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16. Abstract

This report presents an evaluation of the Model 8000 Falling Weight Deflectometer (FWD) manufactured by Dynatest as to variability and repeatability over a nominal range from 1,500 to 24,000 pounds and several rigid pavement structures. For the tests performed in this study the FWD exhibited statistically satisfactory values of variability and repeatability.

Data are presented illustrating insitu moduli of rigid pavement layers using FWD deflection measurements. These values are compared to values generated by other devices.

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THE FALLING WEIGHT DEFLECTOMETER FOR NONDESTRUCTIVE EVALUATION OF RIGID PAVEMENTS

by

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Research Report Number 387-3F

Purchasing and Adapting a Falling Weight
Deflectometer for Non-Destructive Evaluation and
Research on Rigid Pavements in Texas
Research Project 3-8-84-387

conducted for

Texas State Department of Highways
and Public Transportation

in cooperation with the
U. S. Department of Transportation
Federal Highway Administration

by the

Center for Transportation Research
Bureau of Engineering Research
The University of Texas at Austin

November 1985

PREFACE

This report is the third and final report on nondestructive evaluation of pavements conducted under Research Project 3-8-84-387, "Purchasing and Adapting a Falling Weight Deflectometer for Nondestructive Evaluation and Research on Rigid Pavements in Texas". This research project was conducted at the Center for Transportation Research, The University of Texas at Austin, as part of the Cooperative Highway Research Program sponsored by the State Department of Highways and Public Transportation and the Federal Highway Administration. An evaluation of the Falling Weight Deflectometer and methods for void detection and joint efficiency are presented in this report.

The authors gratefully acknowledge valuable discussions and contributions of Professor B. F. McCullough and Chhote L. Saraf, Research Engineer in the Center for Transportation Research, The University of Texas at Austin. The authors are especially grateful to the staff of the Center for Transportation Research, who provided technical assistance and support. Appreciation is also extended to Gustavo Morales-Valentin for his assistance in writing the draft for Chapters 2, Thanks are also due to Messrs. Jerome Daleiden, Richard Rogers, Bob Mikulin, and others at the Texas State Department of Highways and Public Transportation for their cooperation and interest in the research project.

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LIST OF REPORTS

Research Report 387-1, "A Methodology for Structural Evaluation of Pavements Based on Dynamic Deflections," by Waheed Uddin, A. H. Meyer, and W. Ronald Hudson, presents the development of two computer programs, RPEDD1 and FPEDD1, for comprehensive structural evaluation of rigid and flexible pavements using dynamic deflection basin data, for use by Texas State Department of Highways and Public Transportation. July, 1985.

Research Report 387-2, "A User's Guide for Pavement Evaluation Programs RPEDD1 and FPEDD1," by Waheed Uddin, A. H. Meyer, and W. Ronald Hudson, is a stand-alone user's manual for computer programs RPEDD1 and FPEDD1, developed and described in Research Report 387-1. August 1985.

Research Report 387-3F, "The Falling Weight Deflectometer for Nondestructive Evaluation of Rigid Pavements," by Eduardo A. Ricci, A. H. Meyer, W. R. Hudson, and K. H. Stokoe II, presents the use of the FWD in rigid pavement structural evaluation, void detection, and determination of joint-efficiency for the Texas State Department of Highways and Public Transportation. November 1985.

ABSTRACT

This report presents an evaluation of the Model 8000 Falling Weight Deflectometer (FWD) manufactured by Dynatest as to variability and repeatability over a nominal range from 1,500 to 24,000 pounds and several rigid pavement structures. For the tests performed in this study the FWD exhibited statistically satisfactory values of variability and repeatability.

Data are presented illustrating insitu moduli of rigid pavement layers using FWD deflection measurements. These values are compared to values generated by other devices.

A procedure and criteria are presented for evaluating the load transfer efficiency of joints in rigid pavements.

A procedure and criteria are presented for detecting the presence of voids under the surface layer of rigid pavements.

KEYWORDS: Nondestructive testing (NDT), falling weight deflectometer (FWD), load transfer, void detections, insitu elastic modulus, pavement evaluation, joint evaluation, and rigid pavement.

SUMMARY

A Model 8000 Falling Weight Deflectometer (FWD) manufactured by Dynatest was purchased, evaluated, and implemented for use by the Texas State Department of Highways and Public Transportation (SDHPT).

A series of measurements using nominal loads ranging from 1,500 to 24,000 pounds were made on a variety of rigid pavement structures to evaluate the variability and the repeatability of the FWD. The variability and the repeatability of the FWD were found to be as good as or better than those of other devices used for similar purposes. It was observed that measurements made with loads below 6,000 pounds showed higher variability than those made with loads above 6,000 pounds.

Insitu elastic moduli (E) for the pavement layers were back calculated from deflection measurements made with the FWD using the RPEDD1 program. These values are compared to those generated by other devices. For rigid pavements the FWD generates higher E values for the surface layer than does the Dynaflect. For insitu moduli measurements with the FWD it is recommended that a nominal load of 18,000 pounds be used.

A procedure and criteria are presented for evaluating the load transfer efficiency of joints in rigid pavements. These are based on the joint deflection ratios for deflections measured with the load applied to one side of the joint and then the other.

A procedure and criteria for indicating the presence of a void beneath the pavement surface are presented. The criteria are based on angles generated by the deflection basins.

Data and results of field measurements for insitu elastic moduli, load transfer joint efficiency, and void detection are presented.

Conclusions and recommendations concerning the implementation of the FWD by the Texas State Department of Highways and Public Transportation (SDHPT) are presented.

IMPLEMENTATION STATEMENT

Procedures and criteria for using the FWD to measure insitu moduli, to evaluate joint load transfer efficiency, and to detect the presence of voids in rigid pavements, have been developed and can be implemented immediately by the Texas State Department of Highways and Public Transportation (SDHPT). These represent an improvement over the procedures now used for void detection and joint load transfer evaluation. These procedures may result in a substantial savings for both project and network levels of pavement management.

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CHAPTER 1. INTRODUCTION

BACKGROUND

Nondestructive structural evaluation of pavements is an important part of the pavement management process, particularly at the project level. Measurements of pavement surface deflection are generally used for this purpose. These deflection data are analyzed to determine the structural adequacy of the pavement. The ever growing demand for faster, easier to use, and more mobile nondestructive testing (NDT) devices for pavement evaluation has resulted in the development of dynamic devices, such as the Dynaflect, in the 1960's (Ref 1), to replace the conventional time-consuming Benkelman Beam. Because pavement materials do not exhibit ideal linear elastic behavior and because pavement response is affected by the applied stress level, as well as the rate and mode of loading, several other types of NDT devices, such as the Road Rater (Ref 2) and the Falling Weight Deflectometer (Ref 3), have also been developed.

The development of commercially available dynamic NDT devices and increased research efforts towards applying a more rational and mechanistic approach for structural evaluation of pavements have resulted in the application of multilayered linear elastic theory for analyzing the measured deflection basins to estimate insitu material characteristics of pavement layers and for subsequent overlay design by predicting critical strains and stresses in the pavement.

The Dynaflect has traditionally been used for structural evaluation of rigid pavements in Texas. Instead of the transient load signal induced in the pavement structure by a moving truck, the Dynaflect applies a sinusoidal force of relatively light magnitude on the pavement surface. Moreover, it has been found that the Dynaflect deflections are significantly influenced at the pavement edge and corner by temperature differentials in the slab. These factors and some unusual field results have suggested that special problems may exist in the evaluation of rigid pavements. The capability of the Falling Weight Deflectometer to induce a transient pulse on the pavement surface similar to the load of a moving truck wheel and to vary the load amplitude suggest it is a reasonable choice for rigid pavement evaluation.

OBJECTIVES AND SCOPE OF STUDY

The objective of this study were as follows:

(1) To purchase and adapt for immediate use by the Texas State Department of Highway and Public Transportation (SDHPT) a commercially available Falling Weight Deflectometer (FWD) which would apply variable loads to the pavements to approximate the overloads which are causing damage to the pavements.

(2) To use the capability of the FWD to vary the magnitude of peak load to investigate the behavior of rigid pavements in the nonlinear range, such as when curling or with voids under the slab.

(3) To compare the material characterization of pavement layers from measured FWD deflections with those of the Spectral-Analysis-of-Surface-Waves Method (SASW) [developed in Research Project 3-8-80-256 (Ref 24)] and the Dynaflect for structural evaluation and overlay design of rigid pavements.

(4) To develop a procedure for using FWD testing to evaluate load transfer efficiency across joints and cracks.

(5) To improve the analysis of FWD deflection data by devoting research efforts to developing a model for dynamic analysis of FWD test results.

A commercially available FWD was purchased by the Center for Transportation Research for use by the Texas State Department of Highways and Public Transportation (SDHPT). A brief description of the activities related to this task is included in Chapter 2. The equipment has been in use under the supervision of the Texas SDHPT since its delivery in July 1984.

An experiment was designed to evaluate the influence on FWD measurements of environmental effects which cause the pavement to warp or curl. The experiment included other factors, such as void detection and load transfer across tranverse joints and cracks. A description of this experiment is included in Chapter 3.

The capabilities of the FWD were evaluated, including data collection from the field experiment described in Chapter 3. Guidelines for making measurements with the FWD were as described in Chapter 4. A comparison of the FWD with other NDT devices, such as the Dynaflect and SASW (Spectral Analysis of Surface Waves), is described in Chapter 5.

Chapter 6 presents a discussion of the use of the FWD in joint and void testing and Chapter 7 presents final recommendations.

CHAPTER 2. THE FALLING WEIGHT DEFLECTOMETER

GENERAL DESCRIPTION

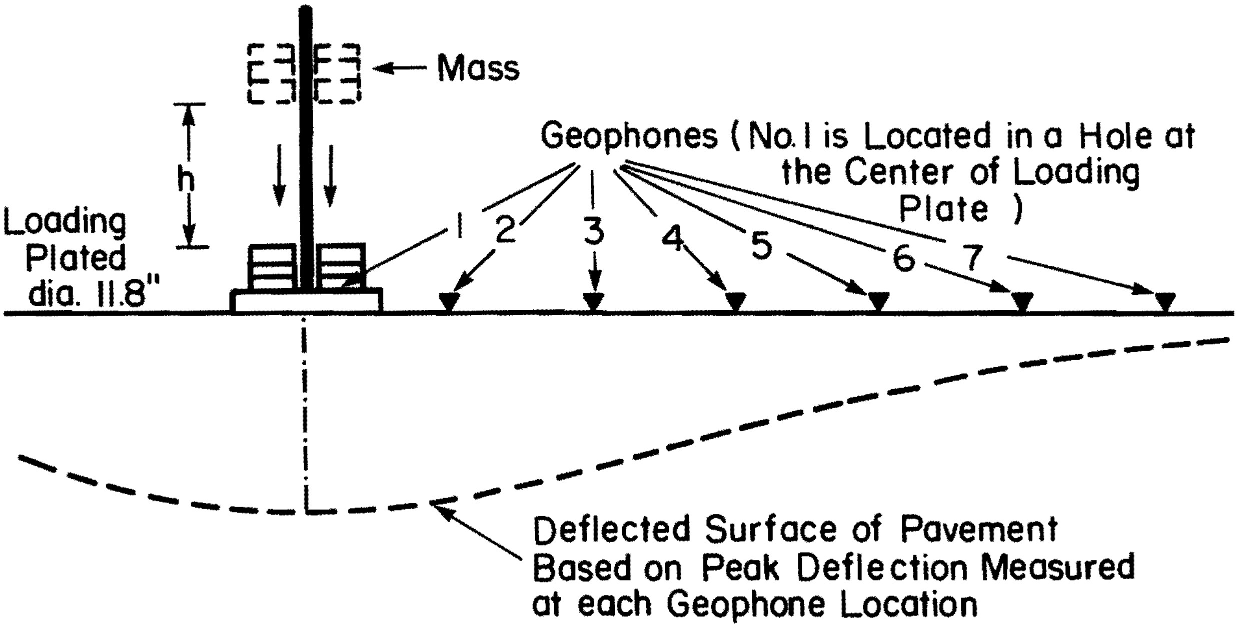
The Falling Weight Deflectometer (FWD) is a pavement loading device used to produce transient impulse forces. The load or equivalent analysis is applied to the pavement through a circular loading plate. The applied load, measured by a load cell above the loading plate, produces a corresponding deflection of the pavement structure. This deflection is measured by seismic deflection transducers placed at selected points to determine the deflection basin.

While the FWD may be towed by a mid-size or larger automobile it is recommended that a truck-type towing vehicle with a heavy duty alternator, radiator, transmission, and air conditioner be used. The test procedures for the FWD can be controlled by the driver via the keyboard of a microcomputer inside the vehicle. The microcomputer is interfaced with the system processor which controls the FWD operation and performs scanning and conditioning of the transducer signals.

Loading and Deflection Measuring System

Basically an FWD applies an impulse load by dropping a known mass from a predetermined height, as illustrated in Fig 2.1. The mass falls on a foot plate connected to a rigid base plate by rubber buffers, which act as springs. A properly designed mass configuration and springs are very important to achieving the desired peak stress, shape, and duration of the FWD force signal. The force can theoretically be calculated using the following relationship:

$$P = (2 \cdot g \cdot h \cdot m \cdot k)^{1/2} \qquad (2.1)$$



(a) FWD in operating position.

(b) Load-time history of FWD
on pavement surface.

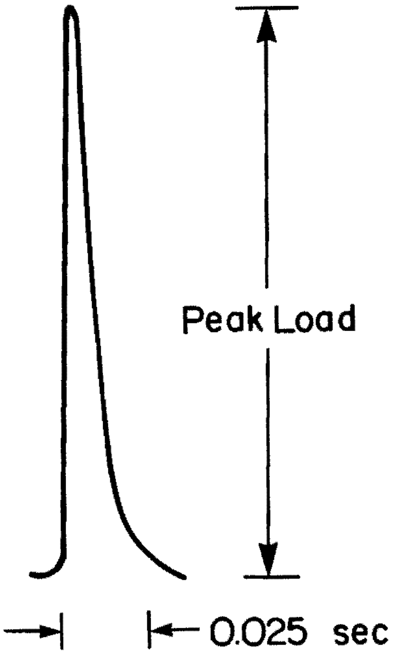


Fig 2.1. Principle of a Falling Weight Deflectometer - FWD test.

where

P = peak force, pounds-force;

g = acceleration due to gravity, feet/second;

h = height of drop of the mass, feet;

m = mass of FWD, pounds; and

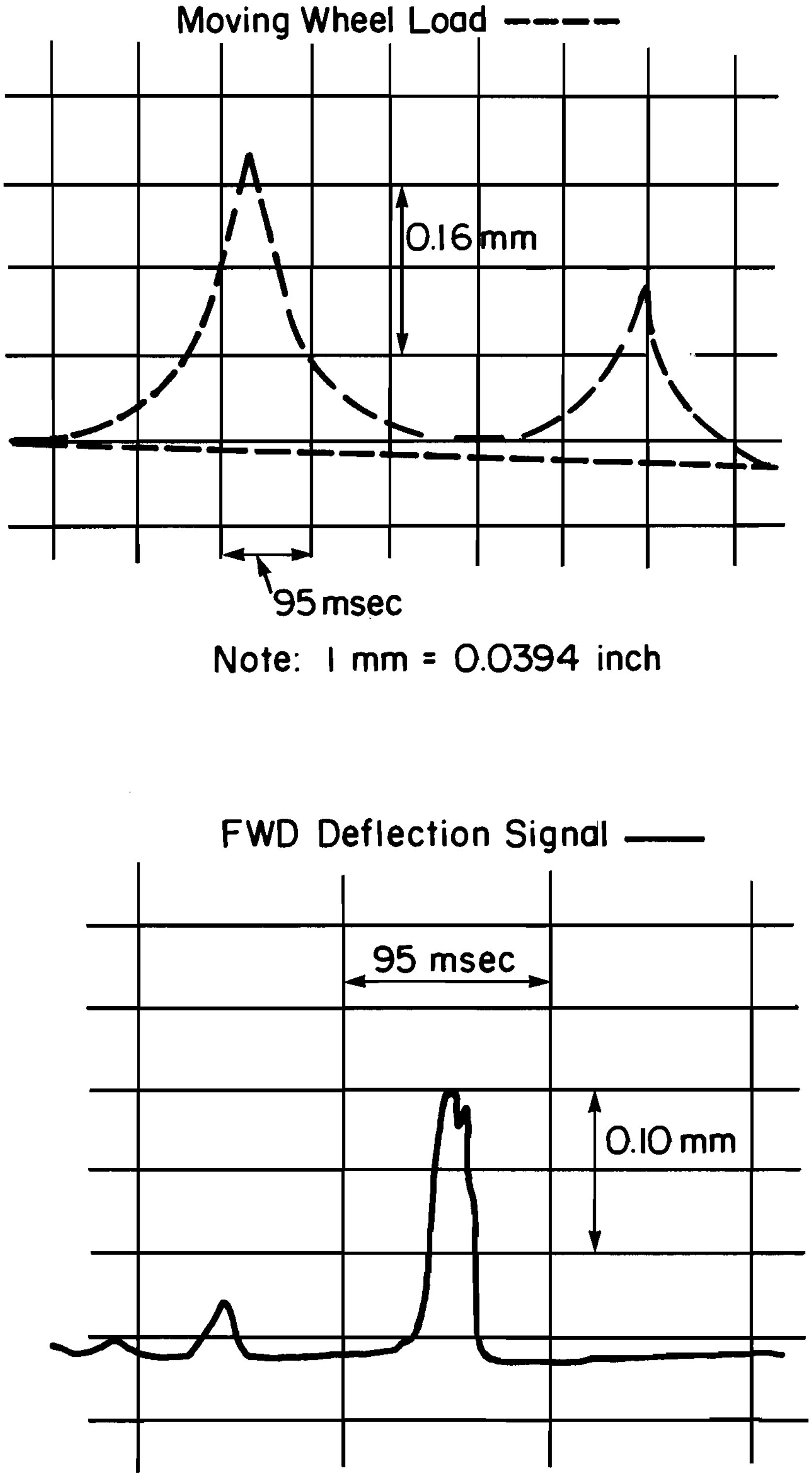
k = spring constant.

However, in routine FWD testing, peak force is measured by a load cell. The Danish version of the FWD has been studied in detail by comparing the results with a moving wheel load, as described by Bohn et al (Ref 3). Tholen et al (Ref 10) describe good agreement of FWD and moving wheel load deflections. Typical FWD dynamic deflection signals are illustrated in Fig 2.2(a). The same figure also shows measured deflection signals under a moving wheel load, indicating that the FWD test response resembles a moving wheel load response. The duration of the FWD deflection signal is around 25 milliseconds, somewhat shorter than the duration of the deflection signal under a moving wheel load. The comparisons of stresses and strains as reported by Bohn et al (Ref 3) are illustrated in Fig 2.2(b). The capability of the FWD to apply a variable load in both the low and higher load ranges is a useful feature for structural evaluation of pavements. In the last few years, many agencies in the U. S. have acquired FWD units and have used them for structural evaluation and insitu material characterization of pavements and also for load transfer and void detection studies on rigid pavements (Ref 11). A comparative field study was made in Texas of the FWD and the Dynaflect on rigid and flexible pavements (Ref 12). A comparative study in Illinois of the FWD and the Road Rater has been reported (Ref 13). Bush (Ref 6) describes laboratory checks on the accuracy of force signals and geophone outputs and field comparisons of FWD and other NDT devices, which are summarized in Table 2.1.

After much discussion of the pros and cons of the equipment available a study advisory panel selected for purchase the Model 8000 Dynatest FWD marketed in the United States by Dynatest. The selection was strongly influenced by the recent history of use by several agencies in the United

TABLE 2.1. SUMMARY OF ACCURACY CHECKS ON MEASUREMENTS OF DYNAMIC FORCE AND DEFLECTION SIGNALS

Signal	Device	Percent Error
Deflection Signal (Velocity Transducers)	Dynaflect	5.5
	FWD	5.1
Dynamic Force Signal	Dynaflect	
	Rigid Pavements	- 4.2
	Flexible Pavements	- 12.9
	FWD	- 5.4



Note: 1 mm = 0.0394 inch

Fig 2.2(a). Typical deflection-time history records (Ref 3).

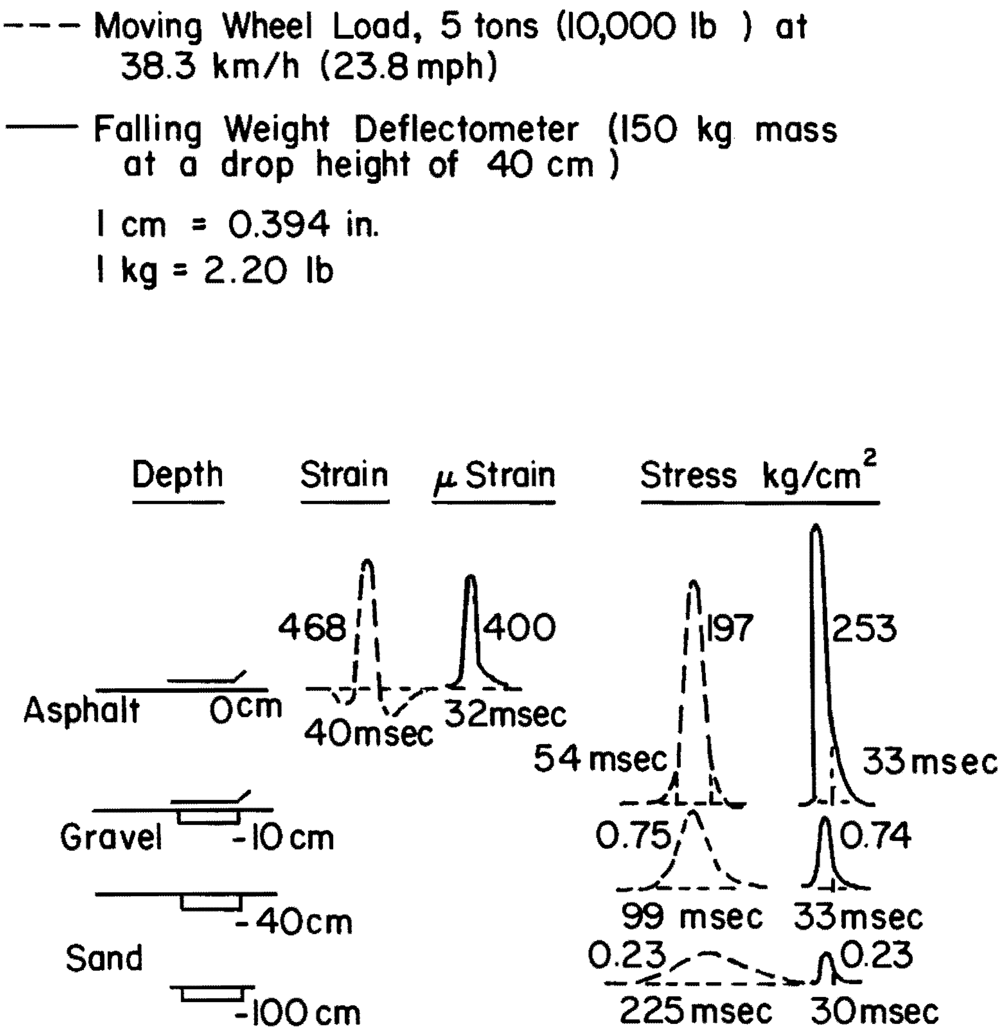


Fig 2.2(b). Typical records of stress-time history and strain-time history at different depths in a pavement (Ref 3).

States. The equipment was purchased by the Center for Transportation Research for the Texas State Department of Highways and Public Transportation and was delivered in July of 1984.

Description and Operating Characteristics of Model 8000 Falling Weight Deflectometer

The material presented here is based on the information provided in Ref 14. The FWD is a trailer mounted device which can be towed by any standard passenger car or van at highway speeds. The total weight of the impulse generating device and the trailer does not exceed 2,000 pounds. The transient pulse generating device is the trailer mounted frame capable of directing different mass configurations to fall from a preset height, perpendicular to the surface. This gives the capability to produce a wide range of peak force amplitudes, as indicated by Eq 2.1, where peak force can be changed by varying mass and/or height. (In the older models, a fixed mass was used, as described in Refs 3, 12, and 13.) The assembly consists of the mass, the frame, loading plates, and a rubber buffer, which acts as a spring. The operation of lifting and dropping the mass on the loading plate is based on an electro-hydraulic system.

The falling weight/buffer subassembly is furnished so that four different configurations of mass can be employed. All four mass configurations produce a transient reproducible load pulse of approximately a half-sine wave and 25 to 30 milliseconds in duration. The drop weights are constructed so that the falling weight/buffer subassembly can be quickly and conveniently changed between falling masses. The buffers are constructed so as to clearly indicate which drop weight configuration they accompany. Each of these falling weight/buffer combinations is constructed to be capable of releasing the weight from various heights, such that different peak loads for the four specified masses are producible in the following ranges:

Falling Weight (lb)	Peak Loading Force (lbf)
110	1,500 - 4,000
220	3,000 - 8,000
440	5,500 - 16,000
660	8,000 - 24,000

For routine testing, a loading plate 11.8 inches (300 mm) in diameter is used. The mass guide shaft is perpendicular to the road surface in the measuring mode as well as the transport mode. The system includes a load cell capable of accurately measuring the force that is applied perpendicular to the loading plate. The force is expressed in terms of pressure. The load cell can be removed for calibration.

The system can provide seven separate deflection measurements per test. One of the deflection sensing transducers (geophones) measures the deflection of the pavement surface through the center of the loading plate, while the six remaining transducers can be positioned along the raise/lower bar, up to 7 feet from the center of the loading plate. All deflection sensing transducer holders are spring loaded, insuring good contact between the transducers and the surface being tested. An extension geophone bar is provided to measure deflection on the opposite side of the load plate. This facilitates load transfer studies on jointed rigid pavements. The unit is capable of testing in the long distance towing position by simply lowering the loading plate/mass/seismic detector bar subassembly to the pavement surface with controls located within the towing vehicle. The trailer is also equipped with a hand pump so that the loading plate/mass/seismic detector bar subassembly can be raised manually if the electro-hydraulic system fails. The electronic registration equipment is operated by a nominal 12 volt DC power supply taken from the towing vehicle. The system purchased includes a Hewlett-Packard Model 85 Computer, which features a cassette tape recording/playback, a CRT display, and a thermal printer for recording data from field testing and keyed-in site identification information (Fig 2.3). All operations of testing are performed from the keyboard of the computer.

Test Procedure

The routine test procedure is briefly described here.

(1) The FWD trailer is towed to the test location. The trailer is positioned in the desired test location.

(2) The processing equipment and HP-85 computer which are carried in the towing vehicle are activated.

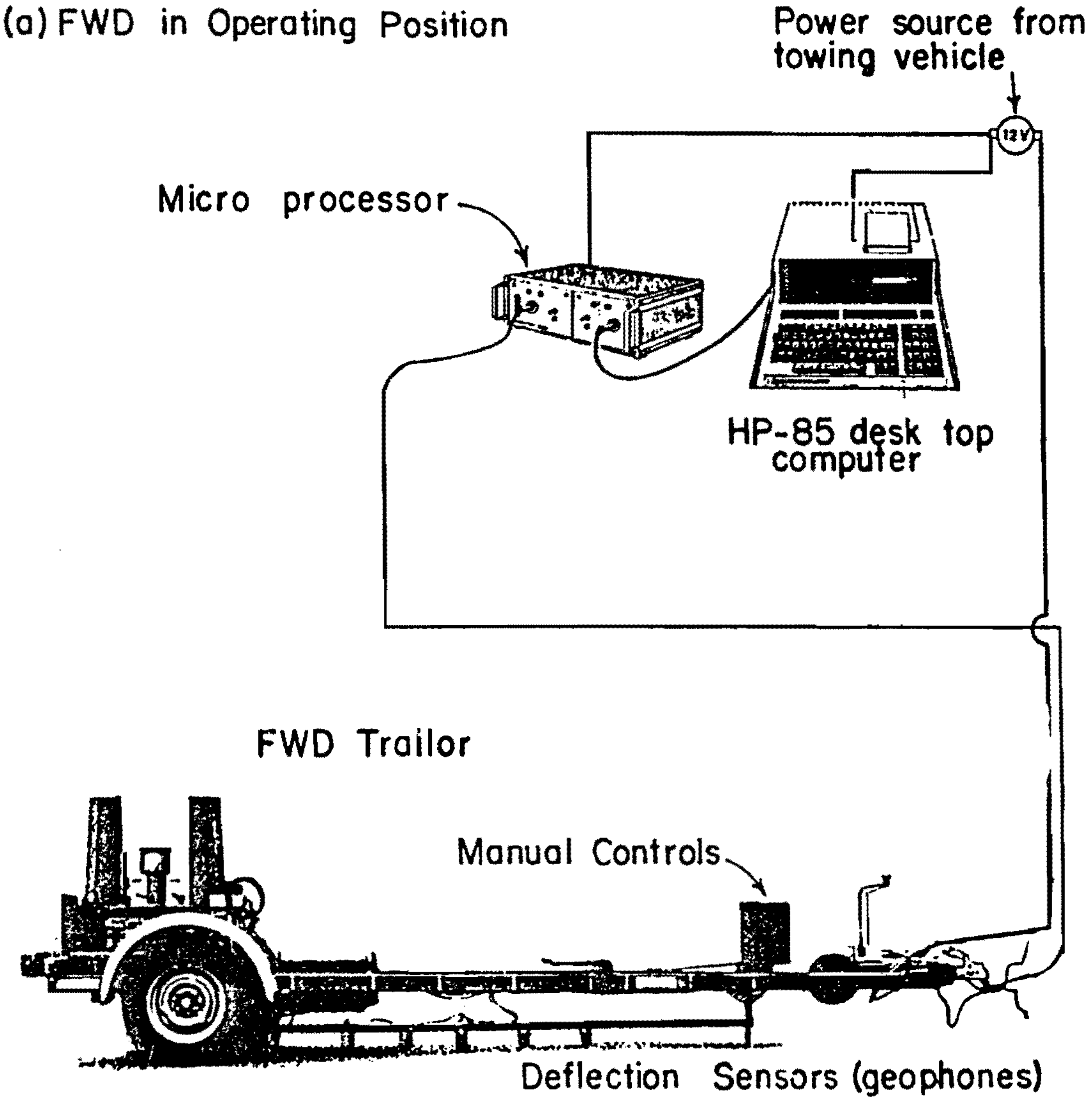
(3) The mass configuration is selected using the guide lines given in the earlier section and secured in place.

(4) A test sequence is identified and programmed from the HP-85 keyboard (site identification, height and number of drops per test point, etc.). When the operator enters a "run" command, the FWD loading plate/buffer/geophone bar assembly is lowered to the pavement surface. The weight is dropped (e.g., 3 times) from the pre-programmed height and the plate and bar assembly are raised again.

(5) A beep signal indicates that driving to the next test location is allowed. The test sequence described in Step 4 lasts approximately one minute.

(6) The measured set of deflection data (peak values of geophone responses) is displayed on the HP-85 CRT screen for direct visual inspection.

(7) If the operator does not enter a "skip" command within a pre-programmed time, the deflection data are stored on the HP-85 magnetic tape cassette together with the peak force magnitude and site identification information. The data are also printed, using the thermal printer.


(a) FWD in Operating Position

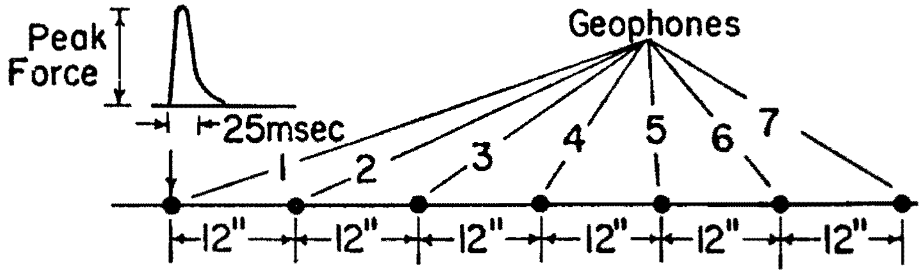

(b) Geophones Configuration

Fig 2.3. Illustration of Model 8000 FWD.

SOFTWARE PACKAGE FOR DATA PROCESSING

An operating software package is provided with the system and used to control the FWD operation from the keyboard of the computer in an interactive mode. The menu driven program guides the operator during testing with appropriate messages on the CRT screen and audio signals.

A special software package called FFPLOT plots the deflection and load-time history in a three dimensional representation. FFPLOT was developed for research purposes and was provided for this study.

CHAPTER 3. EXPERIMENTAL DESIGN

In order to evaluate the variability of the FWD with respect to applied load and measured deflections, an experiment was designed using six load levels and three deflection levels.

LOAD LEVEL

The six load levels were nominally 1,300; 3,000; 6,000; 9,000; 18,000; and 24,000 pounds. Using the guidelines provided in the operating manual the appropriate masses and drop heights were selected to generate the nominal loads. The actual load obtained is a function of, in addition to the masses used, the drop height, the stiffness of the pavement structure, and the temperature. The stiffer the pavement structure the higher the actual load for a given mass and drop height.

Since the FWD uses a set of polymeric springs to damper the applied load, the spring constant increases as the temperature decreases and thus the indicated actual load increases for the same mass and drop height.

The manufacturer recommends brief experimentation when testing new sections of pavement to verify that the desired load ranges are being obtained or if not to make necessary adjustments.

DEFLECTION LEVEL

Three deflection levels were used which represented three deflection thresholds. The deflection level is a function of the pavement structure and is influenced by the strength and/or stiffness and the thickness of each layer and the strength and/or stiffness of the supporting subgrade. For two locations with the same surface structure, higher deflections will be measured at the locations with the weaker subgrade support.

For purposes of this analysis the locations are grouped by the magnitude of the measured deflections for similar loads into a high, medium, or low groups. Four locations were used in this experiment, with repeated measurements at two locations for a total of six test sites. The location of each site and the general cross section of the pavement structure at each site are shown in Figs 3.1(a) and 3.1(b).

The Gainesville location is a jointed pavement near the end of its design life and was being prepared for overlay or reconstruction. The two Houston locations are new construction before being opened to traffic. The Balcones Research Center (BRC) location is a research test slab facility.

TEST CONDITIONS

In all cases, for this particular experiment, tests were made at the center of the slab away from any edge, joint, or crack. This procedure was used because the purpose of the experiment was to evaluate the equipment under various conditions and not necessarily to evaluate the pavement structure.

Two test conditions were used to measure repeatability and reproducibility. One condition was to lower the sensor arm to the pavement and to drop the predetermined weight eight times and to record the deflection of each sensor after each drop. The second condition was to raise and lower the sensor arm between each of the eight drops.

The experimental design is illustrated graphically in Fig 3.2.

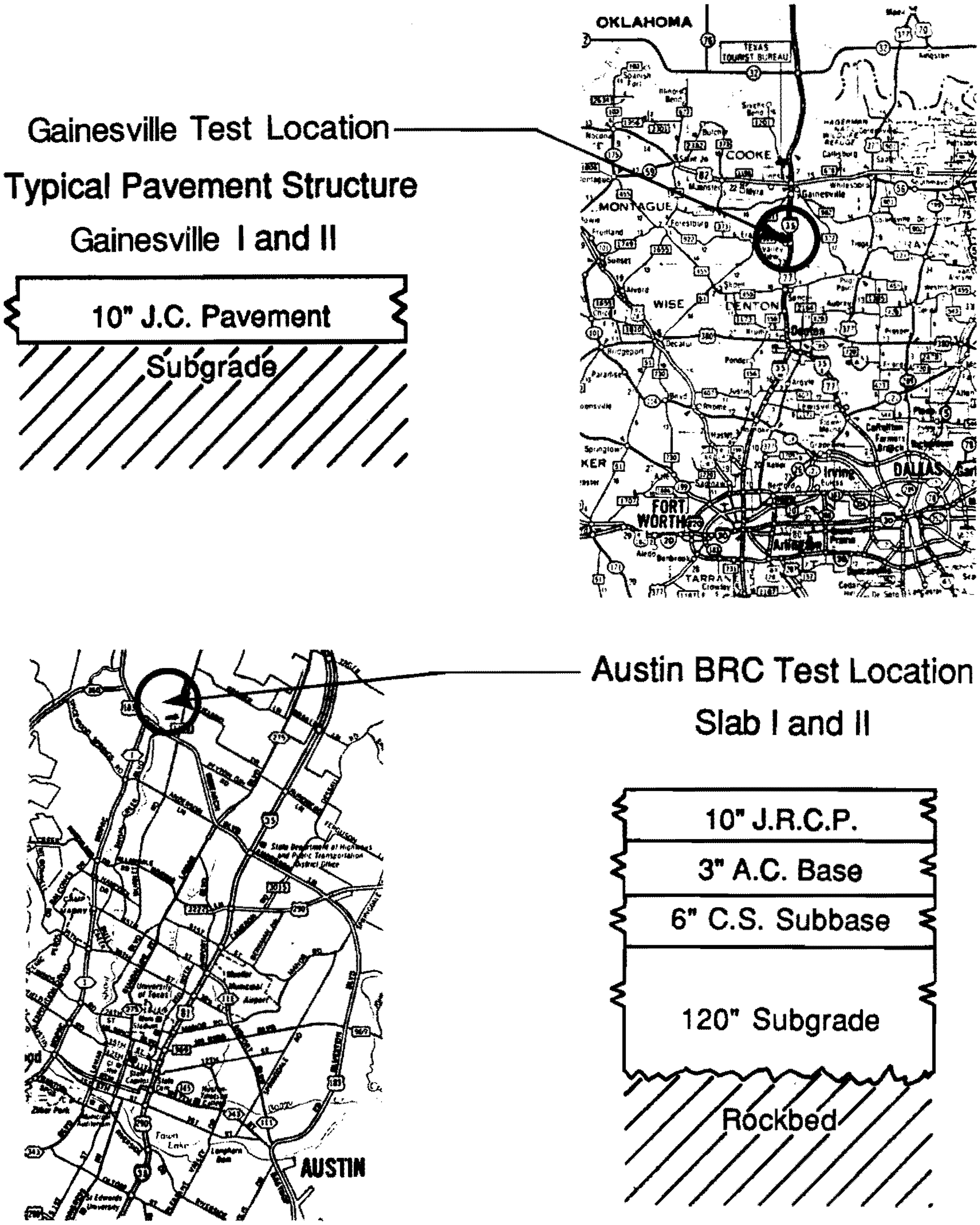


Fig 3.1(a). Test site locations.

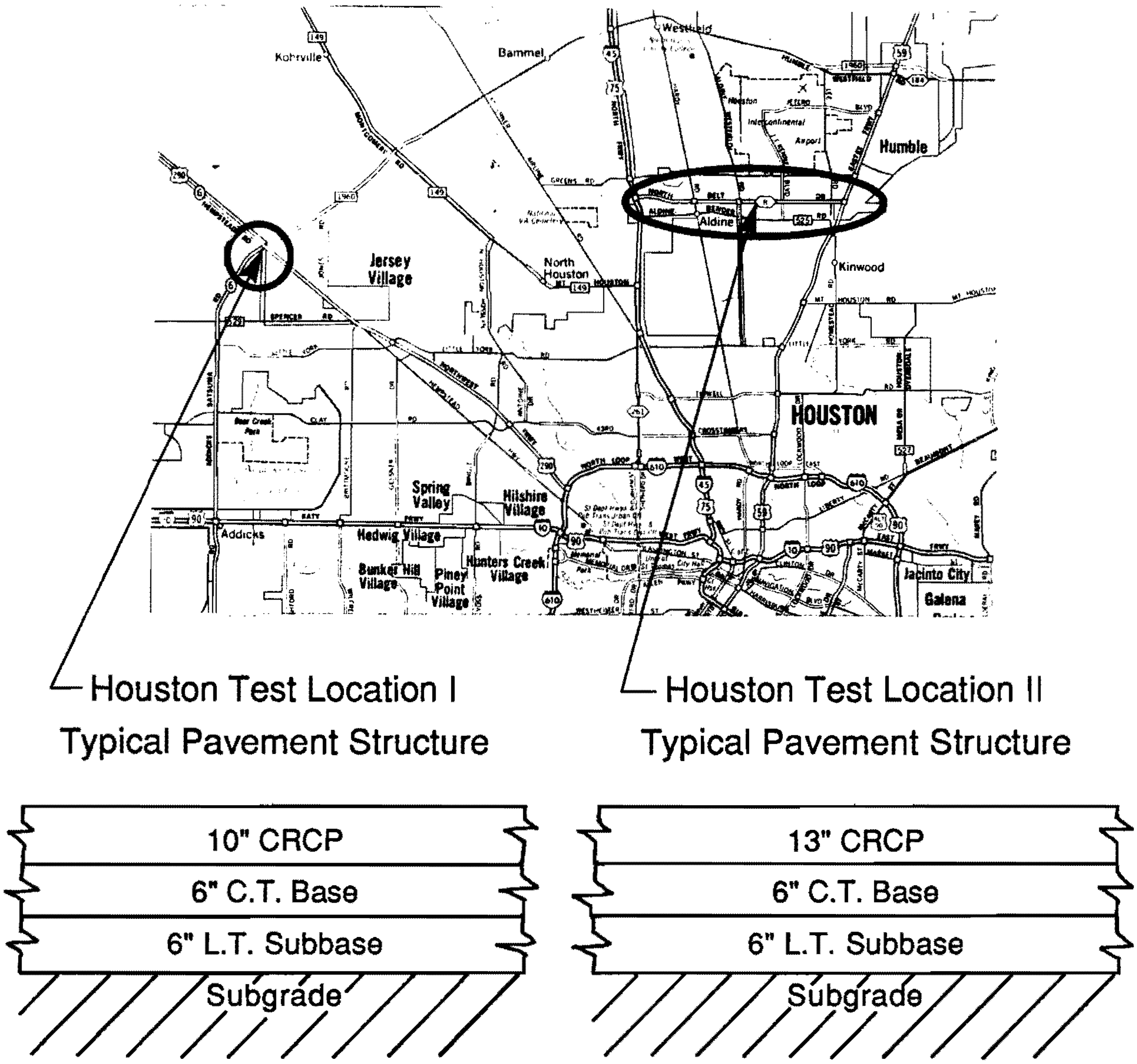


Fig 3.1(b). Test site locations.

Deflection Level

Force Level (lb)	Low	Medium	High
24,000			
18,000			
9000			
6000			
3000			
1300			

Low Level Deflections :Houston Test Location I

Medium Level Deflections : Houston Test Location II
B.R.C. Slab. I and II

High Level Deflections : Gainesville I and II

Fig 3.2. Experimental design.

CHAPTER 4. FALLING WEIGHT DEFLECTOMETER (FWD) EVALUATION ANALYSIS

There were two phases in this evaluation of the FWD capabilities:

(1) evaluate the repeatability of the load applied to the pavement surface by the FWD and
(2) evaluate the capability of the FWD to produce a well defined measurement of the deflection basin.

To accomplish phase (1) eight repetitions of each test drop were made at each peak force level at each of two treatments (lifting the system and not lifting the system between each one of the eight repetitions). The eight repetitions were made in order to evaluate the repeatability of the FWD.

On each of the eight repetitions the computerized system recorded the load and the deflections at each of the seven sensors (geophones). The tests were first performed without lifting the loading plate and the geophones from the pavement surface, and dropping the weights 8 times. Then, at the same location (without moving the towing vehicle) the weights were dropped eight times but the loading plate and geophones were lifted and lowered before each drop. The lifting or not lifting of the system was defined as parameter to determine if the repeatability of the FWD was affected significantly by the choice of operating procedure.

There were 6 peak force levels used at all test sites. These forces were nominally 1,300; 3,000; 6,000; 9,000; 18,000; and 24,000 pounds. The actual force generated by the FWD is a function not only of the drop height, but also of the stiffness of the pavement being examined. The stiffer the pavement the higher the indicated load.

To summarize, the tests were performed at six sites, with six peak force levels, with eight repetitions per site, and with or without lifting the system between each drop at a given location. The deflection at each sensor and the measured forces were recorded for each drop. The factorials used for these experiments are presented in Tables 4.1 and 4.2.

TABLE 4.1. FWD FORCES (LB) - FACTORIAL

Approximate Peak Force Level (lb)	Block Variable	Treatment*	Dependent Variable (Force)		
			Mean (lb)	S.D. (lb)	C.V. (Percent)
1300	1	1			
		2			
3000	2	1			
		2			
6000	3	1			
		2			
9000	4	1			
		2			
18000	5	1			
		2			
24000	6	1			
		2			

*1: without lifting
2: with lifting

TABLE 4.2. FWD DEFLECTION (MILS) - FACTORIAL

Dependent Variable (Sensor)	Block Variable (Force)	Treatment*	(M)	S.D.
S1	1	1		
		2		
	2	1		
		2		
	3	1		
		2		
	4	1		
		2		
	5	1		
		2		
	6	1		
		2		
S2	1	1		
		2		
	2	1		
		2		
	3	1		
		2		
	4	1		
		2		
	5	1		
		2		
	6	1		
		2		
S3	1	1		
		2		
	2	1		
		2		
	3	1		
		2		
	4	1		
		2		
	5	1		
		2		
	6	1		
		2		
S4	1	1		
		2		
	2	1		
		2		
	3	1		
		2		
	4	1		
		2		
	5	1		
		2		
	6	1		
		2		
S5	1	1		
		2		
	2	1		
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	4	1		
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	5	1		
		2		
	6	1		
		2		
S6	1	1		
		2		
	2	1		
		2		
	3	1		
		2		
	4	1		
		2		
	5	1		
		2		
	6	1		
		2		
S7	1	1		
		2		
	2	1		
		2		
	3	1		
		2		
	4	1		
		2		
	5	1		
		2		
	6	1		
		2		

*1: without lifting
2: with lifting

ANALYSIS OF THE DATA

The statistical approach for the analysis of variance is presented first. Afterwards, the analysis and conclusions based on the data are presented.

Analysis of Variance

The analysis of variance was based on randomized block design (Ref 4). The model used is as follows:

$$Y_{ij} = \mu + \beta_i + \tau_j + \varepsilon_{ij}$$

$$i = 1, 2, 3, 4, 5, 6$$
$$j = 1, 2$$

where

Y_{ij} = dependent variable,
β_i = effect of i^{th} block,
τ_j = effect of j^{th} treatment, and
ε_{ij} = error terms $(0, \sigma^2)$.

In this case, the dependent variable is the deflection of a sensor, the block variable is the peak force level, and the treatment is test condition 1 for not lifting the loading plate, and, 2, for lifting it between drops.

Since there were six force levels, two treatments, and eight drops each time, the total number of data points for each sensor (at each testing section) was: 6 x 2 x 8 = 96.

Analysis of the Data

In Tables 4.3 through 4.14, the data from tests performed at the six sites are shown. The results show clearly that at the six sites, the trend was the same. The means of the deflections for each sensor, force level, and treatment are significantly different for every site. This is because the main experimental design included three deflection levels and their replicates, as shown in Chapter 3, Fig 3.2. The results shown in Tables 4.3, 4.5, 4.7, 4.9, 4.11, and 4.13 indicate, based on the standard deviations and the coefficients of variation, that the FWD has an excellent repeatability. The maximum coefficient of variation observed was 4.13 percent. For loads of more than 6,000 pounds (the approximate load level of 6,000 pounds is the one that corresponds to the block variable 3) the coefficient of variation for each set of eight repetitions was typically lower than it was for loads of less than 6,000 pounds.

Tables 4.4, 4.6, 4.8, 4.10, 4.12, and 4.14, illustrate that the deflections measured for the lower loads (1,300 and 3,000 pounds approximately [block variables 1 and 2]) are too small. It should be noted that, for these force levels, all of the deflections have one of two values. This kind of data is, of course, not desirable because it does not define a reasonable deflection basin. In order to get a well defined deflection basin it is necessary to get different values of deflections at the different sensors.

The problem at the lower load levels is the sensitivity of the equipment. The equipment records the deflections with a precision of one tenth of a mil (1/10,000 of an inch). In rigid pavements, the deflections obtained from the lower loads are less than 1 mil, even under the loading plate. As shown in Tables 4.4, 4.6, 4.8, 4.10, 4.12, and 4.14, for the lower loads the deflections obtained do not vary much. In other words, the data are not adequate to describe a reasonable deflection basin. On the other hand, it can be seen that, for loads higher than approximately 6,000 pounds, the data look reasonable.

It is also observed from these tables that the two treatments have little effect on the deflection data. In fact, raising and lowering the

TABLE 4.3. FWD FORCES (LB) RESULTS OF THE TEST AT BRC TESTING FACILITY ON JULY 1985 - SLAB II

Approximate Peak Force Level (lb)	Block Variable	Treatment*	Dependent Variable (Force) Mean (lb)	S.D. (lb)	C.V. (Percent)
1300	1	1	1685	23.8	1.41
		2	1649	68.1	4.13
3000	2	1	2646	81.4	3.08
		2	2738	35.2	1.29
6000	3	1	6741	20.9	0.31
		2	6737	16.3	0.24
9000	4	1	9372	16.0	0.17
		2	9401	46.5	0.46
18000	5	1	18709	106.5	0.57
		2	18748	56.5	0.30
24000	6	1	22829	62.0	0.27
		2	22809	50.3	0.22

*1: without lifting
2: with lifting

TABLE 4.4. FWD DEFLECTION (MILS), RESULTS OF THE TEST AT BRC TESTING FACILITY IN JULY 1985 - SLAB II

Dependent Variable (Sensor)	Block Variable (Force)	Treatment*	(M)	S.D.
S1	1	1	0.3	0.04
		2	0.3	0
	2	1	0.5	0
		2	0.5	0.04
	3	1	1.8	0.05
		2	1.7	0.05
	4	1	2.3	0
		2	2.3	0
	5	1	5.0	0.04
		2	5.0	0.05
	6	1	5.9	0.05
		2	6.0	0.05
S2	1	1	0.2	0.04
		2	0.2	0
	2	1	0.5	0.05
		2	0.5	0.05
	3	1	1.8	0.05
		2	1.4	0
	4	1	2.1	0.05
		2	2.1	0.04
	5	1	4.3	0
		2	4.3	0
	6	1	5.2	0.05
		2	5.2	0.05
S3	1	1	0.2	0
		2	0.2	0.04
	2	1	0.4	0
		2	0.4	0.04
	3	1	1.3	0
		2	1.3	0
	4	1	1.7	0
		2	1.7	0
	5	1	3.7	0.04
		2	3.7	0
	6	1	4.4	0
		2	4.4	0.04
S4	1	1	0.2	0.05
		2	0.2	0.05
	2	1	0.4	0
		2	0.4	0.05
	3	1	1.3	0.05
		2	1.3	0.04
	4	1	1.7	0.04
		2	1.7	0.04
	5	1	3.7	0
		2	3.7	0
	6	1	4.4	0
		2	4.4	0
S5	1	1	0.1	0.05
		2	0.1	0
	2	1	0.3	0.04
		2	0.8	0.05
	3	1	1.1	0
		2	1.0	0
	4	1	1.5	0.04
		2	1.5	0
	5	1	3.1	0.05
		2	3.1	0.05
	6	1	3.7	0.05
		2	3.7	0.06
S6	1	1	0.1	0
		2	0.1	0
	2	1	0.3	0.04
		2	0.3	0.05
	3	1	0.9	0.05
		2	0.9	0.05
	4	1	1.2	0
		2	1.2	0
	5	1	2.6	0
		2	2.6	0
	6	1	3.1	0.05
		2	3.1	0.05
S6	1	1	0.1	0
		2	0.1	0
	2	1	0.2	0.04
		2	0.2	0.05
	3	1	0.8	0.05
		2	0.7	0.05
	4	1	1.0	0
		2	1.0	0
	5	1	2.1	0
		2	2.1	0
	6	1	2.5	0.05
		2	2.4	0.05

*1: without lifting
2: with lifting

TABLE 4.5. FWD FORCES (LB) RESULTS OF THE TEST AT BRC TESTING FACILITY ON DECEMBER 1984 - SLAB I

Approximate Peak Force Level (lb)	Block Variable	Treatment*	Dependent Variable (Force)		
			Mean (lb)	S.D. (lb)	C.V. (Percent)
1300	1	1	1722	45.2	2.63
		2	1784	17.6	0.99
3000	2	1	3005	79.9	2.66
		2	3101	20.9	0.67
6000	3	1	7226	33.1	0.46
		2	7174	33.1	0.46
9000	4	1	9856	36.5	0.37
		2	9781	29.0	0.30
18000	5	1	20078	100.2	0.50
		2	20062	25.9	0.13
24000	6	1	23886	127.6	0.53
		2	23713	42.6	0.18

*1: without lifting
2: with lifting

TABLE 4.6. FWD DEFLECTIONS (MILS), RESULTS OF THE TEST AT BRC TESTING FACILITY IN DECEMBER 1984 - SLAB I

Dependent Variable (Sensor)	Block Variable (Force)	Treatment*	(M)	S.D.	Dependent Variable (Sensor)	Block Variable (Force)	Treatment*	(M)	S.D.	Dependent Variable (Sensor)	Block Variable (Force)	Treatment*	(M)	S.D.
S1	1	1	0.2	0	S4	1	1	0.2	0.04	S7	1	1	0.1	0.05
		2	0.2	0			2	0.2	0.04			2	0.1	0.04
	2	1	0.4	0.05		2	1	0.5	0.05		2	1	0.2	0.04
		2	0.4	0.05			2	0.4	0.05			2	0.3	0.04
	3	1	1.4	0		3	1	1.1	0.04		3	1	0.7	0.05
		2	1.4	0			2	1.1	0			2	0.7	0.05
	4	1	2.1	0.04		4	1	1.6	0.04		4	1	0.9	0
		2	2.0	0.05			2	1.6	0.05			2	0.9	0.05
	5	1	4.3	0		5	1	3.4	0		5	1	2.0	0.05
		2	4.3	0			2	3.4	0			2	1.9	0.05
	6	1	5.2	0.05		6	1	4.0	0		6	1	2.3	0
		2	5.1	0			2	4.0	0.04			2	2.3	0.06
S2	1	1	0.2	0	S5	1	1	0.2	0.05					
		2	0.2	0.04			2	0.2	0.05					
	2	1	0.4	0		2	1	0.3	0.08					
		2	0.4	0			2	0.3	0					
	3	1	1.3	0		3	1	0.9	0.04					
		2	1.3	0.05			2	0.9	0					
	4	1	1.9	0		4	1	1.4	0.05					
		2	1.9	0			2	1.4	0.05					
	5	1	3.9	0.05		5	1	2.7	0.05					
		2	3.9	0			2	2.7	0.05					
	6	1	4.6	0		6	1	3.2	0.05					
		2	4.6	0			2	3.2	0.05					
S3	1	1	0.2	0	S6	1	1	0.1	0.05					
		2	0.2	0.05			2	0.1	0.04					
	2	1	0.4	0		2	1	0.3	0.08					
		2	0.4	0.04			2	0.3	0.05					
	3	1	1.3	0		3	1	0.8	0					
		2	1.3	0.05			2	0.8	0					
	4	1	1.8	0		4	1	1.0	0.04					
		2	1.9	0.05			2	1.1	0.07					
	5	1	3.9	0.05		5	1	2.3	0.05					
		2	3.9	0			2	2.3	0					
	6	1	4.6	0		6	1	2.7	0					
		2	4.6	0.04			2	2.7	0.05					

*1: without lifting
2: with lifting

TABLE 4.7. FWD FORCES (LB) RESULTS OF THE TEST AT GAINESVILLE SITE I

Approximate Peak Force Level (lb)	Block Variable	Treatment*	Dependent Variable (Force) Mean (lb)	S.D. (lb)	C.V. (Percent)
1300	1	1	1751	15.7	0.90
		2	1802	41.2	2.29
3000	2	1	3201	32.4	1.01
		2	3276	19.1	0.58
6000	3	1	7845	123.2	1.57
		2	2855	33.2	1.16
9000	4	1	9762	94.3	0.97
		2	10075	86.6	0.86
18000	5	1	20003	107.2	0.54
		2	19819	29.0	0.15
24000	6	1	24023	144.5	0.60
		2	23822	68.5	0.29

*1: without lifting
2: with lifting

TABLE 4.8. FWD DEFLECTIONS (MILS), RESULTS OF THE TEST AT GAINESVILLE - SITE I

Dependent Variable (Sensor)	Block Variable (Force)	Treatment*	(M)	S.D.	Dependent Variable (Sensor)	Block Variable (Force)	Treatment*	(M)	S.D.	Dependent Variable (Sensor)	Block Variable (Force)	Treatment*	(M)	S.D.
S1	1	1	0.7	0	S4	1	1	0.5	0	S7	1	1	0.3	0.04
		2	0.7	0			2	0.5	0			2	0.3	0
	2	1	1.2	0		2	1	0.9	0		2	1	0.4	0.18
		2	1.2	0			2	0.9	0.04			2	0.5	0
	3	1	3.4	0.05		3	1	2.7	0.04		3	1	1.4	0
		2	3.4	0.04			2	2.7	0			2	1.4	0
	4	1	5.0	0		4	1	4.0	0		4	1	2.2	0
		2	4.9	0.05			2	3.9	0.04			2	2.1	0.04
	5	1	10.0	0.05		5	1	8.0	0.05		5	1	4.3	0
		2	9.9	0.05			2	7.9	0.05			2	4.3	0.04
	6	1	11.5	0.04		6	1	9.2	0		6	1	4.5	0.04
		2	11.3	0.09			2	9.1	0.05			2	4.9	0
S2	1	1	0.6	0.04	S5	1	1	0.4	0					
		2	0.6	0.05			2	0.4	0					
	2	1	1.1	0		2	1	0.8	0.05					
		2	1.1	0			2	0.8	0					
	3	1	3.1	0.05		3	1	2.2	0					
		2	3.1	0			2	2.2	0					
	4	1	4.6	0		4	1	3.3	0.04					
		2	4.5	0.05			2	3.2	0.07					
	5	1	9.1	0.04		5	1	6.6	0.05					
		2	9.0	0			2	6.6	0					
	6	1	10.4	0.05		6	1	7.6	0.05					
		2	10.4	0.05			2	7.6	0					
S3	1	1	0.6	0	S6	1	1	0.3	0.05					
		2	0.6	0.05			2	0.4	0.05					
	2	1	1.1	0		2	1	0.6	0					
		2	1.1	0.04			2	0.6	0.04					
	3	1	3.2	0		3	1	1.8	0					
		2	3.2	0.04			2	1.8	0					
	4	1	4.6	0.04		4	1	2.8	0.04					
		2	4.5	0.08			2	2.6	0.04					
	5	1	9.2	0.05		5	1	5.5	0					
		2	9.1	0.09			2	5.4	0					
	6	1	10.5	0		6	1	6.3	0					
		2	10.2	0.11			2	6.2	0.05					

*1: without lifting
2: with lifting

TABLE 4.9. FWD FORCES (LB) RESULTS OF THE TEST AT GAINESVILLE SITE II

Approximate Peak Force Level (lb)	Block Variable	Treatment*	Dependent Variable (Force) Mean (lb)	S.D. (lb)	C.V. (Percent)
1300	1	1	1794	23.7	1.32
		2	1805	14.1	0.78
3000	2	1	2930	39.6	1.35
		2	3009	25.5	0.85
6000	3	1	6980	41.2	0.59
		2	6953	16.3	0.23
9000	4	1	9669	109.8	1.14
		2	9593	22.4	0.23
18000	5	1	19662	37.2	0.19
		2	19692	20.5	0.10
24000	6	1	23366	79.7	0.34
		2	23262	28.3	0.12

*1: without lifting
2: with lifting

TABLE 4.10. FWD DEFLECTIONS (MILS), RESULTS OF THE TEST AT GAINESVILLE - SITE II

Dependent Variable (Sensor)	Block Variable (Force)	Treatment*	(M)	S.D.	Dependent Variable (Sensor)	Block Variable (Force)	Treatment*	(M)	S.D.	Dependent Variable (Sensor)	Block Variable (Force)	Treatment*	(M)	S.D.
S1	1	1	0.4	0	S4	1	1	0.3	0	S7	1	1	0.2	0
		2	0.4	0			2	0.3	0			2	0.2	0
	2	1	0.9	0.04		2	1	0.7	0		2	1	0.4	0
		2	0.9	0.05			2	0.7	0			2	0.4	0
	3	1	2.4	0		3	1	1.9	0		3	1	1.1	0.04
		2	2.4	0			2	1.9	0			2	1.1	0
	4	1	3.3	0.43		4	1	2.6	0.37		4	1	1.5	0.23
		2	3.4	0			2	2.7	0			2	1.6	0
	5	1	7.0	0.04		5	1	5.5	0		5	1	3.3	0
		2	7.0	0			2	5.5	0			2	3.3	0.04
	6	1	8.2	0.04		6	1	6.4	0		6	1	3.8	0
		2	8.2	0.08			2	6.4	0			2	3.8	0
S2	1	1	0.4	0	S5	1	1	0.3	0					
		2	0.4	0			2	0.3	0.04					
	2	1	0.8	0		2	1	0.6	0					
		2	0.8	0.05			2	0.6	0.05					
	3	1	2.1	0		3	1	1.6	0					
		2	2.1	0			2	1.6	0					
	4	1	2.9	0.39		4	1	2.2	0.30					
		2	3.1	0.05			2	2.3	0.05					
	5	1	6.2	0		5	1	4.7	0					
		2	6.2	0			2	4.7	0					
	6	1	7.2	0.04		6	1	5.5	0.05					
		2	7.2	0			2	5.4	0.05					
S3	1	1	0.4	0.05	S6	1	1	0.2	0.04					
		2	0.4	0			2	0.2	0					
	2	1	0.8	0.04		2	1	0.5	0					
		2	0.8	0.05			2	0.5	0					
	3	1	2.1	0.05		3	1	1.4	0.04					
		2	2.0	0.04			2	1.4	0.04					
	4	1	2.8	0.05		4	1	1.8	0.29					
		2	3.0	0.05			2	1.9	0.05					
	5	1	6.2	0.05		5	1	4.0	0					
		2	6.2	0.05			2	4.0	0					
	6	1	7.1	0.05		6	1	4.7	0.04					
		2	7.1	0.07			2	4.6	0					

*1: without lifting
2: with lifting

TABLE 4.11. FWD FORCES (LB) RESULTS OF THE TEST AT HOUSTON - US 290 HOUSTON SITE I

Approximate Peak Force Level (lb)	Block Variable	Treatment*	Dependent Variable (Force)		
			Mean (lb)	S.D. (lb)	C.V. (Percent)
1300	1	1	1715	27.7	1.61
		2	1736	20.5	1.18
3000	2	1	2702	52.2	1.93
		2	2846	31.9	1.12
6000	3	1	6903	96.1	1.39
		2	6917	17.1	0.25
9000	4	1	9387	21.4	0.23
		2	9388	12.1	0.13
18000	5	1	19261	34.5	0.18
		2	19244	23.4	0.12
24000	6	1	23656	61.4	0.26
		2	23544	37.8	0.16

*1: without lifting
2: with lifting

TABLE 4.12. FWD DEFLECTIONS (MILS), RESULTS OF THE TEST AT HOUSTON - US 290 HOUSTON SITE I

Dependent Variable (Sensor)	Block Variable (Force)	Treatment*	(M)	S.D.	Dependent Variable (Sensor)	Block Variable (Force)	Treatment*	(M)	S.D.	Dependent Variable (Sensor)	Block Variable (Force)	Treatment*	(M)	S.D.
S1	1	1	0.2	0.04	S4	1	1	0.1	0	S7	1	1	0.1	0.05
		2	0.2	0			2	0.1	0			2	0.1	0.05
	2	1	0.4	0.05		2	1	0.3	0		2	1	0.2	0
		2	0.4	0			2	0.3	0			2	0.2	0
	3	1	1.4	0		3	1	1.1	0		3	1	0.6	0
		2	1.4	0.04			2	1.1	0			2	0.6	0.04
	4	1	2.0	0		4	1	1.4	0		4	1	0.8	0.04
		2	2.0	0			2	1.4	0			2	0.8	0.05
	5	1	4.1	0.04		5	1	3.0	0.05		5	1	1.9	0.05
		2	4.1	0			2	2.9	0			2	1.9	0.08
	6	1	5.2	0.07		6	1	3.5	0.05		6	1	2.0	0.20
		2	5.1	0.10			2	3.5	0.05			2	2.3	0.12
S2	1	1	0.2	0	S5	1	1	0.1	0					
		2	0.2	0			2	0.1	0.05					
	2	1	0.4	0		2	1	0.3	0.03					
		2	0.4	0.04			2	0.3	0.05					
	3	1	1.3	0		3	1	0.9	0.05					
		2	1.3	0			2	0.9	0.05					
	4	1	1.8	0		4	1	1.3	0.03					
		2	1.8	0			2	1.3	0.05					
	5	1	3.8	0		5	1	2.6	0.09					
		2	3.8	0			2	2.6	0.05					
	6	1	4.5	0.07		6	1	3.1	0.08					
		2	4.5	0.05			2	3.0	0.06					
S3	1	1	0.2	0.04	S6	1	1	0.1	0					
		2	0.2	0.05			2	0.1	0.04					
	2	1	0.4	0.05		2	1	0.2	0.04					
		2	0.4	0.05			2	0.2	0					
	3	1	1.1	0		3	1	0.8	0					
		2	1.1	0			2	0.8	0.04					
	4	1	1.5	0		4	1	1.1	0					
		2	1.6	0			2	1.1	0.04					
	5	1	3.3	0		5	1	2.2	0.05					
		2	3.3	0			2	2.2	0					
	6	1	3.9	0		6	1	2.7	0.09					
		2	3.8	0.09			2	2.6	0.07					

*1: without lifting
2: with lifting

TABLE 4.13. FWD FORCES (LB) RESULTS OF THE TEST AT HOUSTON - BELTWAY 8 STATION - HOUSTON SITE II

Approximate Peak Force Level (lb)	Block Variable	Treatment*	Dependent Variable (Force) Mean (lb)	S.D. (lb)	C.V. (Percent)
1300	1	1	1814	29.9	1.64
		2	1890	12.7	0.67
3000	2	1	2985	41.3	1.38
		2	3101	23.4	0.75
6000	3	1	7666	57.2	0.75
		2	7731	34.5	0.45
9000	4	1	9897	109.5	1.11
		2	9828	38.5	0.39
18000	5	1	19673	20.7	0.11
		2	19699	28.3	0.14
24000	6	1	23959	43.5	0.18
		2	23867	84.3	0.35

*1: without lifting
2: with lifting

TABLE 4.14. FWD DEFLECTIONS (MILS), RESULTS OF THE TEST AT HOUSTON - BELTWAY 8 STATION - HOUSTON SITE II

Dependent Variable (Sensor)	Block Variable (Force)	Treatment*	(M)	S.D.	Dependent Variable (Sensor)	Block Variable (Force)	Treatment*	(M)	S.D.	Dependent Variable (Sensor)	Block Variable (Force)	Treatment*	(M)	S.D.
S1	1	1	0.1	0.04	S4	1	1	0.1	0.04	S7	1	1	0.1	0
		2	0.1	0.05			2	0.1	0			2	0.1	0
	2	1	0.3	0		2	1	0.3	0.05		2	1	0.2	0.05
		2	0.3	0			2	0.2	0.05			2	0.2	0
	3	1	1.0	0		3	1	0.8	0.04		3	1	0.6	0
		2	1.0	0			2	0.8	0			2	0.6	0
	4	1	1.4	0.05		4	1	1.2	0.04		4	1	0.9	0
		2	1.4	0.04			2	1.2	0.05			2	0.9	0
	5	1	3.1	0		5	1	2.5	0		5	1	1.8	0
		2	3.1	0			2	2.5	0.04			2	1.8	0
	6	1	3.8	0		6	1	2.9	0		6	1	2.1	0
		2	3.7	0.09			2	2.9	0.04			2	2.1	0.04
S2	1	1	0.2	0	S5	1	1	0.1	0.07					
		2	0.2	0.04			2	0.2	0.06					
	2	1	0.3	0.04		2	1	0.2	0.05					
		2	0.3	0			2	0.3	0.07					
	3	1	1.0	0.04		3	1	0.8	0.07					
		2	1.0	0.05			2	0.8	0.16					
	4	1	1.4	0		4	1	1.1	0.05					
		2	1.4	0.04			2	1.0	0.05					
	5	1	2.9	0		5	1	2.3	0					
		2	2.9	0			2	2.3	0					
	6	1	3.4	0		6	1	2.6	0					
		2	3.4	0			2	2.7	0.09					
S3	1	1	0.2	0.05	S6	1	1	0.1	0.05					
		2	0.2	0.05			2	0.1	0.05					
	2	1	0.3	0.05		2	1	0.2	0.05					
		2	0.3	0			2	0.3	0.08					
	3	1	0.9	0		3	1	0.7	0					
		2	0.9	0.05			2	0.7	0.09					
	4	1	1.3	0		4	1	1.0	0.05					
		2	1.3	0			2	1.0	0.05					
	5	1	2.7	0		5	1	2.1	0					
		2	2.7	0			2	2.1	0					
	6	1	3.1	0		6	1	2.4	0					
		2	3.2	0.05			2	2.4	0.11					

*1: without lifting
2: with lifting

system between tests often produced lower, though not significantly, variations. Hence, if repeated measurements are required the system should remain in place.

GUIDELINES FOR ROUTINE FWD MEASUREMENTS ON RIGID PAVEMENTS

Based on the analysis of the data presented above, it is recommended that:

(1) A force of 6,000 pounds or greater, be used.
(2) For project level evaluation, the measurements be repeated three times at each testing station. The values obtained should be visually checked for gross errors. In the case of network level evaluations, one drop should be adequate.
(3) The system not be lifted between measurements at specific testing point, but must be lifted between testing points (unlike the Dynaflect).

These suggested guidelines for routine FWD measurements are for deflections of rigid pavements, and the pavements that were tested were typical of rigid pavements found in the state of Texas.

CHAPTER 5. COMPARISONS WITH OTHER NDT DEVICES

INTRODUCTION

Many procedures have been used for comparing NDT devices. This study approach compares results of field pavement evaluations.

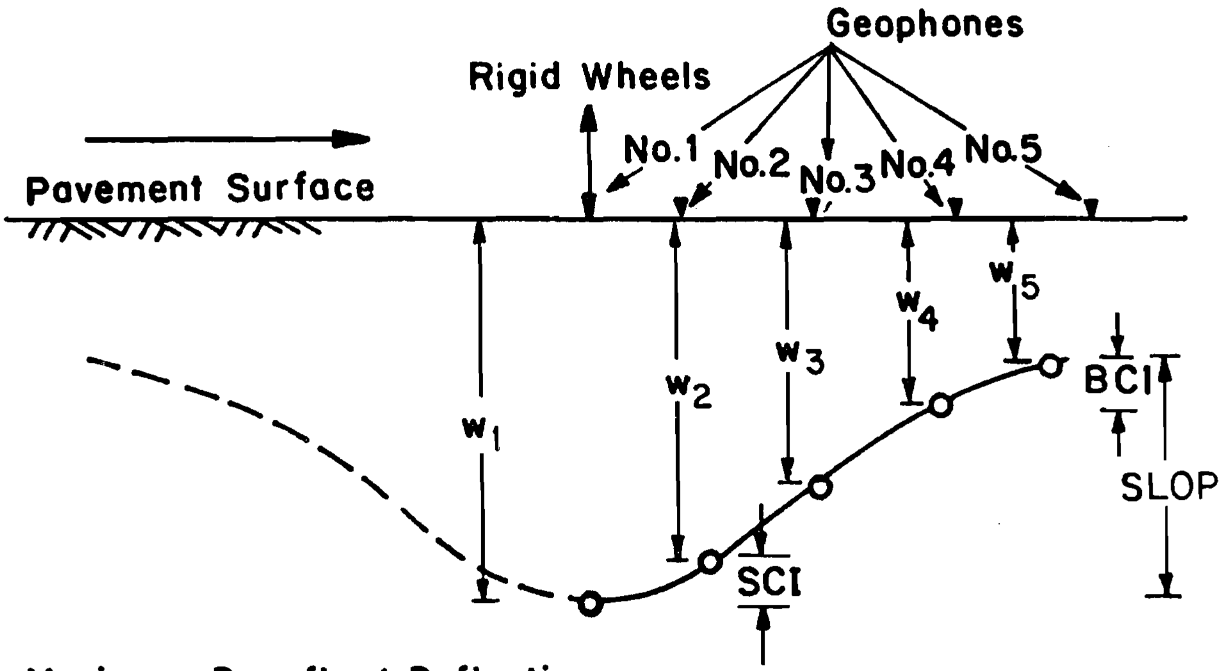
In this comparison the graphical representations of the normalized deflection basins of each device are compared with the results of Young's modulus predictions using the RPEDD1 program.

GRAPHICAL REPRESENTATION OF NDT DEFLECTIONS

Dynaflect Deflection Basin

A typical Dynaflect deflection basin for use in comparing dynamic deflection data from other NDT devices is illustrated in Fig 5.1. When the Dynaflect loading is modelled in a layered theory analysis, such as Chevron or ELSYM5 (Refs 7, 16, and 18), the theoretical deflection levels are computed at the five geophone locations by specifying their radial distances from the center of one loading wheel. The radial distances are 10.0, 15.6, 26.0, 37.4, and 49.0 inches, respectively, with the first sensor at 10.0 inches, as illustrated in Fig 5.2. This rational approach to plotting the Dynaflect deflection basin provides more uniform and consistent results.

A commonly used basin parameter for structural evaluation is the deflection measured at geophone no. 1, also termed the Dynaflect maximum deflection, DMD (Ref 17). This term can be misleading because, for some pavements, the maximum Dynaflect deflection may not occur midway between the loading wheels (location of geophone no. 1). This phenomena is illustrated in Fig 5.3 by plotting the theoretical Dynaflect deflection basins computed using the layered theory program, ELSYM5. For the stiff rigid pavement case, the maximum deflection occurs at geophone no. 1, i.e., midway between the two loading wheels. This happens because a stiff pavement spreads the load



Maximum Dynaflect Deflection = w_1

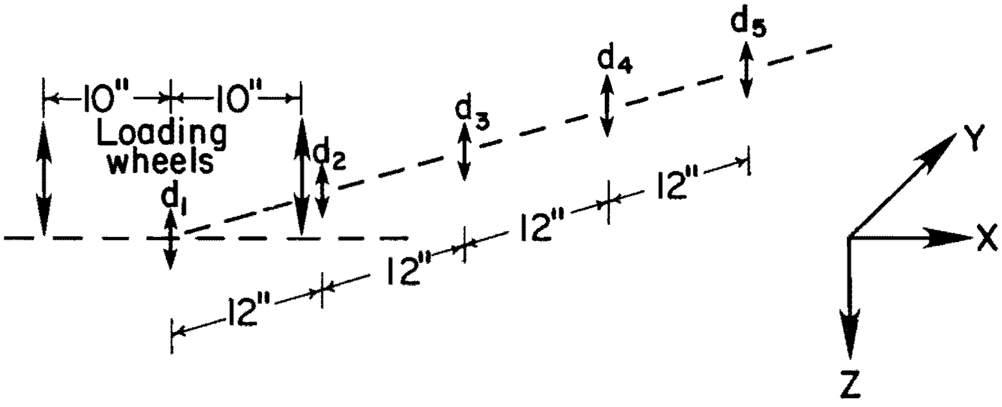
Surface Curvature Index, SCI = $w_1 - w_2$

Base Curvature Index, BCI = $w_4 - w_5$

Spreadibility, % = $100(w_1 + w_2 + w_3 + w_4 + w_5)/(5w_1)$

Basin Slope, SLOP = $w_1 - w_5$

Fig 5.1. Typical Dynaflect deflection basin.



Configuration of Dynaflect loading and deflection measurements (d_1, d_2, d_3, d_4, d_5 are peak to peak deflections at radial distance of 10.0, 15.6 26.0, 37.4, 49.0 inches from each loading wheel)

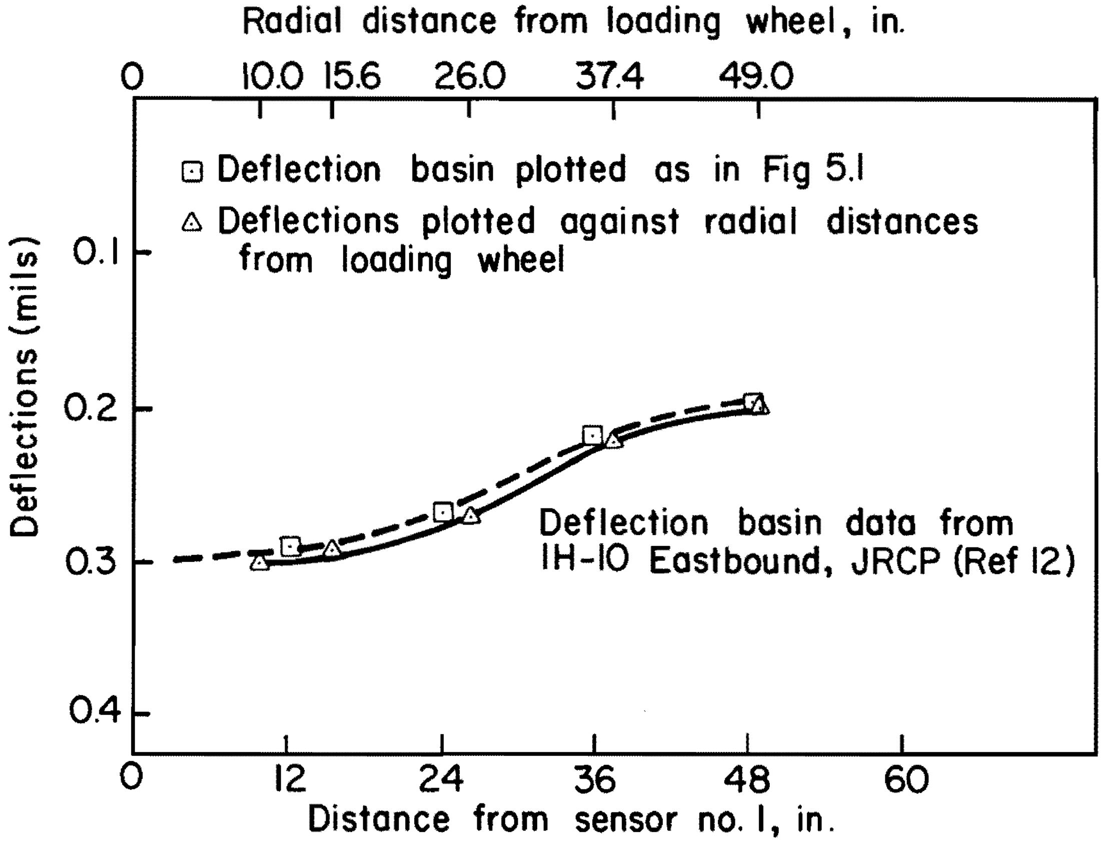


Fig 5.2. Graphical illustration of Dynaflect deflection basin adopted in this study.

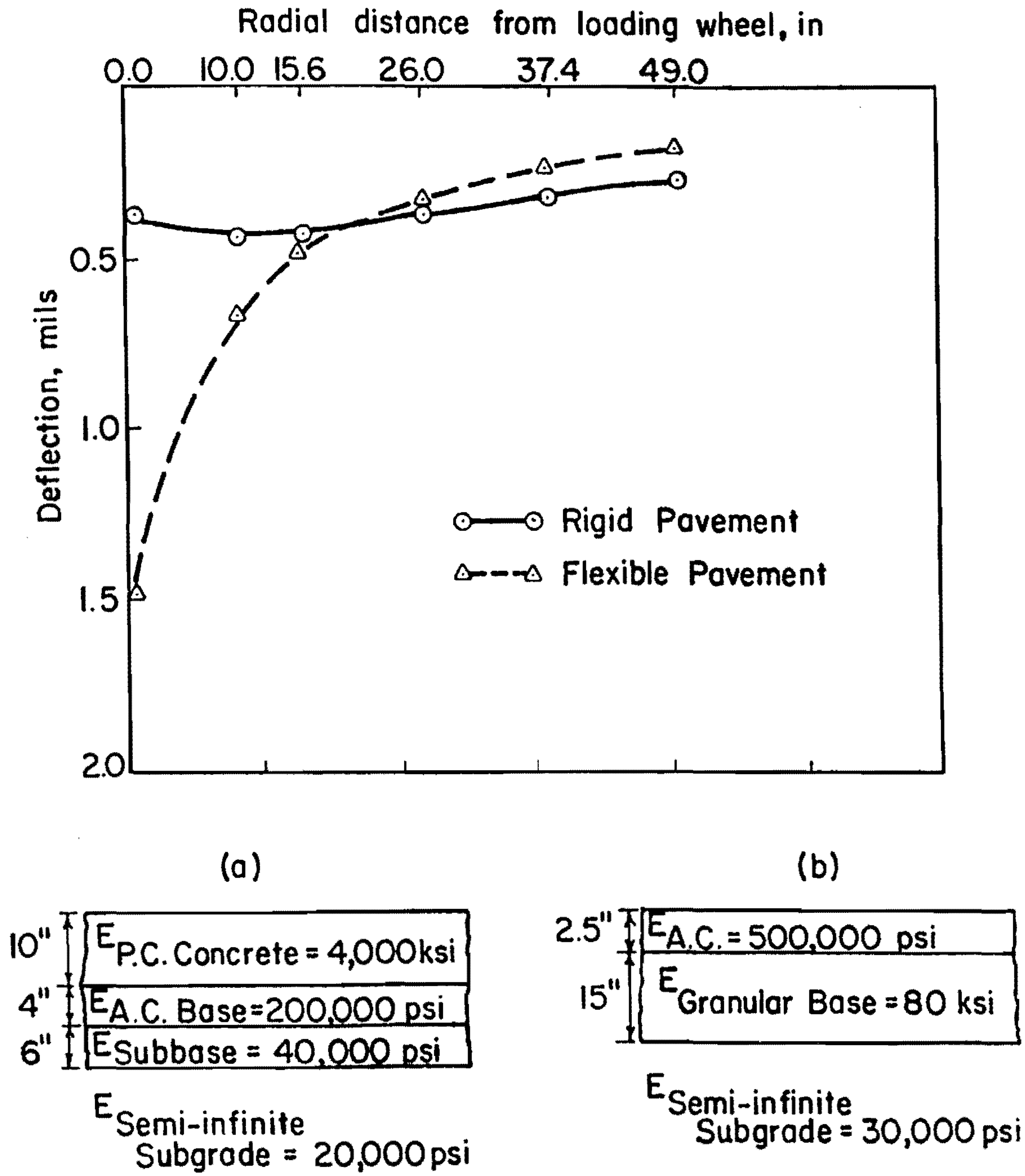


Fig 5.3. Theoretical deflection basins under Dynaflect loading for a very stiff and a weak pavement.

over a large area and the use of the principle of superposition results in the largest deflection at geophone no. 1, due to the additive effect of deflections produced by loads on the two loading wheels. On the other hand, for a weaker flexible pavement, the maximum deflection occurs at the center of the loading wheels. For other NDT devices, such as the FWD, a deflection basin plotted with the relative positions of the sensors from sensor no. 1 coincides with the deflection basin plotted using radial distances from the center of the loading plate. In this case the maximum deflection basin will occur at sensor no. 1, which is in the center of the loading plate. In this study, Dynaflect deflection basins are plotted using the radial distance of the sensors from the center of the loaded area as the abscissa.

FWD Deflection Basin

Figure 5.4 illustrates an FWD deflection basin computed for a rigid pavement using the FWD configuration shown in Fig 2.3. The radial distances of seven sensors are on the abscissa and the ordinates are in terms of normalized deflections. FWD deflections are normalized with respect to the 1,000-pound peak force, as given by following expression:

$$W'_{R_i} = W_{R_i} \times \frac{1000}{P_{FWD}} \qquad (5.1)$$

where

W'_{R_i} = normalized deflection, at the radial distance, R_i,

W_{R_i} = FWD deflection measured at the radial distance, R_i, at the peak force, P_{FWD},

P_{FWD} = peak force on the FWD loading plate, at which deflections are measured or theoretically calculated.

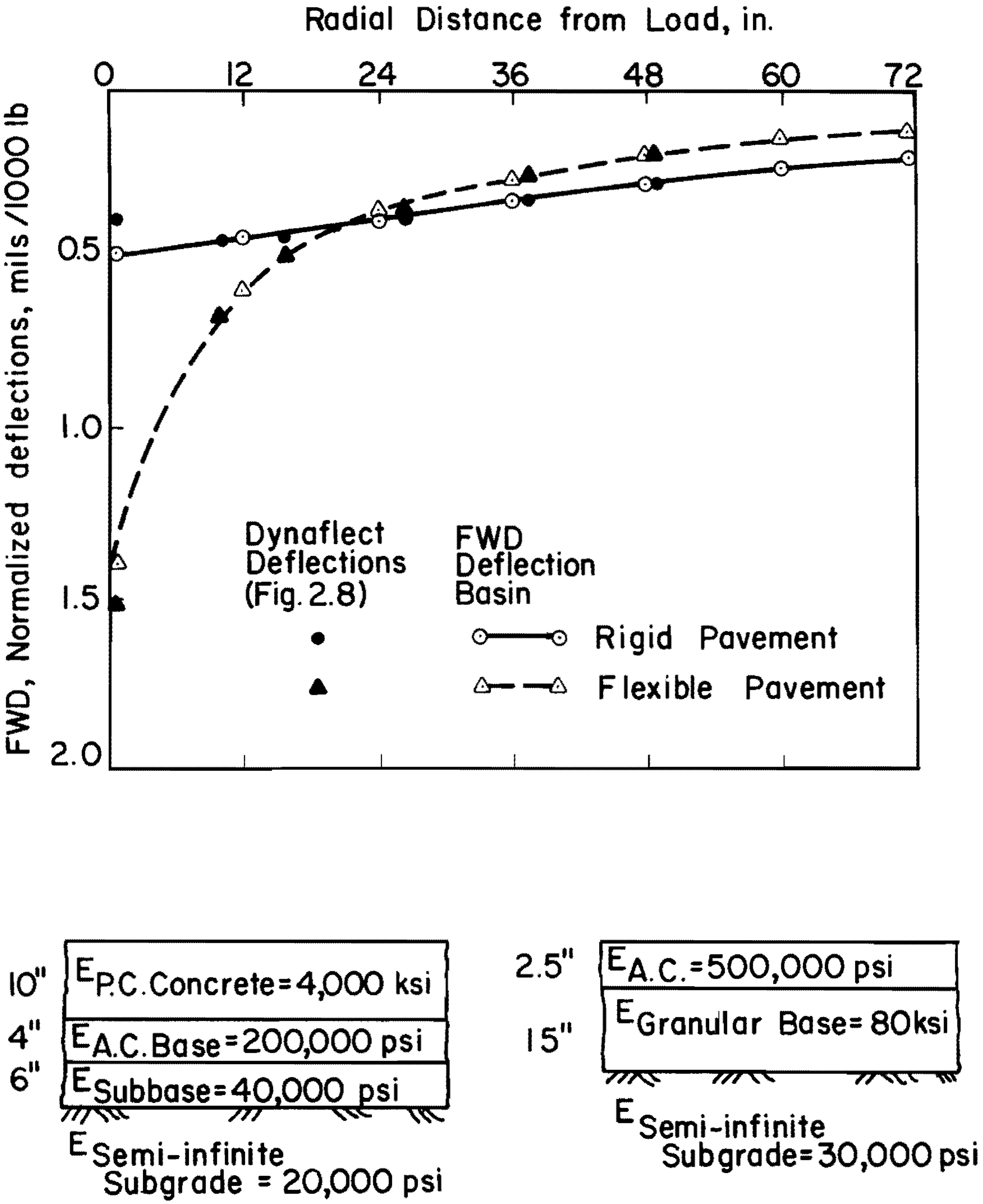


Fig 5.4. Theoretical deflection basins under FWD loading for a very stiff and a weak pavement.

The above method of plotting FWD deflection basins makes it convenient to compare FWD deflections at different levels of peak force as well as with Dynaflect deflection basins.

The deflection basin plots, illustrated in Figs 5.5, 5.6, and 5.7, are for the test sites where the Dynaflect and the FWD were tested for comparison purposes.

The force level at which deflections were measured at the peak force of the FWD are: site Slab III, 22,829 pounds; site Houston I, 23,656 pounds; and site Houston II, 23,959 pounds. For each radial distance the deflection basin was normalized to a peak force of 1,000 pounds in order to compare it with the Dynaflect loading level.

As we can see in the figures the deflection basins are significantly different at the Houston sites, the FWD normalized deflections being constantly smaller than the Dynaflect deflections.

Evaluation Programs RPEDD1 and FPEDD1

A framework for nondestructive evaluation of pavements based on dynamic deflections was developed in the present research study (Ref 19). Computer programs for rigid pavement evaluations based on dynamic deflections, version 1.0 (RPEDD1), and flexible pavement evaluations based on dynamic deflections, version 1.0 (FPEDD1), were developed to estimate the insitu Young's moduli of pavement layers using the approach of inverse application of layered elastic theory (ELSYM5) to obtain the best fit of a measured deflection basin. A simplified flow diagram of the computer program is presented in Fig 5.8.

Basic Input Data

Design load specifications and configuration are required for nonlinear characterization if a Dynaflect deflection basin is analyzed. Additionally, past traffic data in terms of cumulative 18-kip equivalent-single-axle loads are required. Specific guidelines practiced by different user agencies or given in AASHTO Interim Guides (Ref 20) can be used for this purpose. In Fig 5.8, IOPT4 is an input option to omit correction for nonlinear moduli and remaining life analysis.

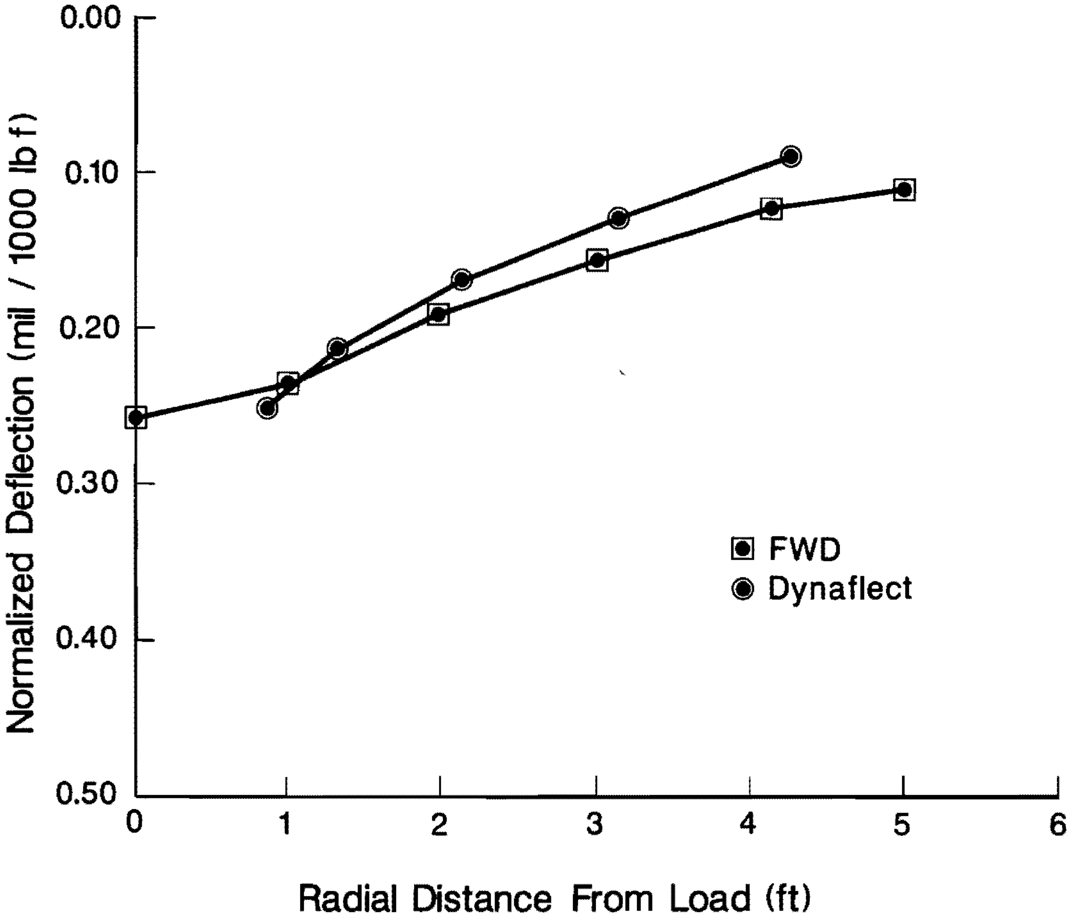


Fig 5.5. Deflection basin plots, BRC Slab II.

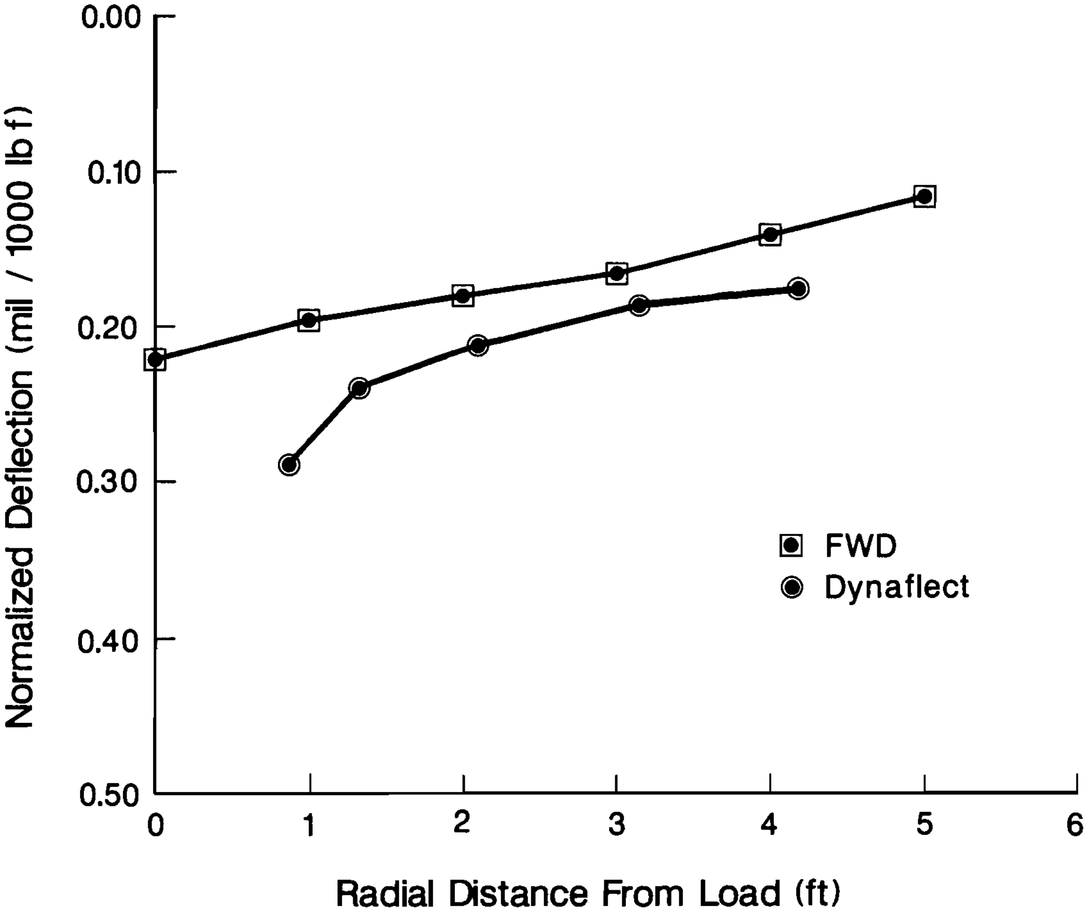


Fig 5.6. Deflection basin plots, Houston Site I.

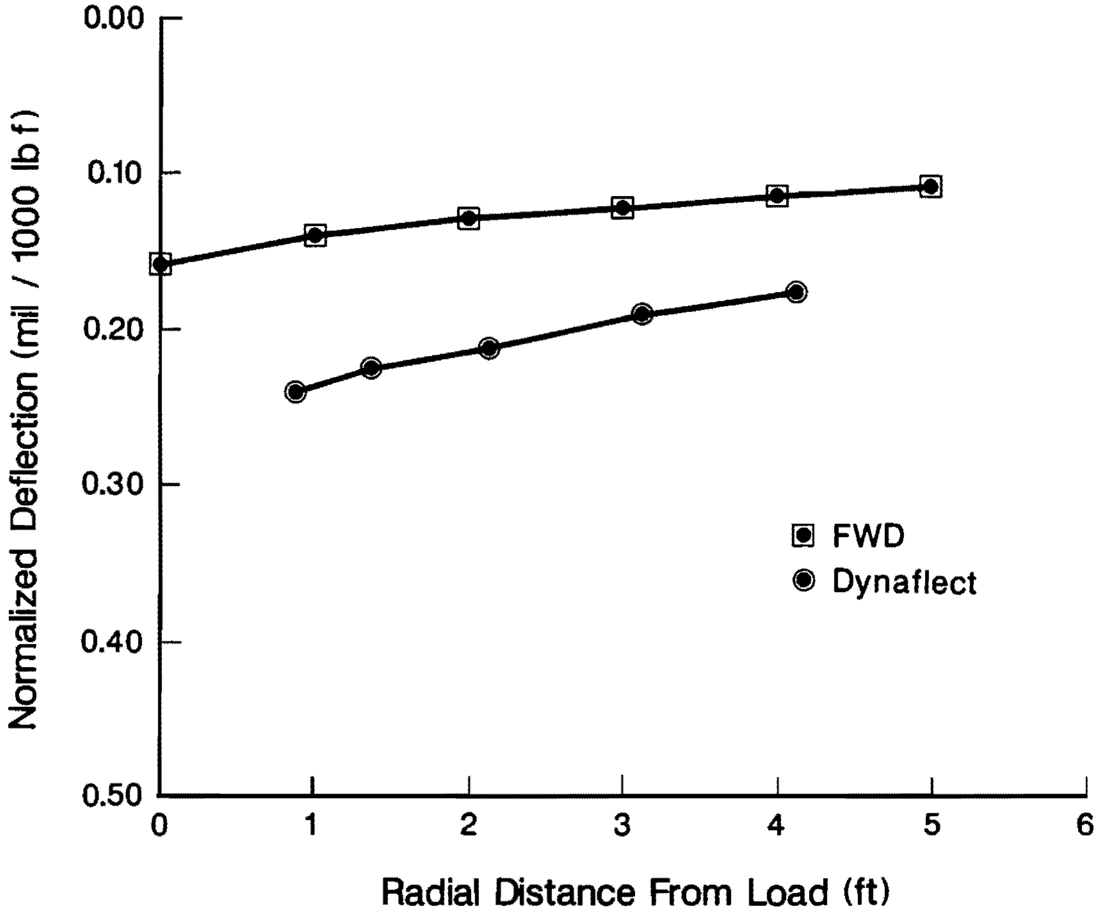


Fig 5.7. Deflection basin plots, Houston Site II.

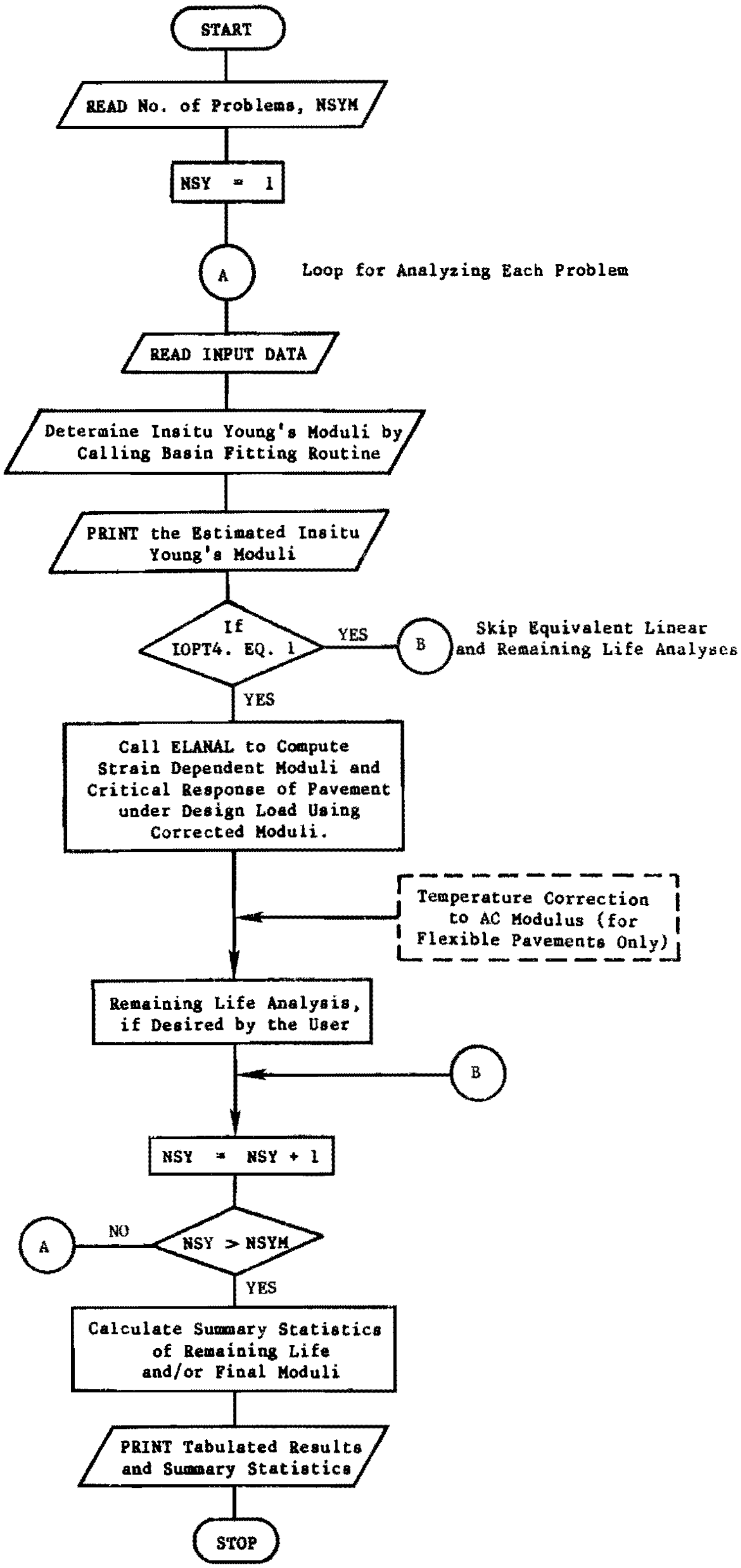


Fig 5.8. Simplified flow diagram of the proposed structural evaluation program based on dynamic deflection.

Back Calculation of Insitu Moduli from Deflection Basins

Insitu moduli of pavement layers are determined by the self-iterative inverse application of ELSYM5. Separate routines have been developed for RPEDD1 (rigid pavements) and FPEDD1 (flexible pavements). These routines are based on the procedure described in Chapter 4 of Ref 19. The salient features of the self-iterative procedure are briefly repeated here.

(1) Handling the finite thickness of the subgrade layer (including a default procedure for consideration of a rigid bottom).
(2) Analyzing dynamic deflection basins measured either by the Dynaflect (standard configuration of five sensors) or by a Falling Weight Deflectometer (not more than seven or less than six sensors) with one sensor under the center of the load. It is recommended that the remainder be placed one foot apart on a line extending outwards in a perpendicular direction to ensure unique combinations of moduli.
(3) Handling a three or four-layered pavement model.
(4) Determining a unique set of insitu moduli by generating initial seed moduli through a default procedure.
(5) Offering better efficiency and using a lesser number of iterations, to keep the computational cost to a minimum.
(6) The deflection basin fitting algorithm is not user dependent because zero input values are recommended for seed moduli.

Corrections for Nonlinear Behavior of Pavement Sublayers

The self-iterative procedure for equivalent linear analysis developed in Ref 1 is basically the same for rigid and flexible pavements.

Nonlinear, Strain-Sensitive Moduli. The equivalent linear analysis approach is based on an iterative use of ELSYM5 and generalized curves of E/E_{max} versus shear strain curves developed using the concept of nonlinear strain-softening materials when the shear strain induced by the design load in these layers exceeds certain threshold strain values. This approach is drawn from the dynamic/seismic response analysis procedure and is well accepted in the field of geotechnical engineering.

Insitu Moduli of Stabilized Layers. The insitu moduli determined for granular materials and cohesive soils which have been stabilized by asphaltic materials, cement, or lime are considered to be insensitive to shear strain and not to exhibit nonlinear behavior. Therefore no corrections are applied to the insitu moduli of such pavement layers.

Temperature Correction

The insitu asphaltic concrete modulus determined from the analysis of the deflection basin measured on a flexible pavement is corrected for temperature sensitivity using the procedure described in Ref 1. The corrected modulus corresponds to asphaltic concrete stiffness at the design temperature. This step is performed after correcting the strain-dependent nonlinear moduli.

Remaining Life Analysis

The final combination of (corrected) insitu pavement moduli is assumed to represent effective insitu stiffness (Young's modulus) under the design load. The existing pavement at this test location is again modelled as a layered "linearly" elastic system for further evaluation. At this stage of structural evaluation existing pavement is analyzed for its remaining life at each test location. The critical pavement responses determined for the computations of fatigue life and remaining life are made before applying a temperature correction to the surface asphalt concrete modulus in FPEDD1.

Insitu Moduli Results

Deflection measurements at center slab away from joints or cracks were made at each location and the elastic modulus for each layer was estimated using the RPEDD1 back calculation program. Values were generated for four load levels. These values are presented in Table 5.1. Based on these values, when the FWD is used to estimate insitu moduli, the nominal load used should be 18,000 pounds. It should be noted that three of these locations (Balcones Research Center, Houston I, and Houston II) were relatively new slabs that had experienced no traffic prior to testing. How traffic influences these measurements with time is not known. However, it is known that the modulus of elasticity of PCC varies significantly in early life (up to three years) and these measurements should be repeated when the slabs are 3 to 5 years of age.

Table 5.2 presents estimated elastic moduli from the FWD, the Dynaflect, and the SASW measurements at the same locations. From these data no "best" method can be identified.

TABLE 5.1. BACK CALCULATED MODULI OF PAVEMENT LAYERS USING RPEDD1

		Falling Weight Deflectometer Nominal Load Level			
Location	Layer	6,000 lbs.	9,000 lbs.	18,000 lbs.	24,000 lbs.
		(6,740)**	(9,370)	(18,700)	(22,830)
BRC[1]	PCC	6,500,000[5&6]*	6,500,000[7]*	6,020,000	6,200,000
Slab II	Base	476,000	1,044,000	589,000	565,000
	Subbase	72,800	48,100	21,200	12,900
	Subgrade	24,500	26,100	27,100	28,600
		(6,900)	(9,390)	(19,260)	(23,660)
Houston[2]	PCC	6,500,000*	6,500,000*	6,500,000*	6,500,000*
Site I	Base	1,549,000	1,613,000	1,200,000	750,000
	Subbase	424,000	885,000	242,000	501,000
	Subgrade	38,000	35,700	39,400	38,900
		(7,670)	(9,850)	(19,670)	(23,960)
Houston[3]	PCC	5,746,000[8]	6,500,000[9]*	6,500,000[10]*	6,500,000[11]*
Site II	Base	2,000,000*	2,000,000*	2,000,000*	2,000,000*
	Subbase	369,000	174,000	291,000	432,000
	Subgrade	43,000	41,000	46,000	48,000
		(7,850)	(9,760)	(20,000)	(24,000)
Gainesville[4]	PCC	4,690,000	3,220,000	4,660,000	3,760,000
Site I	Subgrade I	34,700	52,800	32,400	53,700
	Subgrade II	20,700	16,800	17,000	17,900

(continued)

*Represents the default value in the RPEDD1 program.

**Values in parenthesis are the actual loads indicated at the time of test.

TABLE 5.1

[1] Balcones Research Center (BRC) slab is a 10-inch-thick reinforced portland cement concrete (PCC) slab placed on a 3-inch-thick asphalt cement concrete base course, a 6-inch-thick compacted crushed stone subbase over a caliche soil subgrade with a rock layer approximately 10-feet below the surface.

[2] Houston I slab is a 10-inch-thick CRCP placed on a 6-inch cement treated base course, a 6-inch lime treated subbase course over a clay subgrade.

[3] Houston II slab is a 13-inch-thick CRCP placed on a 6-inch cement treated base course and a 6-inch lime treated subbase course over a subgrade.

[4] Gainesville Site I is a 10-inch-thick JCP placed over lime stabilized subbase over the subgrade.

[5] In the RPED01 program when a default limits is reached the successive interactions are compared to the measured values, if no improvement is made the process stops and provides a precision state in the form of a percentage representing the error between the calculated deflection and the measured deflection. For all cases illustrated the error is less than 10 percent except for:

[6] the error is 17.1 percent.

[7] the error is 10.2 percent.

[8] the error is 30.1 percent.

[9] the error is 21.7 percent.

[10] the error is 18.5 percent.

[11] the error is 11.6 percent.

TABLE 5.2. COMPARISON OF ESTIMATED MODULI USING DIFFERENT EQUIPMENT

Location	Layer	FWD (18,000-lb Load)	Dynaflect	SASW
BRC	PCC	6,020,000	2,735,000	4,680,000
	Base	589,000	189,000	2,510,000
	Subbase	21,200	75,000	98,200
	Subgrade	27,100	38,000	30,800
Houston Site I	PCC	6,500,000	,840,000	7,200,000
	Base	1,200,000	462,000	910,000
	Subbase	242,000	339,000	1,000,000
	Subgrade	39,400	28,000	1,000,000
Houston Site II	PCC	6,500,000	5,150,000	8,600,000
	Base	2,000,000	511,000	850,000
	Subbase	291,000	409,000	690,000
	Subgrade	46,000	25,000	280,000
Gainesville	PCC	4,660,000	2,256,000	--
	Subbase	32,400	57,100	--
	Subgrade	17,000	24,800	--

CHAPTER 6. INVESTIGATION OF JOINT EFFICIENCY AND VOID DETECTION

ROAD SITE DESCRIPTION

Four sections of roadway were selected for making FWD deflection measurements to investigate joint-efficiency and void detection. The overall site ultimately chosen for testing was a section of jointed concrete pavement on IH-35 from MP 490 to MP 483 at Valley View near Gainesville, Texas, approximately 30 miles north of Dallas.

This section was selected partly because the pavement was undergoing localized repairs, such as filling voids under slabs, replacing slabs, and overlaying with asphalt concrete pavement, and, hence, the traffic was diverted.

In addition, other devices were being used at this location, particularly to identify voids under the pavement.

Figure 6.1 shows the locations of the site and the four test sections. Figure 6.2(a) illustrates the typical cross section of the JCP at section 1, and Fig 6.2(b) shows sections 2, 3, and 4. The pavement at section 1 consists of a 1-inch AC overlay on a 10-inch JCP pavement over the natural subgrade. The 1-inch AC overlay is the remaining thickness of an old overlay that had been partially removed. On sections 2, 3, and 4 the pavement structure consists of a 10-inch JCP pavement overlying the natural subgrade. The joint efficiency and the void detection measurements were made in the first week of March 1985. The weather conditions were good; the temperature during the measurements varied from 55°F to 62°F. Section 1 was overlaid with AC and all the joints reflected through the overlay. These are the only visible signs of distress since the pavement condition before overlay is unknown.

The surface condition of section 2 was poor and it was badly cracked; the entire section has been under regular repairs, judging by the number of patches. Section 3 is less damaged than section 2 but has a large number of cracks, as well as apparent pumping and patches of asphalt concrete.

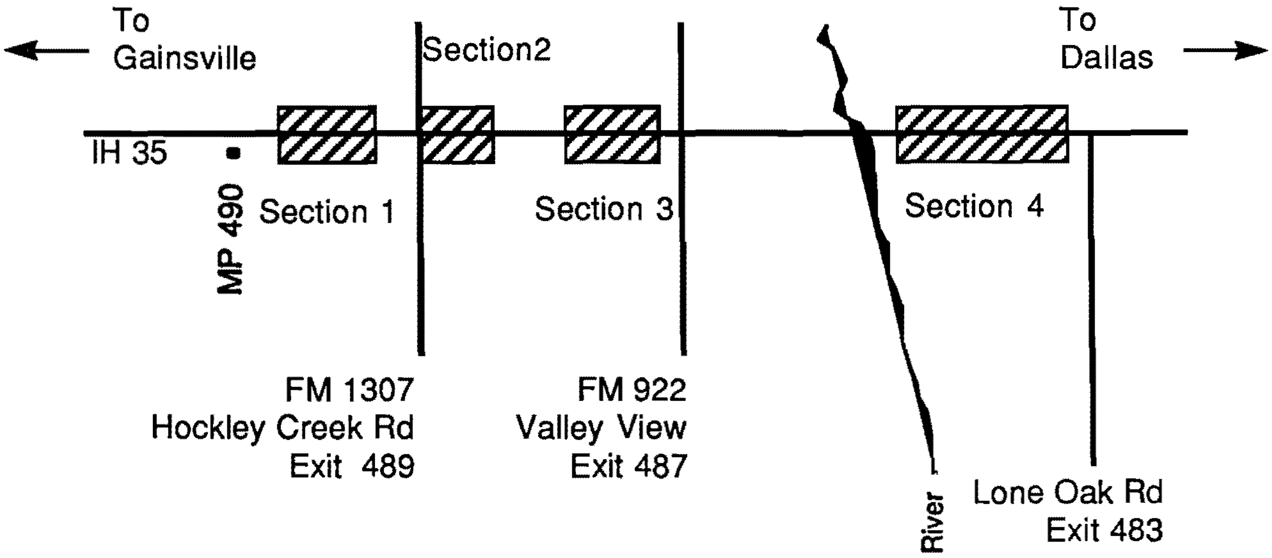
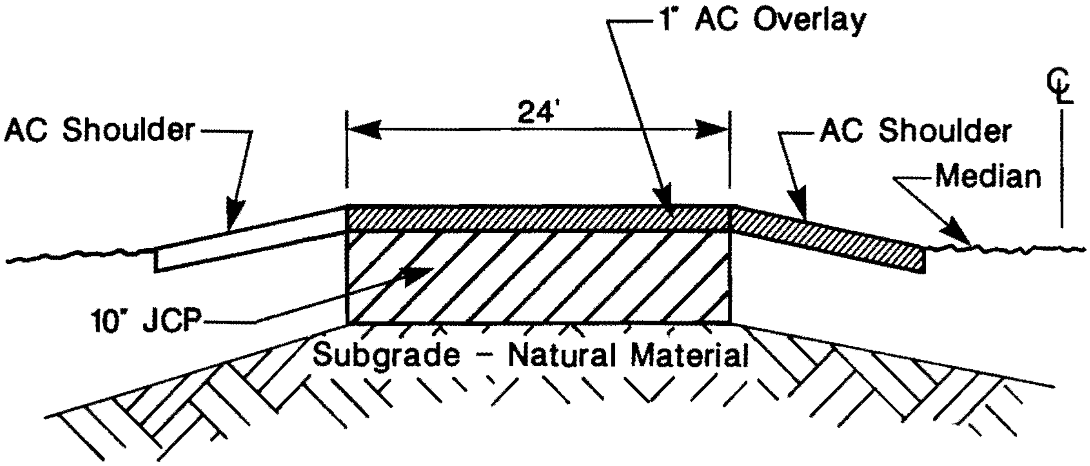
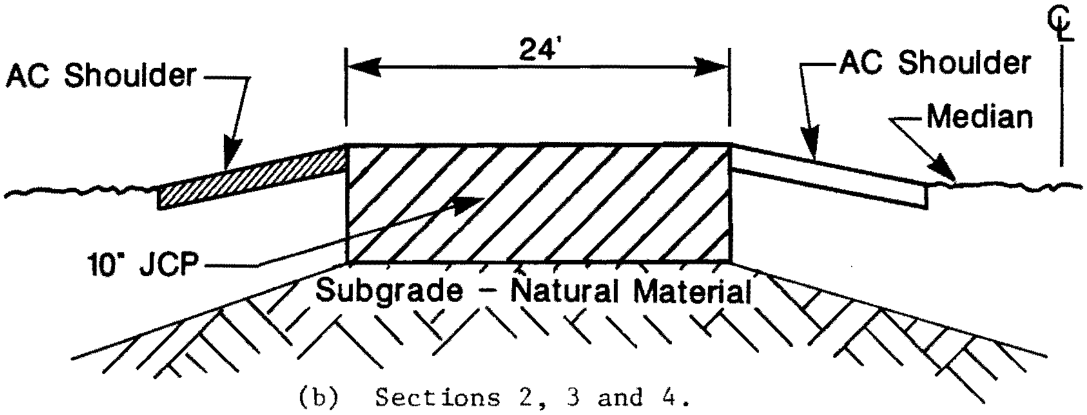


Fig 6.1. General location - FWD measurements, IH-35 Gainesville.



(a) Section 1.



(b) Sections 2, 3 and 4.

Fig 6.2. Typical cross section of JCP at IH-35, Gainesville.

Section 4 was specifically selected because it had been under recent repair. At the time of measurement, all the repairs that were to be made before the overlay were completed. Several locations had been marked as sections where a void under the pavement was indicated by other equipment.

Other locations were selected where there were no voids indicated under the pavement. All sections were tested with the same procedure. In order to confirm all the locations with and without voids, cores were later taken and analyzed.

LOADING CONDITIONS

The FWD system provides seven separate deflection measurements per test (Fig 6.2).

For joint-efficiency and void detection an extension bar was added to measure deflection on the opposite side of the load plate, with the sensor spacing set to the configuration shown in Fig 6.3.

At each location where the FWD was positioned for load transfer measurement and void detection the mass configuration was set up with three sets of weights and dropped from the four fixed heights. The peak loading force for this test varied from 5,000 to 18,000 pounds and the load plate diameter was 11.8 inches (300 mm).

Placement of FWD for Joint and Void Testing

The pattern for the location of the FWD for this series of tests is shown in Fig 6.4 (without voids) and Fig 6.5 (with voids). The three-symbol identification system used for each test location is as follows:

(1) The first symbol is a numeric value representing the number of the joint within the test site. The number increases in the direction of travel.

(2) The second symbol is a letter representing the location across the lane. "I" indicates the inside edge of the pavement next to the

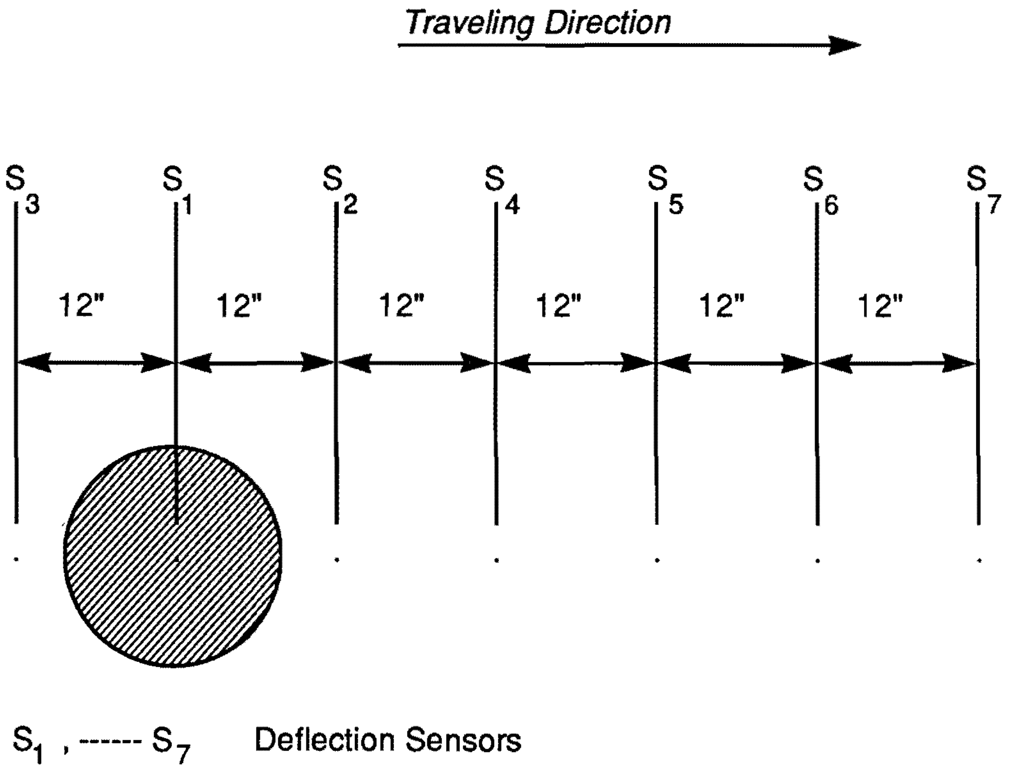


Fig 6.3. Sensor configuration for joint efficiency and void detection.

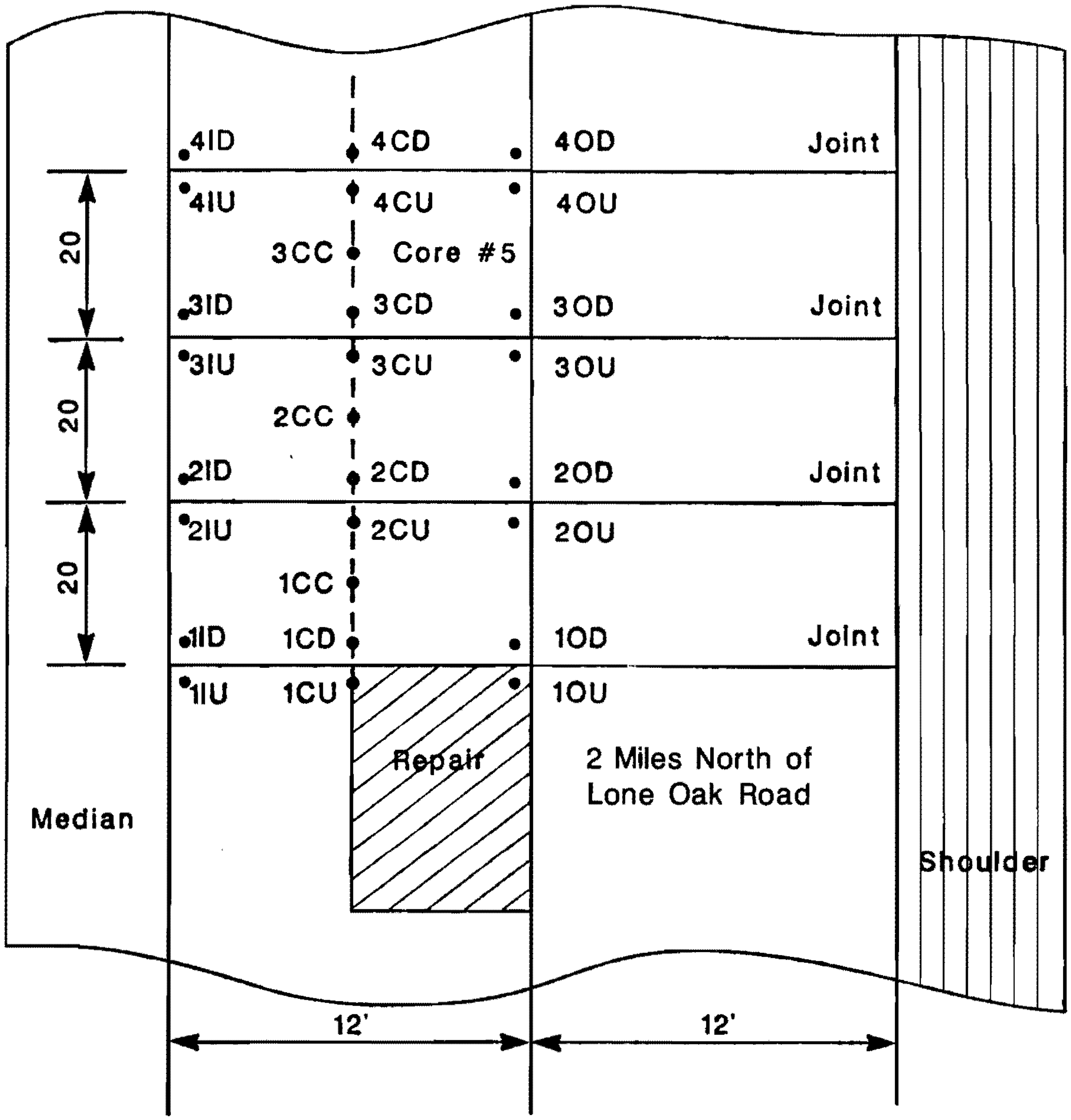


Fig 6.4. Test placement of FWD at location without void.

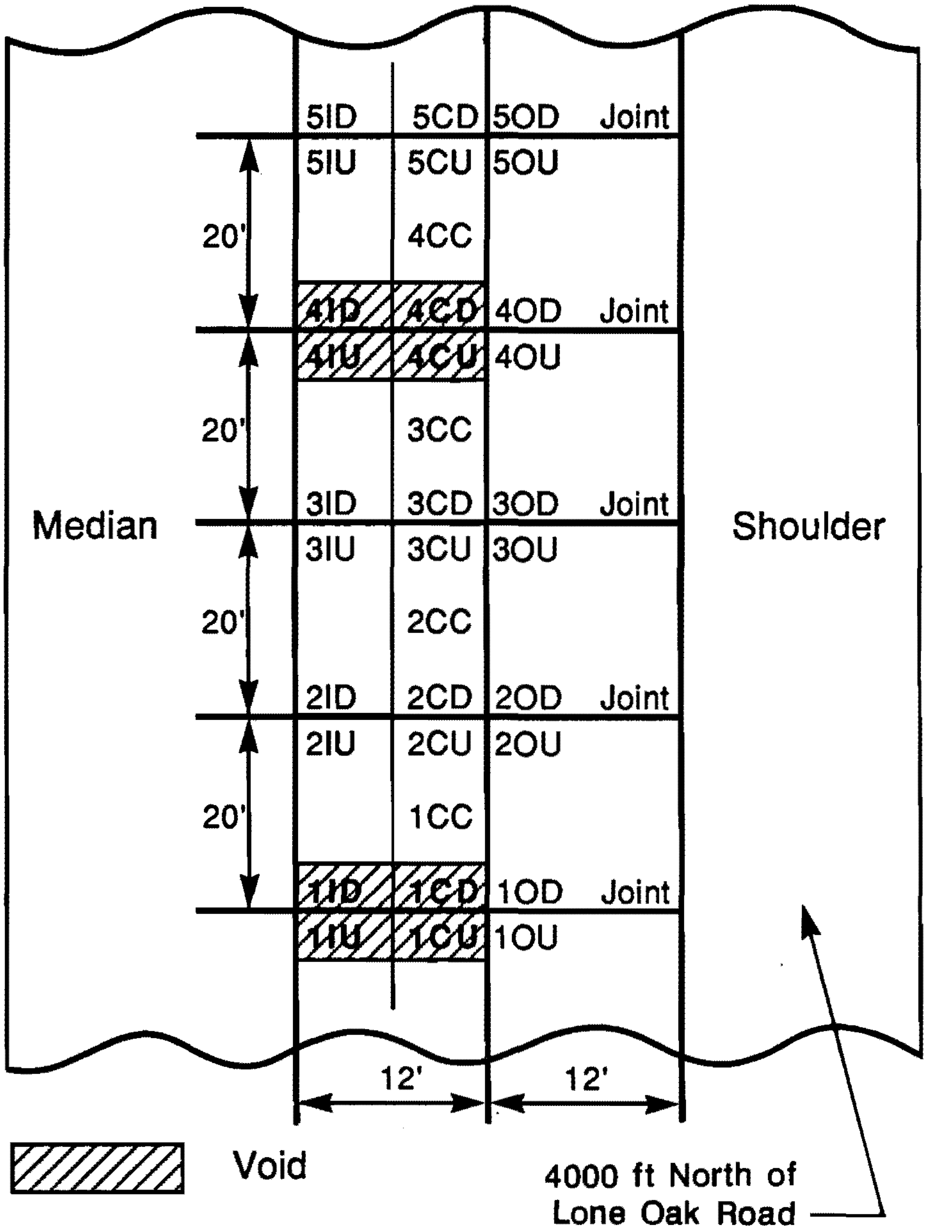


Fig 6.5. Test placement of FWD at location with voids.

median, "C" indicates the center line of the lane, and "O" indicates the edge of the lane adjacent to the longitudinal joint.

(3) The third symbol is a letter representing the location of the loading plate with respect to the joints, as illustrated in Fig 6.6. "U" indicates that the loading plate is upstream from the joint with respect to the direction of travel, "D" indicates that the loading plate is downstream from the joint with respect to the direction of travel, and "C" indicates the loading plate is at center slab away from the joint.

For example "3ID" identifies a test performed at the third joint in the test site, at the inside edge of pavement next to the median, and with the loading plate placed downstream of the joint.

ANALYSIS OF JOINT DATA

Deflection Basins

Typical deflection basins generated with the loading plate upstream and downstream of the joint are shown in Fig 6.7. As shown, the system condition sensors 1 and 3 are upstream and the other sensors are downstream of the joint. For the downstream condition, only sensor 3 is upstream of the joint. Similar pairs of deflection basins were drawn for each joint location tested at the Gainesville section.

The analysis for load transfer is a function of the maximum deflection (senor 1) and the deflection ratio of sensors 2 and 3. For purposes of this analysis the deflection ratio (DR) is defined as the ratio of S_2 to S_3 or S_3 to S_2 and is always calculated to be less than one. In other words, the largest deflection value is always used as the denominator. Hence, UDR is the upstream deflection ratio and DDR is the downstream deflection ratio. The joint deflection ratio (JDR) is therefore $\frac{UDR + DDR}{2}$. If complete (100 percent) load transfer is furnished by the joint, the maximum deflection upstream, S_1U, and the maximum deflection downstream, S_1D, would be equal and the upstream deflection ration UDR would equal the downstream deflection

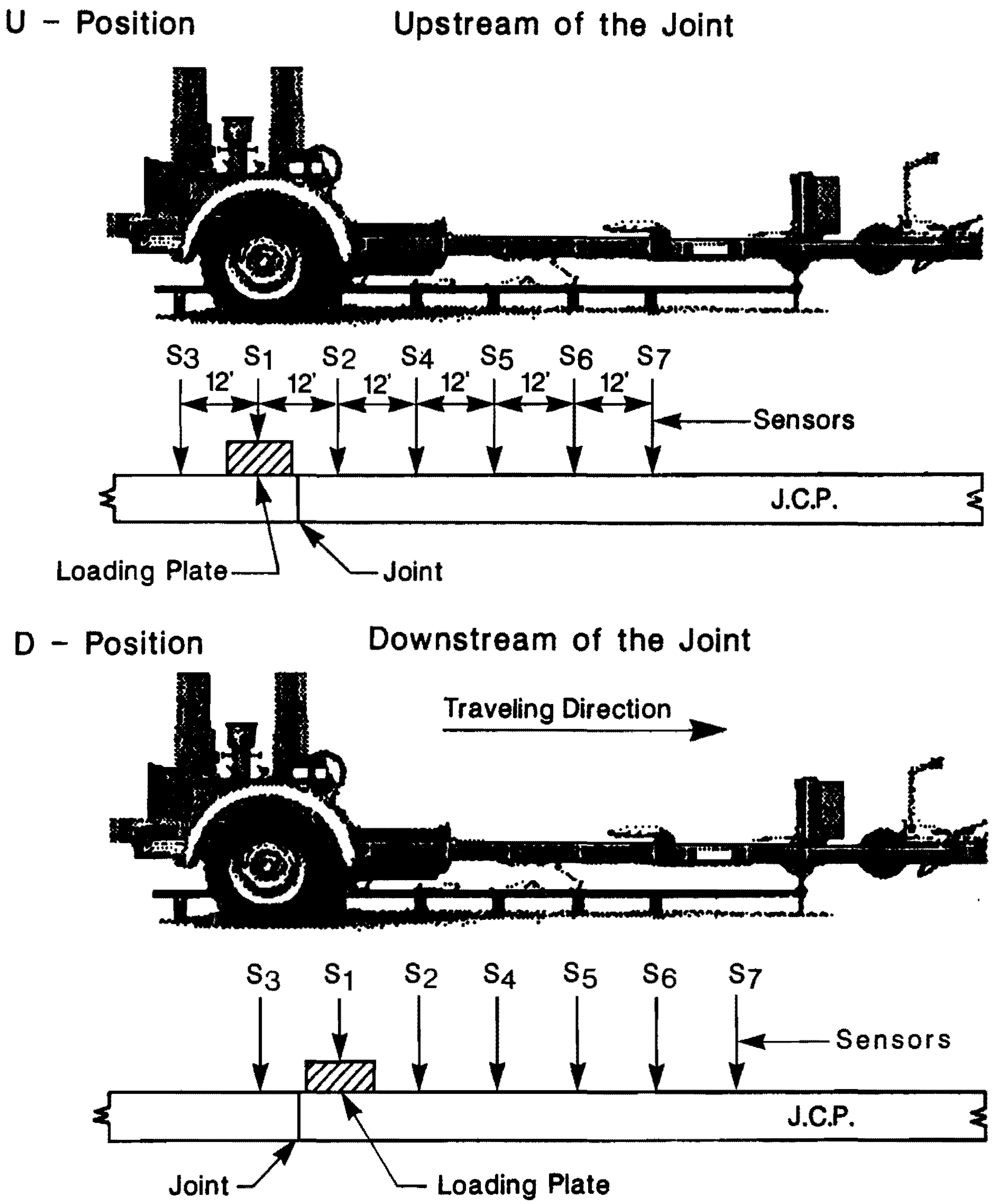
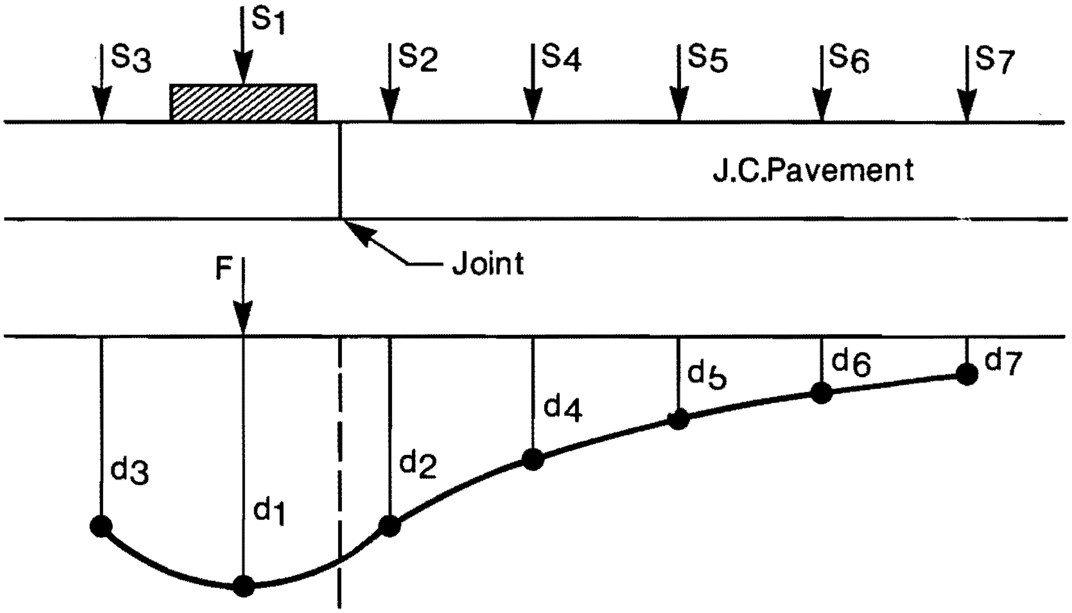


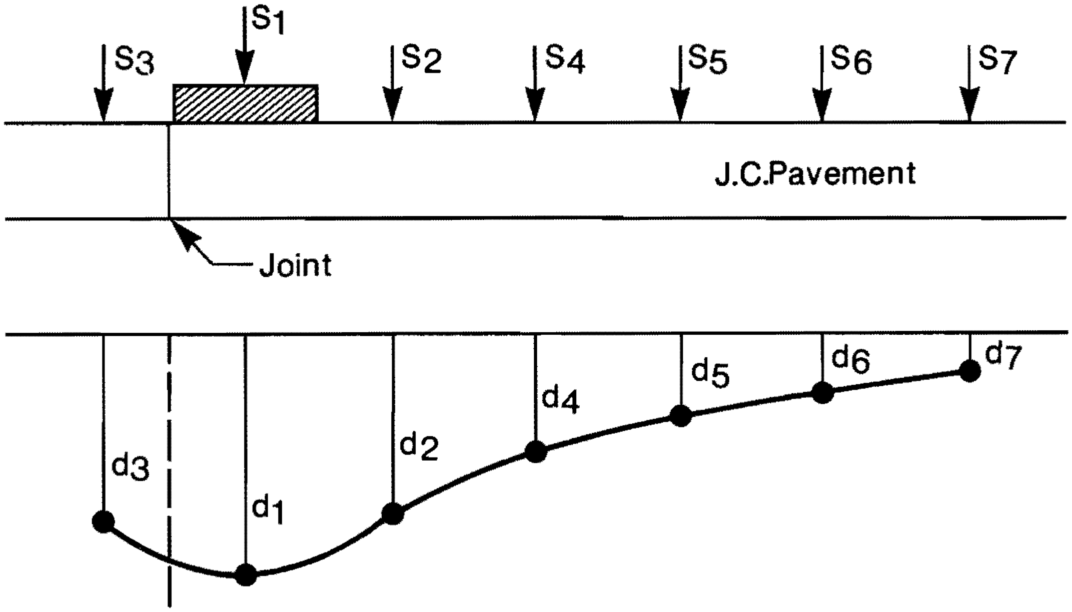
Fig 6.6. FWD positions with respect to the joint for void detection and joint efficiency measurements.

Sensor and Loading Plate Position - Upstream of the Joint



Deflection Basin and Joint Location at Upstream Position

Sensor and Loading Plate Position - Downstream of the Joint



Deflection Basin and Joint Location at Downstream Position

Fig 6.7. Typical deflection basin at test joints.

ratio DDR, which would be equal to one. If no (0 percent) load transfer occurs S_1U might still be equal to S_1D but the deflection UDR and DDR would be zero (0) because S_2U would equal S_3D would equal zero (0).

Figure 6.8 illustrates a case of complete (100 percent) load transfer. Note that

$$S_1U \approx S_1D$$
$$JDR \approx 1$$

Figure 6.9 illustrates the case for little or no load transfer, as shown by

$$S_1U \approx S_1D$$
$$JDR < 1$$

For this case the smaller the deflection ratio the less the load transferred across the joint. In order to evaluate the joint efficiency the following criteria were used:

Load Transfer	Joint Deflection Ratio (JDR)
Complete	.9 to 1
Partial	.21 to .89
None	0 to .2

When $S_1U \not\approx S_1D$, then if UDR or DDR is less than .2 the joint is judged to provide no load transfer. It should also be observed in Fig 6.9 that the slope of sensors 2 through 7 for the upstream position is much flatter than the slope for the same sensors for the downstream position.

Figure 6.10 illustrates a phenomena that can occur for sawed joints when the crack at the base of the saw cut is not vertical. It very graphically

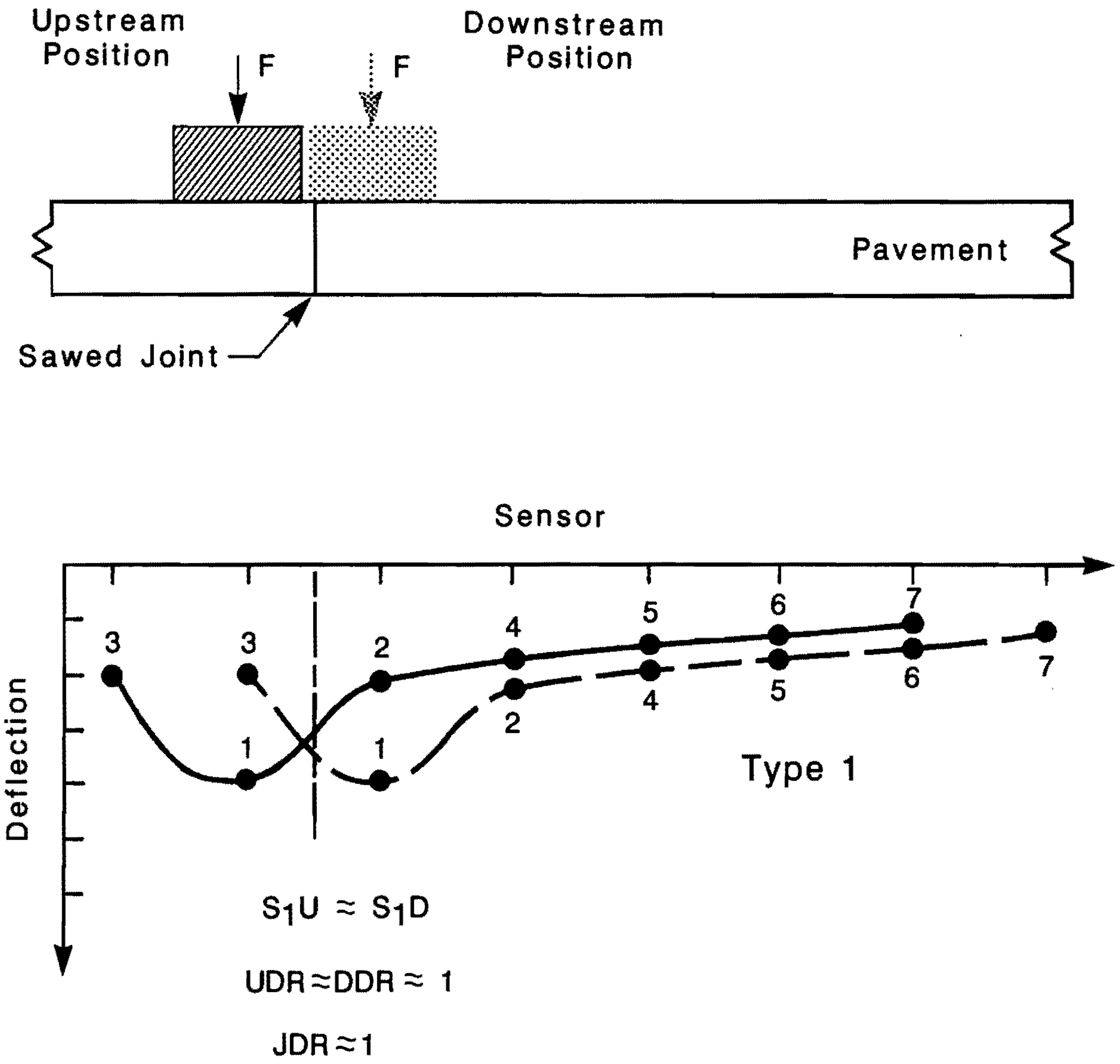
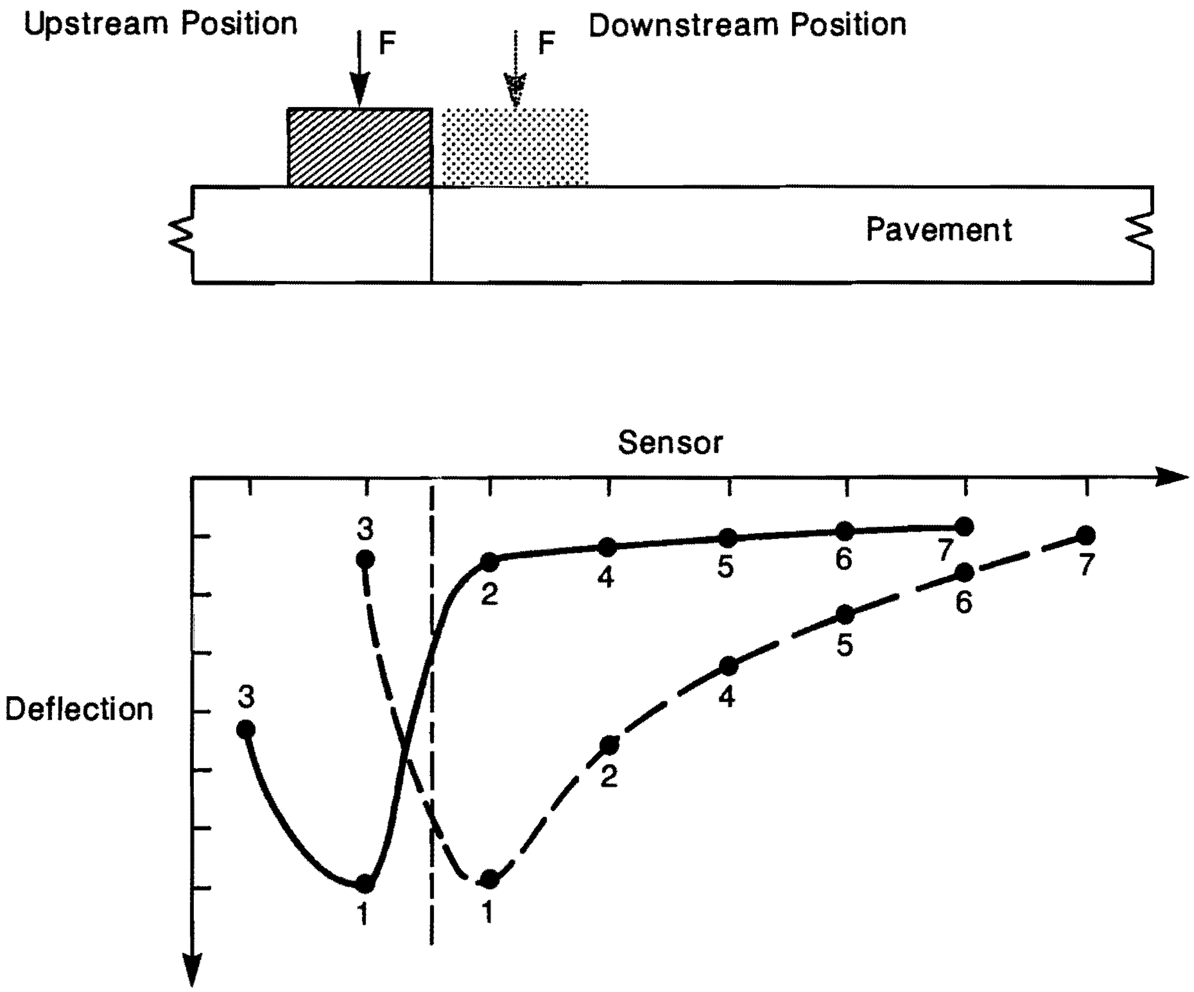


Fig 6.8. Deflection basins complete load transfer.



$$S_1U \approx S_1D$$

$$UDR \approx DDR < 1$$

$$JDR \approx < 1$$

Fig 6.9. Deflection basins for no load transfer.

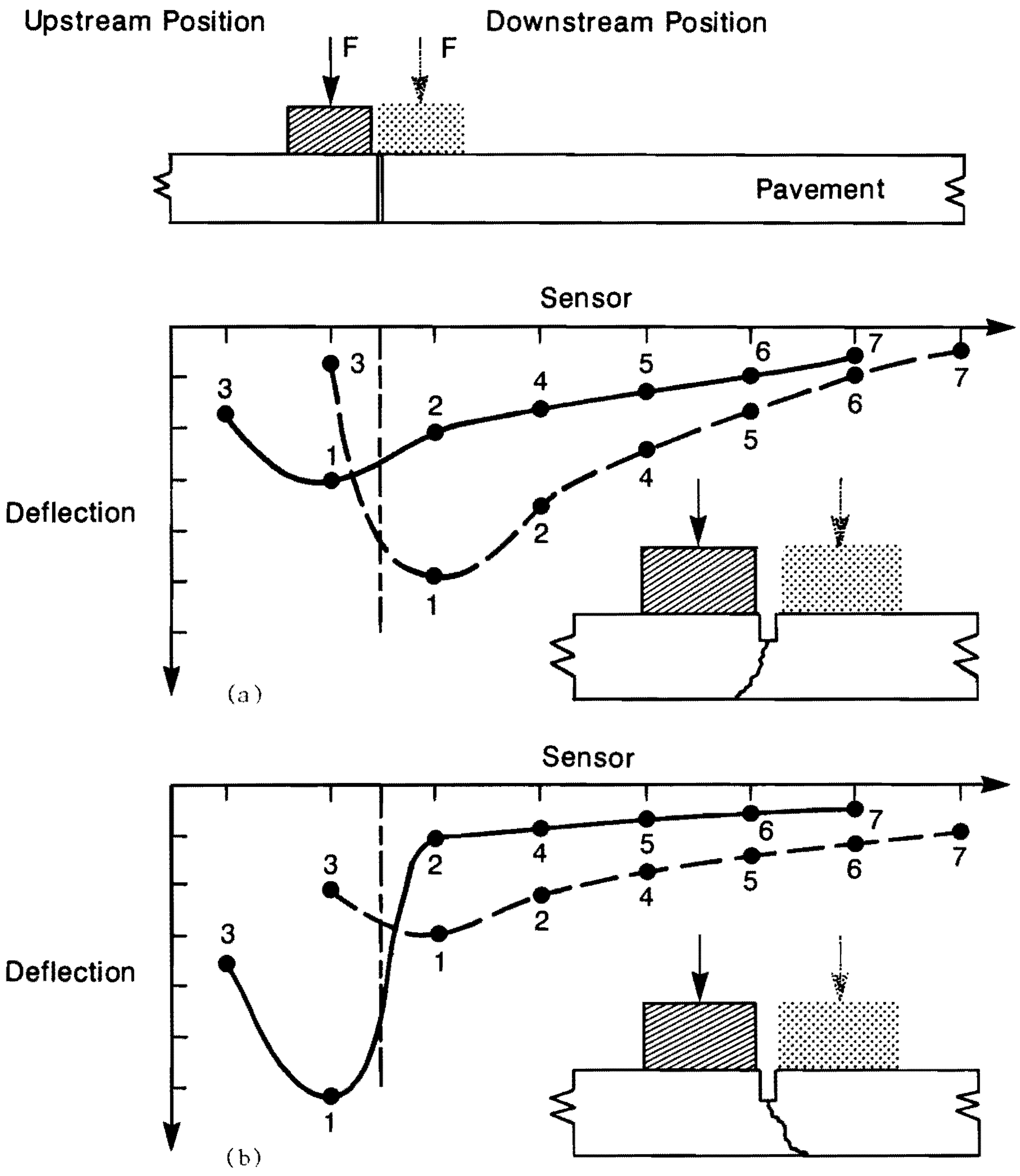


Fig 6.10. Load transfer for a non-vertical joint.

shows the need for using the loading plate on both sides of the joint in order to avoid a false conclusion concerning load transfer. For example in Fig 6.10(a), if only the upstream position is used, the deflection basin would imply that complete load transfer is occurring across the joint. The downstream position clearly shows no load transfer across the joint. Figure 6.10(b) is a mirror image of Fig 6.10(a). If load transfer is occurring the conditions of Fig 6.8 would be met.

No data have been collected for joints other than sawed joints. However, it appears that the conditions illustrated in Figs 6.8 and 6.9 could rationally be applied to other types of joints.

Tables 6.1, 6.2, and 6.3 present the data from the Gainesville site and based on the load transfer criteria presented above, provide an evaluation of the condition of each joint with respect to load transfer.

Tables 6.4, 6.5, and 6.6 present an evaluation of each joint with respect to load transfer efficiency.

Void Detection

The deflection basins plotted for test locations at Gainesville revealed a significant change in the slopes of the deflection basins when a void was present. Based on a visual inspection, two slopes were selected for analysis. These were the slopes between sensors 2 and 7 and sensors 1 and 2. The angle formed by the slope of sensor 2 and 7 and a horizontal or level line was computed as one parameter ($\hat{Q}$). The other parameter ($\hat{M}$) was the angle formed by the slope of sensors 1 and 2 and a vertical or plumb line. The actual angles are very small since the deflections are measured in mils and the horizontal distances in inches or feet. Thus a scaling factor is used to represent the horizontal distances between sensors 1 and 2 and sensors 2 and 7; these are 6 and 24 respectively. Hence, as illustrated in Fig 6.11, the parameters are computed as

$$\hat{Q} = \text{Arc tan } [(S_2 - S_7)/24]$$
$$\hat{M} = \text{Arc tan } [6/(S_1 - S_2)]$$

TABLE 6.1. DEFLECTION BASIN PARAMETERS AT LOCATION WITH VOIDS PREDICTED

Location	Upstream Deflection Ratio (UDR)	Downstream Deflection Ratio (DDR)	Maximum Deflection (Sensor 1) (mils)	Void Parameter M	Void Parameter Q
1V U	.89		32.0	88	12
1V D		.93	85.0	79	11
2V U	.18		22.1	17	4
2V D		.31	22.4	51	29
3V U	.17		19.5	19	4
3V D		.11	21.0	50	89
4V U	.92		51.1	67	19
4V D		.94	31.4	72	19
5V U	.94		16.8	80	23
5V D		.95	17.4	72	83
5V U	.90		14.6	87	21
5V D		.93	16.7	60	20

TABLE 6.2. DEFLECTION BASIN PARAMETER AT LOCATION A

Location	Upstream Deflection Ratio (UDR)	Downstream Deflection Ratio (DDR)	Maximum Deflection (Sensor 1) (mils)	Void Parameter M	Void Parameter Q
1D U	.96		11.5	71	15
1D D		.98	10.0	83	15
2D U	1.00		4.1	81	7
2D D		.84	3.6	80	5
3D U	.87		3.5	85	4
3D D		.94	3.7	86	5
1C U	.82		13.6	53	14
1C D		.83	9.1	76	11
1C C	.98	.98	6.5	84	8
2C U	1.00		3.1	83	4
2C D		.96	2.8	84	4
2C C	.94	.94	4.0	85	6
3C U	1.00		2.8	85	4
3C D		.96	2.8	85	4
3C C	.96	.96	2.6	87	4
4C U	.83		6.2	88	9
4C D		.93	7.3	75	9
1I U	.94		17.2	72	23
1I D		.93	16.7	66	21
2I U	.81		7.7	76	12
2I D		.78	6.0	76	9
3I U	.84		6.4	87	9
3I D		.82	7.5	88	10
4I U	.57		21.3	27	15
4I D		.47	23.5	53	29

TABLE 6.3. DEFLECTION BASIN PARAMETER AT LOCATION B

Location	Upstream Deflection Ratio (UDR)	Downstream Deflection Ratio (DDR)	Maximum Deflection (Sensor 1) (mils)	Void Parameter M	Void Parameter Q
1D U	.36		16.1	27	6
1D D		.21	23.9	44	28
2D U	.92		9.6	78	12
2D D		.90	8.7	78	11
3D U	.88		8.3	88	12
3D D		.94	9.1	76	11
4D U	.58		18.7	30	14
4D D		.93	15.5	60	21
5D U	.86		7.4	88	11
5D D		.96	8.5	76	10
1C U	.26		17.6	23	4
1C D		.18	24.4	49	29
1C C	1.00	1.00	7.4	85	8
2C U	.88		8.5	89	12
2C D		.91	9.4	74	11
2C C	.99	.98	6.9	85	8
3C U	.93		8.5	89	12
3C D		.93	8.4	78	10
3C C	.99	.98	7.1	83	8
4C U	.32		20.2	22	7
4C D		.90	14.5	63	20
4C C	.98	.99	6.9	85	9
5C U	.88		8.2	86	12
5C D		.93	8.7	76	10
1I U	.20		30.5	13	6
1I D		.13	42.9	29	43
2I U	.92		15.7	83	22
2I D		.93	15.8	70	19
3I U	.94		15.1	81	21
3I D		.98	14.5	73	18
4I U	.20		43.7	9	10
4I D		.98	28.2	56	31
5I U	.93		15.3	80	18
5I D		.97	15.1	73	18

TABLE 6.4. JOINT EVALUATION AT LOCATION WITH VOIDS PREDICTED

	Joint Condition (Load Transfer)				
Location	Full (%)	None (%)	Partial (%)	Void Indicated	No Void Indicated
IV	90				X
2V			30	X	
3V		14		X*	
4V	93			X*	
5V U	95			X*	
5V D	92			X*	

*Core was taken and void confirmed.

TABLE 6.5. JOINT EVALUATION AT LOCATION A

Location	Joint Condition (Load Transfer) Full (%)	None (%)	Partial (%)	Void Indicated	No Void Indicated
10	97				X
20	92				X
30	90				X
40	92				X
1C			83		X
1C C	98				X*
2C	98				X*
2C C	94				X*
3C	98				X*
3C C	96				X
4C			88		X
1I	93			X	
2I			79		X
3I			83		X
4I			52	X	

*Core taken and no void confirmed.

TABLE 6.6. JOINT EVALUATION AT LOCATION B

	Joint Condition (Load Transfer)				
Location	Full (%)	None (%)	Partial (%)	Void Indicated	No Void Indicated
10			29	X	
20	91				X
30	91				X
40			75	X	
50	91				X
1C		22		X*	
1C C	100				X
2C			89		X
2C C	99				X
3C	93				X
3C C	99				X
4C			61	X*	
4C C	99				X
5C	90				X
1I			18		X
2I	92				X
3I	96				X
4I			59		X*
5I	95				X*

*Core taken and void confirmed.

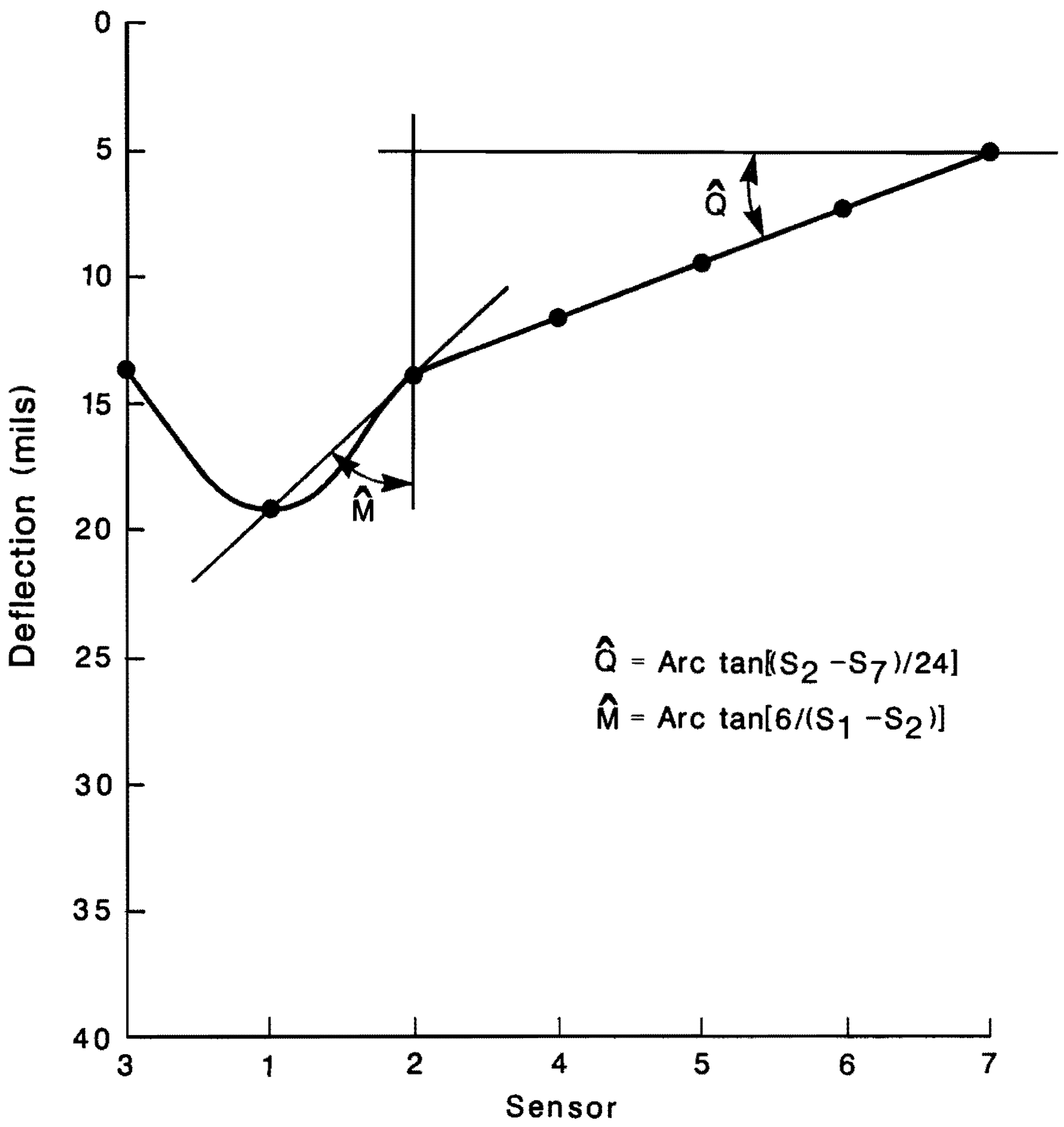


Fig 6.11. Deflection basin parameters for void detection.

where

S_1 = deflection in mils at sensor 1,
S_2 = deflection in mils at sensor 2, and
S_7 = deflection in mils at sensor 7.

Values of $\hat{Q}$ and $\hat{M}$ were calculated for each test in the Gainesville site and are tabulated in Tables 6.1, 6.2, and 6.3. These were then plotted as $\hat{M}$ versus $\hat{Q}$ in Fig 6.12. For those locations where a void was indicated by other equipment the value of $\hat{Q}$ was greater than 18 for all tests except one. For locations where no void was indicated the value of $\hat{Q}$ was less than 18 with few exceptions. For all tests at center slab away from either joints or cracks the values for $\hat{Q}$ were less than 10, the values for $\hat{M}$ were greater than 85 with one exception, and the values for JDR were approximately one. These values should be expected if no void is present and load transfer is 100 percent. With few exceptions when $\hat{Q}$ was greater than 18, $\hat{M}$ was less than 70. For those exceptions where $\hat{Q}$ was greater than 18 and $\hat{M}$ was greater than 70, the JDR was greater than .9 indicating full load transfer. Hence, the value of $\hat{M}$ may indicate the size of the void. When $\hat{Q}$ is greater than 18, the smaller the value of $\hat{M}$ the larger the diameter of the void. Of course the values of $\hat{Q}$ and $\hat{M}$ are influenced by the thickness and the flexural strength of the PCC layer. Additional data for other locations with known voids and PCC pavement types will be necessary to validate the proposed criteria and determine if any valid judgements can be made relating the size of the void to the value of $\hat{M}$.

Tables 6.4, 6.5, and 6.6 present an evaluation of the joints with respect to an indicated void using the criteria for $\hat{Q}$ greater than 18. Cores were taken at several locations to determine whether or not a void was present. These are identified in the tables. In all cases where a void was indicated and a core taken, the presence of a void was confirmed. Likewise, in all cases where a void was not indicated and a core was taken, no void was identified.

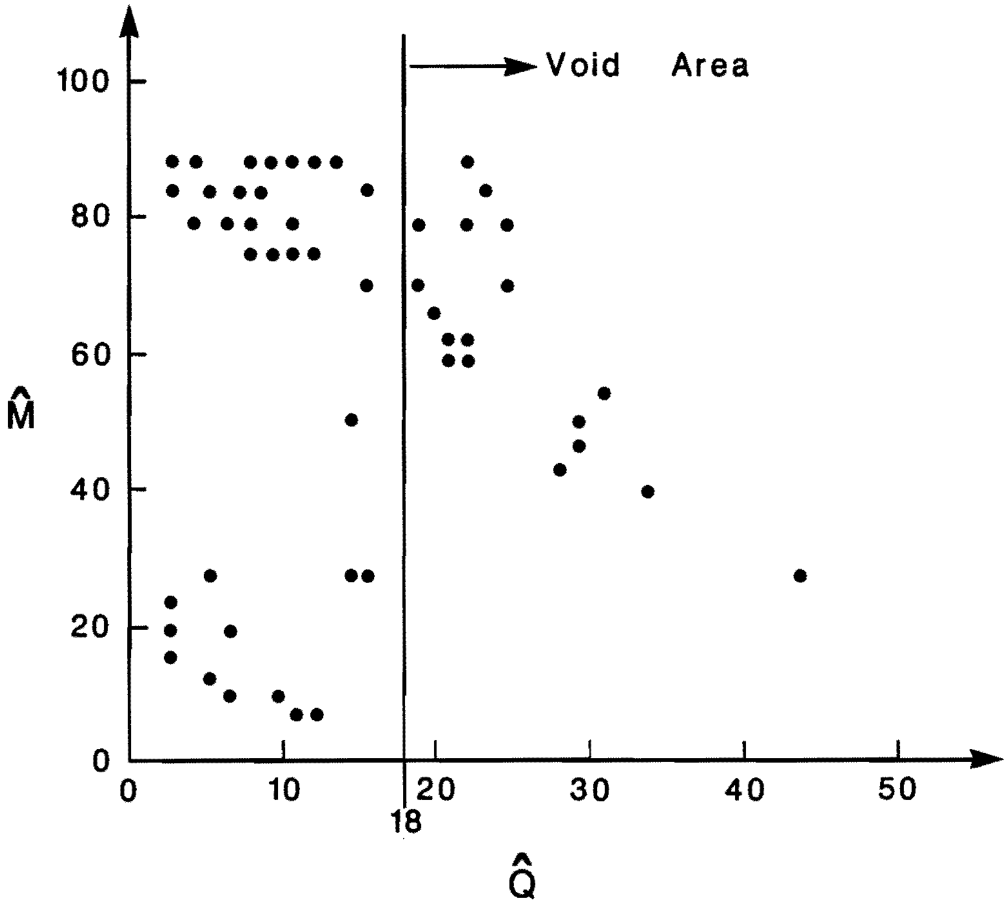


Fig 6. 12. Relationship between angles $\hat{M}$ and $\hat{Q}$.

CHAPTER 7. CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

A major goal of this study was to purchase, evaluate and implement the use of an FWD for rigid pavement testing for the Texas State Department of Highways and Public Transportation (SDHPT). This goal was accomplished and a Model 8000 FWD manufactured by Dynatest has been in service since July of 1984.

This report finalizes the results of Research Study 3-8-84-387, "Purchasing and Adapting a Falling Weight Deflectometer for Non-Destructive Evaluation and Research on Rigid Pavement in Texas." Two previous reports have been submitted and stand alone with their findings. The overall conclusions from this report and the study as a whole are given here.

(1) The FWD is a satisfactory tool for structural evaluation of rigid pavements.

(2) The variability and repeatability of the FWD are statistically acceptable for the applications tested and are equal to or less than those of other NDT devices used for rigid pavements.

(3) For test loads greater than 6,000 pounds the variability is less than for test loads of less than 6,000 pounds. Test loads below 2,000 pounds can not effectively be generated.

(4) Temperature has an effect on the polymeric spring system used in the FWD and tests below 50°F may be erroneously interpreted.

(5) Raising and lowering the geophone sensor system between tests had no significant influence on the resulting measurements.

(6) The FWD predicts higher values of moduli for the surface layers of rigid pavements when compared to the Dynaflect, as calculated in the RPEDD1 program.

(7) For the pavements tested, and the load ranges used, no non linear behavior of any of the layers could be detected.

(8) The FWD is effective in evaluating the load transfer efficiency of sawed undoweled joints in rigid pavements.

(9) The FWD is effective in indicating the presence of a void underneath a rigid pavement surface at joints.

RECOMMENDATIONS

Based on the results of this study and the conclusions outline above, the following recommendations are made:

(1) Data generated by the FWD on rigid pavements should be used to (a) evaluate the structural capacity of rigid pavements, (b) evaluate the insitu moduli of pavement layers, (c) evaluate the load transfer efficiency of joints, and (d) evaluate the presence of voids underneath the pavement surface.

(2) For all tests the nominal load applied should be in the range of 6,000 to 20,000 pounds.

(3) For all tests the ambient temperature should be in the range of 50°F to 100°F.

(4) For insitu moduli, determination of the test should be made in the wheel path or at center slab away from a joint or crack with a nominal load of 18,000 pounds.

(5) The criteria presented in Chapter 6 should be used to evaluate load transfer efficiency of joints.

(6) The criteria presented in Chapter 6 should be used to detect the presence of voids.

(7) Additional measurements for moduli, load transfer, and void detection be made on a variety of rigid pavements to validate or refine the criteria presented herein.

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