. Thickness variations are dependent on construction practice and maintenance activities. However, it should be noted that any deviation between the assumed and actual in-place layer thicknesses may affect the backcalculated layer moduli significantly.

3.1 Records Review

Part of any project level investigation is a review of available construction history as well as other information items such as traffic and environmental data. Sources of pavement structure information are available geotechnical investigation reports, as-built contract documents, and pavement reports produced for projects included within or perhaps nearby the section of interest. This information should be considered as guidance; verifying records through field testing is essential in order to properly evaluate deflection data.

3.2 Pavement Coring and Soil Borings

Several standards and procedures exist and are routinely used in performing pavement core and soil boring activities. Knowledge of subgrade soils and approximate depth to a rock layer or zone of increased stiffness (sudden increase/refusal in Standard Penetration Test blow count or cone penetrometer tip resistance) are important for understanding backcalculation results. Thickness of bound pavement layers may be determined either from cores, trench cuts in the pavement, or by augering through the surface and direct measurement of the exposed layers.

Project conditions may dictate a more aggressive field sampling plan to obtain materials for laboratory study. For purposes of deflection analysis, verifying or determining pavement structure while minimizing the number of cores (for logistical concerns) is desirable. The AGDPS, Part III, Chapter 3, provides some guidance on the number of samples needed to achieve a desired confidence in the result using limit of reliability statistics. That discussion reveals that as-built thickness variation is commonly greater than tolerance acceptable for backcalculation for individual pavement layers. As such, a sampling plan would need to have a large number of cores in order to achieve an acceptable confidence interval for the thickness tolerance desired (±0.2 inches for bound and ±1.0 inches for unbound). For example, at a 95 percent confidence interval, one would need to obtain between 10 and 20 cores to ensure an asphalt thickness tolerance of ± 0.2 inches. Because coring requires static traffic control and is a relatively time consuming activity (as compared to deflection testing), this is an unacceptable number of cores. Therefore, it is important for the Engineer to assess the available information, the results of an initial analysis deflection data and the impact on project schedule, funds and the traveling public when deciding how many cores will provide acceptable comfort.

To illustrate the problem, Figure 50 shows a project having 5 different pavement structures along its length but with the same surface throughout, a common occurrence. Figure 51 is response data measured along another project showing the zones of relatively similar conditions. Figure 52 is a cumulative difference plot of deflection versus distance. Appendix J of the AGDPS describes the methodology of cumulative difference; it is a powerful tool in defining zones of similar response within a project. Pavement areas with consistent response appear as straight lines on the cumulative difference plot, while points where the slope changes dramatically correspond to section boundaries. When applied to deflection data sets, it allows the Engineer to choose core locations in zones of interest rather than simply fixed intervals.

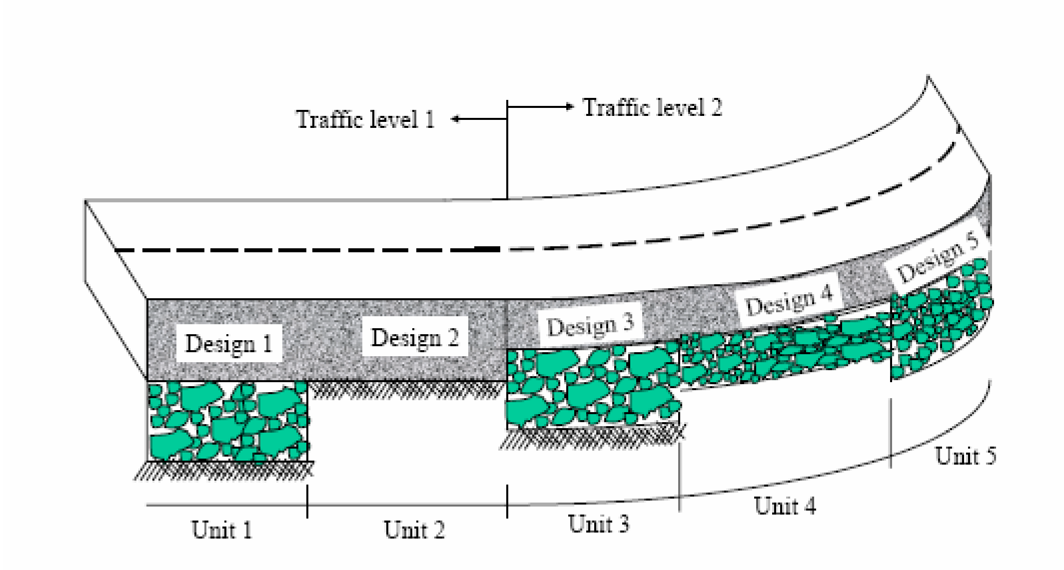

Figure 50. Structure Variation Along a Project[5]

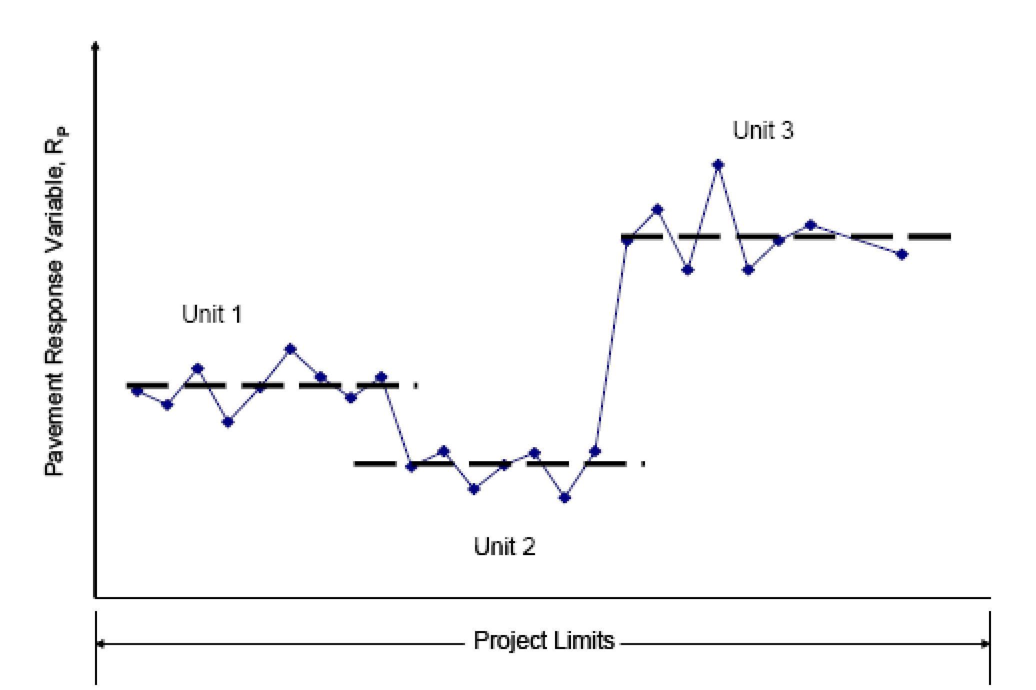

Figure 51. Response (e.g. maximum deflection) along a project[5]

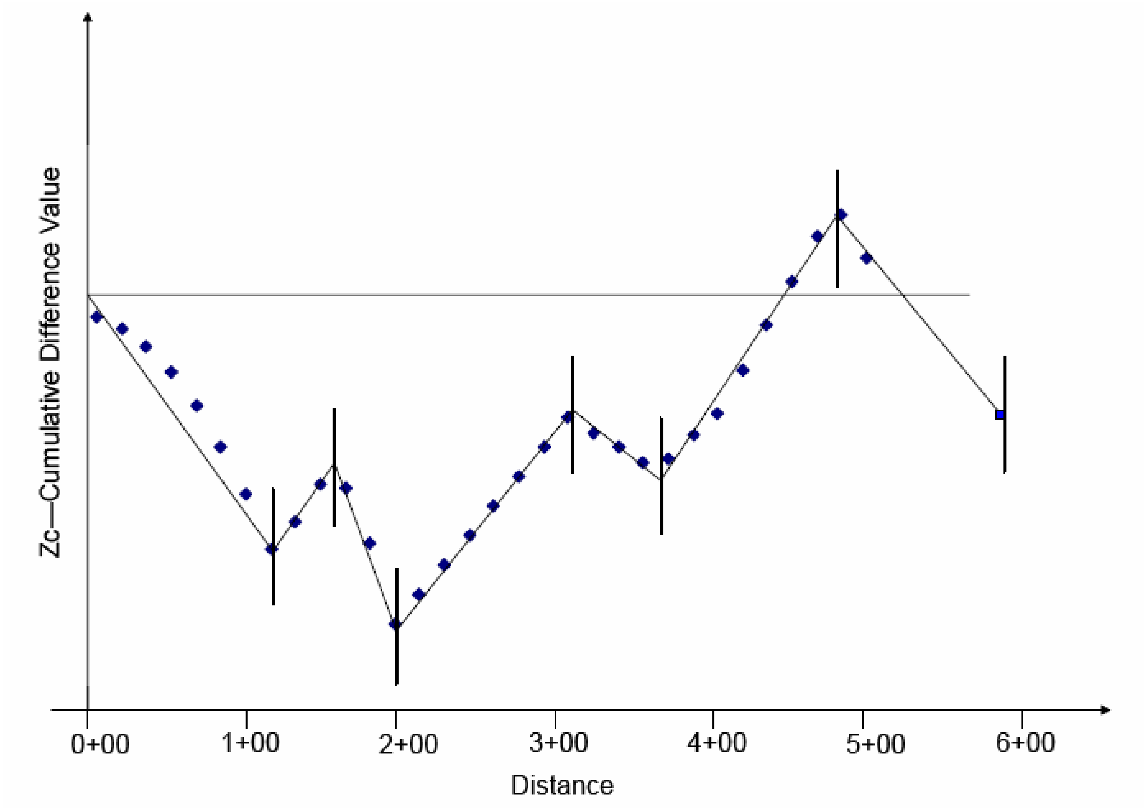

Figure 52. Cumulative difference of deflection - section delineation[5]

3.3 Ground Penetrating Radar

A rapid, non-destructive, non-disruptive, high productivity approach to pavement layer thickness determination is ground penetrating radar (GPR). While not eliminating the need for pavement cores, GPR is extremely informative with regard to changes in pavement structure along a project as well as providing data to be interpreted for layer thickness estimation.

Figure 53 illustrates the principles of GPR. Electromagnetic energy is generated and directed (A_0 in the figure) into the pavement structure and reflected from zones of changing electrical properties of the materials. The reflected energy is recorded as it arrives at the receiving antenna providing values for the amount of reflected energy (amplitude or voltage) and the travel time of the pulse from the transmitting antenna to the receiver (A_1, A_2, A_3). As shown in the figure, plotting each trace with distance where the amplitude is colorized or varied based on magnitude, gives the appearance of layering. The analysis relies on this pseudo-layering coupled with calibration data to arrive at an estimate of layer thickness.

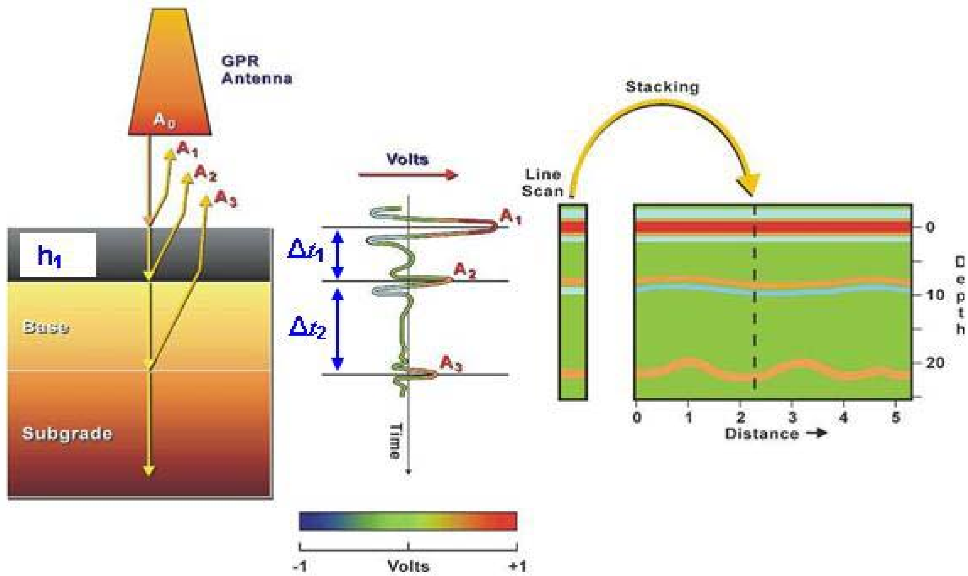

Figure 53. Principles of Air-launched GPR[11]

GPR data can be collected continuously along the project at variable intervals (from inches to feet) and always at prevailing traffic speeds. Data interpretation then takes several forms as described above; evaluation of stacked traces, layer thickness determination, and layer property determination. Stacked traces are valuable for identifying sudden changes in the pavement cross section along the length of the project as shown in Figure 54. Visual examination of the GPR data allows the user to see locations where properties change; these may indicate sudden pavement section changes (patches) or changes in pavement materials. Further analysis of these results can provide pavement layer thickness and condition.

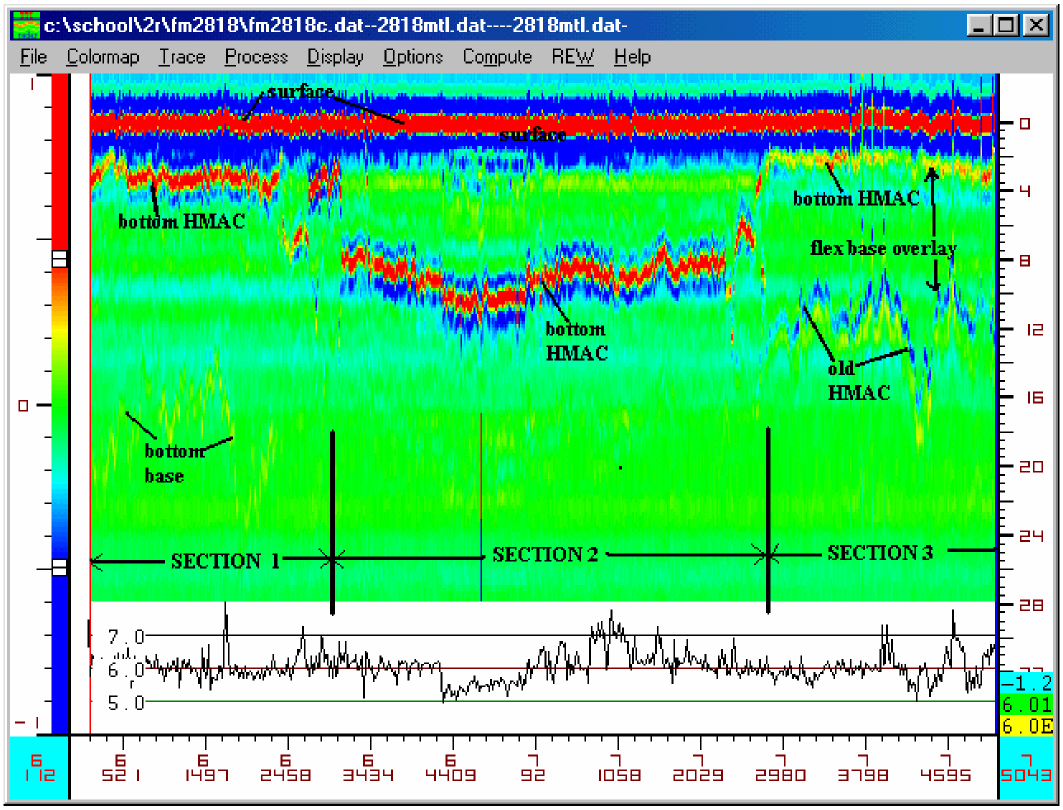

Figure 54. Section Delineation from GPR Data[11]

Layer thickness from GPR is useful in tying together cores located far apart, essentially "connecting the dots." The GPR analysis provides information on the variation in layer thicknesses along the project while a few core locations verify actual thickness to enhance confidence in the results.

Accuracy of layer thickness from GPR with a 1 GHz air-launched antenna has been evaluated and reported by Maser, and is shown in Table 11.[12] Higher frequency antennas will have greater accuracy at the expense of reduced penetration into the pavement structure.

Table 11. Accuracy of Layer Thickness from GPR

Material Type	Accuracy
New Asphalt Concrete	3 – 5%
Existing Asphalt Concrete	5 – 10%
Portland Cement Concrete	5 – 10%[1]
Aggregate Base	8 – 15%[1]

Note: 1 - Requires adequate contrast between layers

3.4 Recommended Thickness Data Collection

The following recommendations are provided to assist the FLH pavement engineer in developing a layer thickness data collection plan. These guidelines are intended to support project-level FWD testing as an input to the pavement design process. Network level testing and testing for research or forensic purposes will require different data collection plans.

The first step in developing a layer thickness data collection plan is to obtain and review all available construction history records. The pavement engineer should judge the reliability of the information collected from these records especially with regards to the likelihood of undocumented maintenance activities. The pavement engineer should also split the project into sections with uniform construction history.

If possible, the project should be scheduled such that FWD data can be collected and sub-sectioning performed as described in Section 4.1.2 prior to the collection of layer thickness data. In this case, a minimum of four cores should be taken per sub-section. These cores should be uniformly spaced throughout the length of the subsection and staggered in opposing lanes.

Otherwise, the coring interval should be determined based on the reliability of the construction history data. If the construction history data is judged to be reliable, then coring should be performed at a minimum half-mile interval. Otherwise, coring should be performed at a minimum quarter-mile interval. In both cases, at least four cores shall be taken per section. Cores should be staggered in opposing lanes.

The collection of GPR data should be considered in cases where large variability is expected in layer thickness, such as pavements that have been subjected to many maintenance activities over the years. The collection of GPR data should also be considered in cases where traffic control conditions make it difficult to drill large numbers of cores. Coring is required to calibrate or validate the GPR data. The required number of cores will vary according to the GPR methodology, however at a minimum two cores should be taken per section.

There should be an FWD test in the immediate vicinity of each core. If FWD testing was performed prior to coring, then a core location at the exact location of an FWD test should be selected. If FWD testing is performed after coring, an FWD test should be performed near the location of each core hole, as described in Section 2.5.3.

4 FWD DATA ANALYSIS

This section of the guide discusses the analysis of FWD data. All analysis processes shall be performed using MODTAG. The version of MODTAG acceptable for use shall be specified by and available from the FLH Pavement Engineer.

4.1 Pre-Analysis

Pre-analysis is the process of preparing the FWD data for analysis. Pre-analysis includes quality assurance (QA) reviews of the FWD data, removal of suspect data, and separation of the FWD data into analysis sub-sections.

4.1.1 QA Checks

The QA checks in MODTAG shall be run prior to any analysis. Messages of the type "Data Error" and "SLIC Warning" should be reviewed. We recommend that these checks be performed as soon as possible after testing. This may make errors easier to resolve.

4.1.1.1 SLIC Warning

The SLIC transform is used to check whether the reported deflection sensor positions are reasonable. If this warning is triggered, it is an indication that the sensor spacings listed in the data file may not match the actual sensor spacings. If this check is performed shortly after data collection, the physical sensor locations on the FWD should be checked and the data files should be modified as necessary. If this check is not performed until well after data collection, there is the possibility that the FWD deflection sensors have been moved in the interim, making it difficult to determine what the actual spacings were at the time of testing.

Details on the SLIC transform are provided in the MODTAG user's manual.

4.1.1.2 Data Warnings

MODTAG includes three types of data QC checks on each data record. These checks shall be performed and all errors shall be examined and dealt with. These checks include:

- **"Non-decreasing deflections"**: This check triggers when the reported deflections do not decrease with increasing distance from the load plate. On very soft pavements, this error may commonly occur at the outermost sensors which are reporting very low deflections. In that case, the sensors where the error occurs may be removed from analysis for all records. This error may also occur due to pavement discontinuities (such as areas of high distress) or equipment seating problems. In these cases the specific data record flagged should be removed.

- "**Zeros In Data**": This check triggers when one or more deflection value is reported as zero. If the outermost sensor records zero deflection in several data records, then consider removing all data for the outermost sensor for all records. Otherwise, all data for the flagged record may be removed

- "**Overflow**": This check triggers when a deflection sensor reports more than 80 mils of deflection. This is the upper limit for deflection sensors commonly mounted on Dynatest FWDs. Other types of deflection sensors may be capable of measuring more than this amount of deflection.

  If the pavement surface is really deflecting by an excessive amount, this error will naturally be most common on the center deflection sensor. If it is accompanied by a non-decreasing error, it is an indication of an equipment problem or a localized discontinuity in the pavement surface. If the problem is consistent across data records and appears to be equipment-related, then the specific sensor in question may be removed from analysis provided that it is not the center deflection sensor. In general, overflow errors should be removed by removing the data record in which they occur.

4.1.1.3 Removing Sensors

If the data checks indicate that data from specific sensors is commonly in error, then the data from these sensors may be removed from analysis for all records. Most commonly, this will be the outermost sensors. No more than two of the nine sensors may be removed from analysis. The center sensor may not be removed from analysis.

Currently MODTAG does not include the capability of removing sensors from the analysis. MODTAGUtils, a separate program available from FLH, can be used to remove all data from a specific sensor from a MODTAG project file.

4.1.1.4 Removing Records

Records containing data that fails one or more data checks should not be used in further analysis. It is expected that no more than 2% of records should fail these data checks, after any sensors have been removed pursuant to Section 4.1.1.3. Records that do not fail data checks should not be removed even if they appear to be outliers. If more than 2% of the records fail these checks, the FLH pavement engineer shall be consulted. If the pavement surface is unbound or highly distressed then this circumstance may be acceptable. Otherwise the FLH pavement engineer may request that additional data be collected to replace the failed data.

Currently MODTAG does not include the capability of removing deflection basins that fail data checks from the analysis. MODTAGUtils, a separate program available from FLH, can be used to remove all data corresponding to a deflection basin that fails a data check from analysis.

4.1.2 Sub-Sectioning

If the data for a pavement section includes more than 30 test points in each direction, then it should be analyzed for sub-sections. Sub-section analysis should use MODTAG's "cumulative difference of deflections" approach. Areas with relatively constant slope on the cumulative difference of deflections plot are likely to have similar properties, while inflection points indicate section boundaries. An example cumulative difference of deflection plot is shown in Figure 52. No sub-section should have fewer than 15 test points in each direction. Sub-sections may be analyzed with the same pavement structure if coring or other data does not show a difference in structure, but the results for each sub-section shall be averaged and reported separately.

4.2 Analysis

4.2.1 Backcalculation

Backcalculation using MODTAG shall be the default analysis procedure used on FLH projects. Prior to beginning backcalculation the data checks and sub-sectioning procedures described in Section 4.1 of the guidelines shall be performed.

4.2.1.1 Layer Structure

The pavement structure for each section shall be as a series of layers, based on coring data, construction history, and other information provided by the FLH project engineer. There will usually be at least three layers; surface layer (either AC or PCC), granular base layer and subgrade.

A separate layer shall be included for each distinct material type reported in the pavement structure. Multiple layers for a material type may be used if the coring or construction history information indicates a difference in properties or placement time; however, none of these layers shall be less than 2 inches in thickness. For example, if a pavement was originally constructed with a 5-inch AC surface, but has since been overlayed with 2 inches of AC, then the pavement structure shall be modeled with two AC layers, the top one 2-inch thick and the bottom one 5-inch thick.

To evaluate the depth to hard bottom, use MODTAG's depth to hard bottom analysis. If this analysis indicates that a hard bottom exists at a depth of less than 300 inches, then a hard bottom layer shall be included. MODTAG will compute the depth to hard bottom for each test point; however, that depth should be inputted into the layer model as a single average value for the entire section. The modulus for the hard bottom shall be fixed at 1,000,000 psi.

4.2.1.2 Seed Moduli and Poisson's Ratios

Table 12 includes default seed moduli and Poisson's ratios for various material types. These values may be adjusted based on examination of core samples or other project-specific information.

Table 12: Seed Moduli and Poisson's Ratios

Material Type	Seed Modulus (psi)	Poisson's Ratio
Portland Cement Concrete	4,000,000	0.15
Asphalt Concrete	400,000	0.35
FDR/no stabilizer	60,000	0.35
FDR/cement stabilizer	300,000	0.25
FDR/asphalt emulsion stabilizer	200,000	0.35
Cold in-place recycling	250,000	0.35
Cement treated base	1,000,000	0.20
Aggregate Base	40,000	0.35
Granular Subgrade	20,000	0.40
Fine-grained Subgrade	10,000	0.40
Hard Bottom	1,000,000[1]	0.20

Note: 1 – The modulus of the Hard Bottom shall be input as a known quantity.

4.2.1.3 Temperature Correction

Temperature corrections shall be applied on all analysis sections including an asphalt concrete layer. If the mid-depth temperature of the asphalt concrete layer was directly measured, then this result shall be used in the temperature correction algorithm. Otherwise the BELLS3 estimation provided by MODTAG shall be used. The temperature correction algorithm built in to MODTAG shall be used, with a reference temperature of 68º F. MODTAG's temperature correction procedure is discussed in Section 1.2.7.

4.2.1.4 Non-linear Analysis

Non-linear analysis of FWD data is not required by default, but may be requested by the FLH Pavement Engineer. The FLH Pavement Engineer will specify the non-linear constitutive models to be used. In general, the bulk stress model (Model Number 1 in MODTAG) should be used for coarse-grained materials and the octahedral shear stress model (Model Number 5 in MODTAG) should be used for fine-grained materials. Note that data from four different load levels at each test location is required to perform non-linear analysis in MODTAG.

4.2.1.5 Review of Results

After backcalculation, the results must be reviewed. The calculated moduli and root-mean-squared errors (RMSE) of the calculated versus measured deflection basins shall be checked to ensure that they are within reasonable ranges.

First the RMSE should be evaluated. The average RMSE for the analysis section should be no more than 3%. No individual basin should have an RMSE of more than 5%. If the RMSEs are generally low with some basins with high RMSE, up to 5% of the basins may be removed from consideration. After they are removed the average and maximum RMSE should be re-computed. If the average RMSE is still greater than 3% or the maximum error is greater than 5%, the analysis should be re-performed as discussed in Section 4.2.1.6

Next, the average calculated moduli should be reviewed. The reported averages should fall within the ranges provided in Table 13.

Table 13: Acceptable Moduli Ranges

Material Type	Modulus (psi)	
	Lower Bound	**Upper Bound**
Portland Cement Concrete	1,000,000	7,000,000
Asphalt Concrete	100,000	1,000,000
FDR/no stabilizer	40,000	150,000
FDR/cement stabilizer	80,000	800,000
FDR/asphalt emulsion stabilizer	50,000	600,000
Cold in-place recycling	80,000	800,000
Aggregate Base	15,000	50,000
Granular Subgrade	10,000	50,000
Fine-grained Subgrade	5,000	50,000

If the average modulus for any of the layers falls outside of these ranges, and there is no indication from other data sources that this should be considered reasonable, then the analysis shall be re-performed as discussed in Section 4.2.1.6.

4.2.1.6 Adjusting the Layer Structure

If the analysis results fail the checks described in Section 4.2.1.5, then the layer structure must be adjusted. There are several steps that may be taken, but none of these steps should be taken until an analysis performed without taking these steps is found to be inadequate.

- Combine Layers. Adjacent layers composed of similar materials may be combined into a single layer. Unbound layers may be combined with other unbound layers, and AC layers may be combined with other AC layers.

- Assume the modulus of thin layers. If a layer is less than 2 inches thick and can not be combined with adjacent layers due to large differences in composition, then the modulus of that layer may be assigned as a known value. This known value should be equal to the seed modulus. The report must specify that this modulus was assumed, not calculated.

- Assume the modulus of soft layers over stiff layers. If a layer is immediately above a layer that has a significantly higher modulus, the modulus of that layer may be assumed. This will most commonly occur on AC overlays of PCC pavements. In that case, the modulus of the AC layer may be assigned a known value. This known value should be equal to the seed modulus. The report must specify that this modulus was assumed, not calculated.

If these steps do not solve the problem, then it is likely that the layer structure information is incorrect. Further efforts to solve the problem should be coordinated with the FLH Pavement Engineer. Additional coring in the areas with errors may be possible. Alternatively, the AGDPS analysis may be performed.

4.2.1.7 Structural Number Calculation

After backcalculation is performed and the results are found to be acceptable, the structural layer coefficient for each pavement layer other than the subgrade shall be calculated. The layer coefficient shall be calculated only for the section average moduli, not the individual deflection basin moduli. Equation 25 shall be used for calculating layer coefficients:

$$a_i = 0.0045 \times \sqrt[3]{E_i}$$

Figure 55. Equation 25.

where: a_i = layer coefficient for layer *i*
E_i = elastic modulus backcalculated for layer *i*, psi

The effective structural number (SN_{eff}) shall then be calculated using Equation 26.

$$SN_{eff} = \sum_{i=1}^{n} a_i t_i$$

Figure 56. Equation 26.

where: a_i = layer coefficient for layer *i*
t_i = thickness of layer *i,* inches
n = number of layers in pavement system, excluding the subgrade

4.2.1.8 Reporting

For each deflection basin analyzed, the report shall include a table showing the station, lane, average load, modulus of each layer, RMSE and pavement effective structural number. An example is shown in Table 14. The subgrade resilient modulus in this table shall be uncorrected (i.e. do not multiply it by the C factor).

Table 14. Example Backcalculation Report

Station, feet	Lane	Load, pounds	Layer Moduli, psi			RMSE, %	SN_{eff}
			Layer 1	Layer 2	Subgrade		
0	EB	9,281	412,129	20,448	15,089	1.5	2.8
0	EB	12,975	420,017	22,703	14,781	1.9	3.1
250	EB	9,273	502,789	31,891	12,002	3.2	3.5
250	EB	12,888	533,721	35,272	11,281	2.1	3.7
0	WB	9,245	420,182	21,788	19,073	1.1	2.8
0	WB	12,890	433,856	23,482	17,598	1.2	3.1
125	WB	9,262	495,987	29,780	15,378	2.5	3.3
125	WB	12,927	499,251	31,222	14,221	2.9	3.4

The report shall also contain a summary table showing the average, minimum, maximum and standard deviation of the modulus of each layer, RMSE, effective structural number, and corrected subgrade resilient modulus for each section. The subgrade modulus shall be corrected using a correction factor of 0.33. An example is shown in Table 15.

Table 15. Example Backcalculation Summary Report

Parameter	Average	Minimum	Maximum	Standard Deviation
Load level, pounds	9,265	9,245	9,281	15.5
Layer 1 modulus, psi	457,771	412,129	502,789	48,246
Layer 2 modulus, psi	25,977	20,448	31,891	5,703
Subgrade modulus, psi	15,386	12,002	19,073	5,703
RMSE, %	2.1	1.1	3.2	0.95
SN_{eff}	3.1	2.8	3.5	0.36
Corrected subgrade modulus, psi	5,077	3,961	6,294	955

4.2.2 AGDPS Analysis

Analysis of FWD data according to the AGDPS procedure shall only be performed at the request of the FLH Pavement Engineer. MODTAG shall be used to perform the procedure.

4.2.2.1 Flexible Pavement Analysis

AGDPS flexible pavement analysis shall be performed using MODTAG. Only the drop with a nominal load of 9,000 pounds shall be analyzed. Temperature correction shall be performed using measured mid-depth temperatures if available, or the BELLS3 prediction otherwise. The remaining life calculations need not be performed. Subgrade resilient moduli shall be corrected using a factor of 0.33.

The report shall include a table showing the station, lane, load, effective structural number (SN_{eff}), pavement modulus (E_p), calculated subgrade resilient modulus (M_r) and corrected subgrade modulus for each deflection basin analyzed. An example is shown in Table 16.

Table 16. Example AGDPS Flexible Analysis Report

Station, feet	Lane	Load, pounds	E_p, psi	SN_{eff}	Calculated M_r, psi	Corrected M_r, psi
0	EB	9,015	59,838	2.82	15,089	4,979
250	EB	9,028	83,243	3.14	12,002	3,961
0	WB	9,007	62,441	2.86	19,073	6,294
125	WB	9,011	79,709	3.10	15,378	5,075

The report shall also include a table showing the average, minimum, maximum and standard deviation of the load, effective structural number and corrected resilient modulus for each section analyzed. An example is shown in Table 17.

Table 17. Example AGDPS Flexible Analysis Summary

Parameter	Average	Minimum	Maximum	Standard Deviation
Load level, pounds	9,015	9,007	9,028	9.1
SN_{eff}	3.0	2.8	3.1	0.2
Corrected M_r, psi	5,077	3,961	6,294	955

4.2.2.2 Rigid Pavement Analysis

AGDPS rigid pavement analysis shall be performed using MODTAG. Only the drop with a nominal load of 9,000 lb shall be analyzed. The “PCC Area/K – Composite” option should be used for pavements including both AC and PCC. The “PCC Area/K – Jointed/CRC” option should be used for all other rigid pavements. In both cases, the Poisson’s ratio should be set to 0.15.

The report shall include a table showing the station, lane, load, static k-value, and modulus of the PCC layer for each deflection basin analyzed. An example is shown in Table 18.

Table 18. Example AGDPS Rigid Analysis Report

Station	Lane	Static k-value, psi/inch	E_{pcc} ,psi
0	EB	147	1,468,521
250	EB	163	1,793,278
0	WB	152	1,399,546
125	WB	176	1,802,290

The report shall also include the average load, and the average, minimum, maximum and standard deviation of the static k-value and modulus of the PCC for each section analyzed.

Table 19. Example AGDPS Rigid Analysis Summary

Parameter	Average	Minimum	Maximum	Standard Deviation
Static k-value, psi/inch	160	147	176	12.9
E_{pcc} ,psi	1,615,909	1,399,546	1,802,290	211,923

4.2.3 Load Transfer Efficiency

Load transfer efficiency (LTE) shall be calculated using MODTAG. LTE shall be calculated for all load levels and for both joint approach (JA) and joint leave (JL) tests.

The report shall include a table showing the station, lane, load, test type (i.e. JA or JL), and LTE. An example is shown in Table 20.

Table 20. Example LTE Report

Station	Lane	Test Type	LTE, %
0	EB	JA	72
1	EB	JL	69
258	EB	JA	88
259	EB	JL	85

The report shall also include a summary table for each section, nominal load showing the test type and average, minimum, maximum and standard deviation of LTE for each section analyzed. An example is shown in Table 21.

Table 21. Example LTE Summary.

Parameter	Average	Minimum	Maximum	Standard Deviation
LTE from JA, %	80	72	88	7.5
LTE From JL, %	73	69	79	4.2

4.2.4 Void Detection

Void detection analysis shall be performed using MODTAG. The report shall include a table showing the station, lane, x-intercept and whether a void was detected for each void detection test. An example is shown in Table 22.

Table 22. Example Void Detection Report

Station	Lane	X-intercept, mils	Void Detected?
0	EB	0.8	No
16	EB	0.3	No
31	EB	2.9	Yes
45	EB	1.5	No

4.3 Reporting Requirements

The reporting requirements for analysis results are included in the sections of this document that discuss each analysis type. In addition to those tables described, the report shall include all inputs to the MODTAG program used. These inputs include the following:

- Final layer model for each section, including layer thickness, seed moduli, and Poisson's ratios (if applicable)
- Temperature data and source. If sub-surface temperatures were collected, those measurements shall be documented in the report. Otherwise the previous day's air temperature used in the BELLS3 equation and it's source shall be included in the report

In addition, the raw FWD data files and MODTAG project files shall be submitted to FLH in electronic format.

5 RECOMMENDATIONS FOR RESEARCH AND DEVELOPMENT

The analysis of FWD data has been the subject of much research over the last two decades. However, these research findings have been slow to find their way into practice. Part of the reason for the slow rate of adoption is due to the interrelation of FWD analysis procedures and pavement design procedures: It makes little sense for an agency to use FWD data to determine pavement parameters that are not inputs to the agency's pavement design procedure. Implementation of the MEPDG should spur parallel implementations of findings from research into FWD data analysis procedures.

The MEPDG's treatment of the stress-dependency of unbound pavement materials has important implications for the analysis of FWD data. Several programs, MODTAG included, can backcalculate the parameters for stress dependency models. MODTAG does not include the specific stress dependency model used in the MEPDG, however. The accuracy of non-linear backcalculation requires further research. Changes to certain types of FWD equipment to allow the collection of deflection data at more than four load levels may enhance the accuracy of non-linear backcalculation.

The MEPDG's treatment of the load frequency dependence of asphalt-bound pavement materials also has implications for the collection and analysis of pavement deflection data. The MEPDG uses the dynamic modulus, not the resilient modulus, to characterize the stiffness of asphalt materials. The dynamic modulus is frequency dependent. To determine the dynamic modulus, load and deflection data at several different frequencies must be collected. In contrast, an FWD produces deflections using a load with a spectrum of frequency contents, and that spectrum is not easily modifiable. Further research is required to develop methods to convert the asphalt resilient modulus backcalculated from FWD deflection data to the dynamic modulus used by the MEPDG. Further development of dynamic deflectometer equipment and analysis methods may yield a system more compatible with the MEPDG than current FWDs.

These guidelines were based on the use of MODTAG for the analysis of FWD data as it was determined to be the FWD analysis software most suited to FHL's current and future needs. The following recommendations are provided for future enhancements to MODTAG:

- Removal of deflection basins that fail data checks. MODTAG currently will alert the user to deflection basins that fail data checks, but no provision is made for automatic deletion or suppression of such records.
- Removal of sensor data. MODTAG should include the capability to delete or suppress the data from a specific sensor for all records.
- Addition of constitutive equation used by the MEPDG. MODCOMP (and by extension, MODTAG) should include the constitutive equation used by the MEPDG to model the stress dependency of unbound materials as an option for non-linear backcalculation. This equation is shown in Equation 14.

- Addition of PCC backcalculation methods described in the 1998 supplement to the AGDPS.

We recommend that FWD manufacturers add to their equipment the capability to report the contact load and load pulse duration. Although most analysis procedures do not include this information, it may be of use when comparing results from FWDs of different design.

REFERENCES

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