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16. Abstract

The Multi-Depth Deflectometer (MDD) is an LVDT deflection measuring device which is retrofitted into pavement layers. A maximum of six MDD modules may be installed in a single 1.5 inch diameter hole. The modules are clamped against the sides of the hole at the required depths and the center core is attached to an anchor located approximately 7 feet below the pavement surface. The MDD can measure either the relative elastic deflection or the total permanent deformation of each layer in the pavement system. By placing multiple modules in a single hole, the vertical strains induced in pavement layers can be measured.

This report describes the installation of Multi-Depth Deflectometers at the Texas A&M Research Annex. The pavement response under both Falling Weight Deflectometer and truck loading is described, together with an analysis procedure to backcalculate layer moduli from depth deflection readings. The MDD results obtained are extremely promising. The device is relatively inexpensive and durable. It shows a great potential in assisting in several areas of pavement research, including backcalculation analysis, tire pressure and rutting studies.

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FIELD EVALUATION OF THE

MULTI-DEPTH DEFLECTOMETERS

by

T. Scullion
J. Uzan
J. I. Yazdani
P. Chan

Research Report 1123-2

Study Title: "Nondestructive Test Procedures for Analyzing the Structural Condition of Pavements"

Project 2-18-87-1123

Sponsored by

Texas State Department of
Highways and Public Transportation

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Federal Highway Administration

by

Texas Transportation Institute

September, 1988

METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

LENGTH

Symbol	When You Know	Multiply By	To Find	Symbol
in	inches	2.54	millimetres	mm
ft	feet	0.3048	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km

AREA

Symbol	When You Know	Multiply By	To Find	Symbol
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.0929	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
mi^2	square miles	2.59	kilometres squared	km^2
ac	acres	0.395	hectares	ha

MASS (weight)

Symbol	When You Know	Multiply By	To Find	Symbol
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg

VOLUME

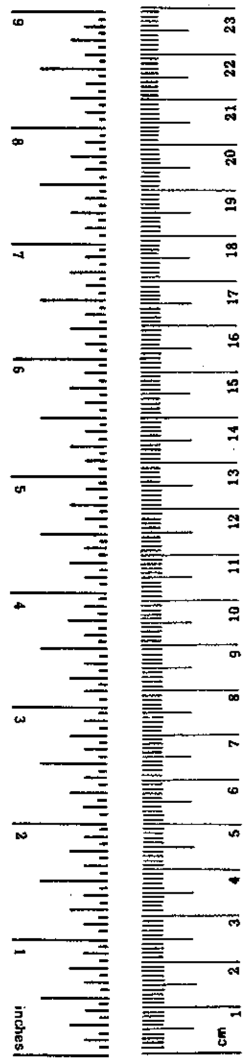
Symbol	When You Know	Multiply By	To Find	Symbol
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.0328	metres cubed	m^3
yd^3	cubic yards	0.0765	metres cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3.

TEMPERATURE (exact)

Symbol	When You Know	Multiply By	To Find	Symbol
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

* SI is the symbol for the International System of Measurements



APPROXIMATE CONVERSIONS TO SI UNITS

LENGTH

Symbol	When You Know	Multiply By	To Find	Symbol
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi

AREA

Symbol	When You Know	Multiply By	To Find	Symbol
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
km^2	kilometres squared	0.39	square miles	mi^2
ha	hectores (10 000 m^2)	2.53	acres	ac

MASS (weight)

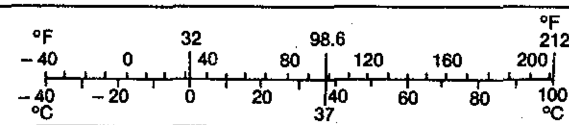
Symbol	When You Know	Multiply By	To Find	Symbol
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1 000 kg)	1.103	short tons	T

VOLUME

Symbol	When You Know	Multiply By	To Find	Symbol
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3

TEMPERATURE (exact)

Symbol	When You Know	Multiply By	To Find	Symbol
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



These factors conform to the requirement of FHWA Order 5190.1A.

ABSTRACT

The Multi-Depth Deflectometer (MDD) is an LVDT deflection measuring device which is retrofitted into pavement layers. A maximum of six MDD modules may be installed in a single 1.5 inch diameter hole. The modules are clamped against the sides of the hole at the required depths and the center core is attached to an anchor located approximately 7 feet below the pavement surface. The MDD can measure either the relative elastic deflection or the total permanent deformation of each layer in the pavement system. By placing multiple modules in a single hole, the vertical strains induced in pavement layers can be measured.

This report describes the installation of Multi-Depth Deflectometers at the Texas A&M Research Annex. The pavement response under both Falling Weight Deflectometer and truck loading is described, together with an analysis procedure to backcalculate layer moduli from depth deflection readings. The MDD results obtained are extremely promising. The device is relatively inexpensive and durable. It shows a great potential in assisting in several areas of pavement research including backcalculation analysis, tire pressure and rutting studies.

DISCLAIMER

This report is not intended to constitute a standard, specification or a regulation and does not necessarily represent the views or policy of the Federal Highways Administration or Texas Department of Highways and Public Transportation.

IMPLEMENTATION STATEMENT

The Multi-Depth Deflectometer can assist the SDHPT in many areas. Studies planned include validation of modulus backcalculation procedures and monitoring the effects of wide base single tires. Both of these should provide information that can be implemented with the Department's ongoing pavement management effort.

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SECTION 1

INTRODUCTION

This report describes the Multi-Depth Deflectometer (MDD) and presents results obtained from three instrumented pavement sections at the Texas A&M Research Annex. The MDD measures both transient deflections and permanent deformations of pavement layers. It has been used to measure in-situ resilient moduli values of pavement layers and to identify individual layer deformations in accelerated loading tests. The main goal of this report is to: (a) describe the MDD and the installation process; (b) show typical results under truck and Falling Weight Deflectometer loadings; and (c) develop an approach to assist in validating modulus backcalculation procedures under Nondestructive Testing.

The procedure used by several investigators to verify modulus backcalculation procedures is to compare the results obtained from an appropriate theoretical analysis of NonDestructive Test (NDT) data to those obtained from laboratory testing of the pavement materials. Resilient modulus tests are commonly performed on base course and subgrade materials using a triaxial test apparatus. For thin surfacings, repeated load diametral tests are performed. The problem with this approach is that it is difficult, if not impossible, to duplicate field loading conditions in the laboratory. The problem is particularly acute for granular base materials, where laboratory specimens have to be remolded to the same moisture and density as in the field and then subjected to loading conditions as close as possible to those under moving vehicles. Despite the problems inherent in this approach, verification of modulus backcalculation procedures remains a crucial concern, particularly with the publication of the new AASHTO Design Procedure (1) which advocates NDT evaluations for pavement rehabilitation designs.

In this report a different approach is taken to verify modulus backcalculation procedures. Three research pavement sections at the Texas Transportation Institute's Research Annex have been instrumented with Multi-Depth Deflectometers (MDD). These devices measure the transient deflection between a particular location in the pavement and an anchor located at approximately 7 feet below the surface. By placing MDDs in each pavement layer, a procedure has been developed to independently calculate the resilient modulus of each pavement layer.

Therefore by measuring MDD response under Falling Weight Deflectometer (FWD) loading, two independent procedures are available for backcalculating layer modulus, one with the FWD sensor readings and the other with the MDD output.

Results are presented in this paper of MDD response measured at a range of Falling Weight Deflectometer loadings. Analysis included developing an automated procedure for estimating layer moduli from MDD readings and comparing these results with those obtained using standard procedures available for interpreting surface deflections.

Preliminary results of MDD response under truck loading are also presented. The MDD shows considerable potential in this area. By processing the signal, it is possible to determine the vertical strains in the base course, the vertical strains in the subgrade, and the surface curvature index (related to the tensile strains at the bottom of the asphalt). Furthermore, by measuring the zero voltage position of each MDD module from the surface, it is possible to monitor permanent deformations in each of the pavement layers.

In the next section of this report, the MDD device and the instrumentation procedure will be described. The Data Logging System is presented in Section 3, which is the followed by a section on the typical results obtained and analysis performed. Conclusions are presented in Section 5.

SECTION 2

DESCRIPTION OF MDD UNIT

The Multi-Depth Deflectometer (MDD) was developed by the National Institute for Transport and Road Research (NITRR) in South Africa (2, 3, 4) as an integral part of their accelerated loading tests. It is used to measure transient deflection and the permanent deformation in pavement layers. It provides a means of measuring the change in pavement deflection at various depths in a vertical direction caused by a passing wheel load, generating a depth deflection profile. The permanent deformation of a pavement at different layer depths can also be measured during the service period of the MDD. The MDD is so constructed that the resilient deflection of a maximum of six levels can be simultaneously measured. The installation of the MDD is an intricate procedure and is described in Section 2.1.

Figure 1 shows a schematic of a typical MDD which consists of modules with Linear Variable Differential Transformers (LVDTs). The LVDTs are positioned at different depths in the pavement to measure any movement in these layers. The modules are locked in position by turning the clamping nut which forces the steel ball outwards, clamping them against the sides of the hole. The interconnecting rod is adjustable and contains LVDT cores at spacings which coincide with the module placement.

A typical MDD installation is shown in Figure 2. In practice up to six modules may be placed in a single hole. The interconnecting rod is fixed to an anchor located at approximately 7 feet below the pavement surface. When data is being collected, a reinforced connector cable is attached which links to the data-capture system. When the MDD is not in use, a brass surface cap, which is flush with the surface, completely seals the hole.

Figure 3 shows a photograph of the MDD Module with the Schaevitz E-300 (0.30 inch equals 10 volts) series LVDT. The total length of the module is approximately 5 inches. If the E-100 (0.10 inch equals 10 volts) series LVDT is used, the total length drops to 4 inches. The length of the module is the only factor which dictates how close the modules can be placed within the pavement layers.

In order for the MDD to operate satisfactorily, certain mechanical and electrical requirements have to be met. Mechanical requirements include the

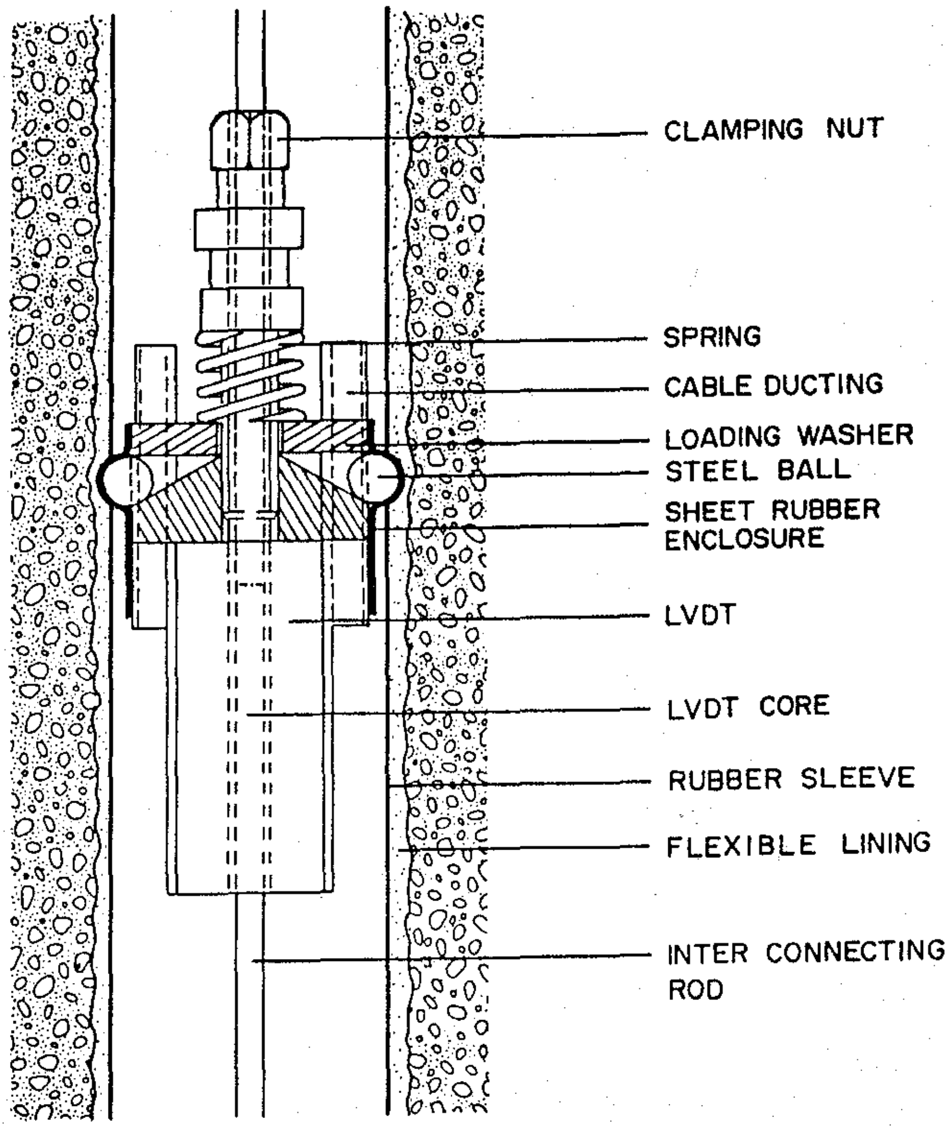


FIGURE I

COMPONENTS OF A MDD MODULE

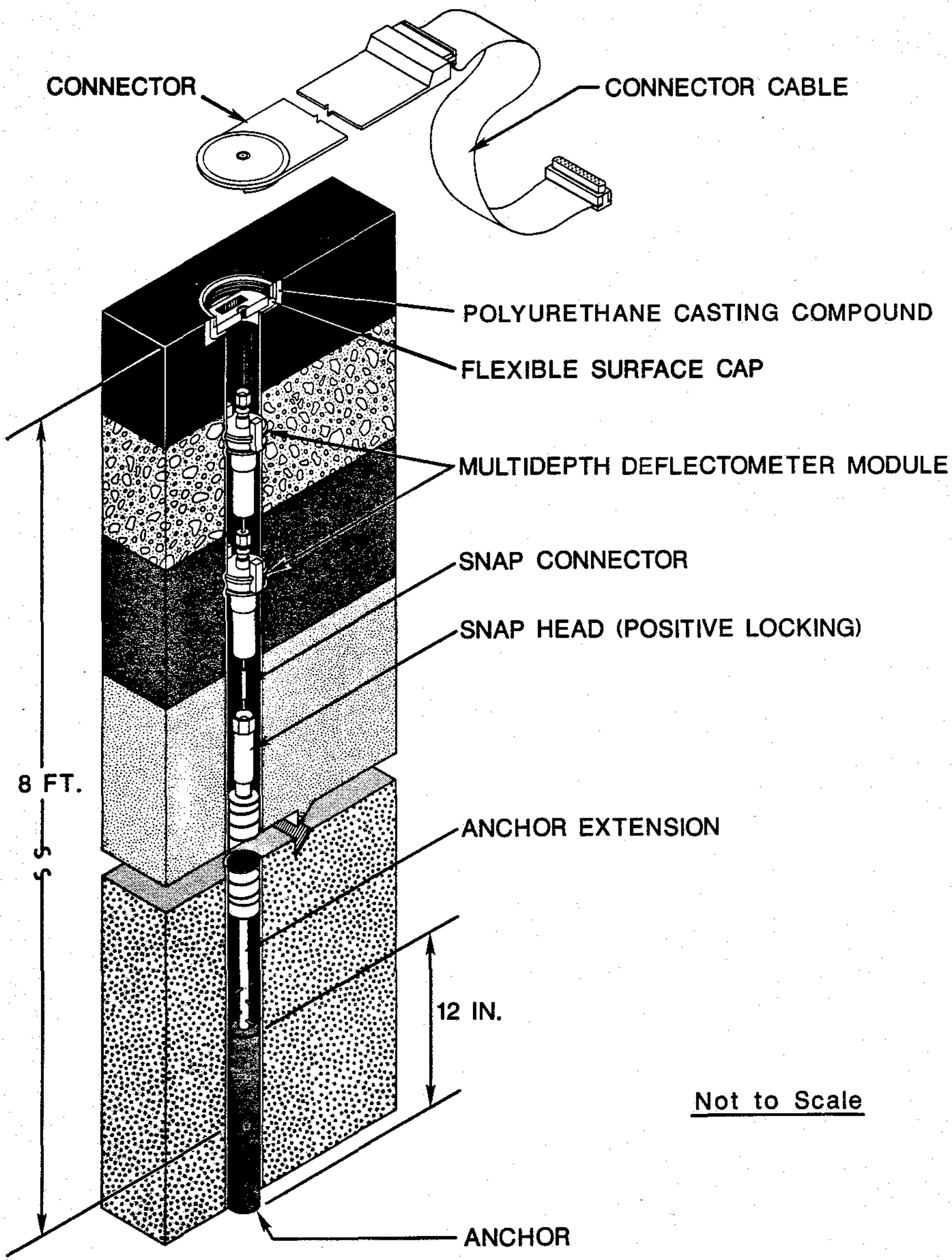


Figure 2. Typical Cross Section of MDD after Installation

Figure 3. Photograph of MDD Module

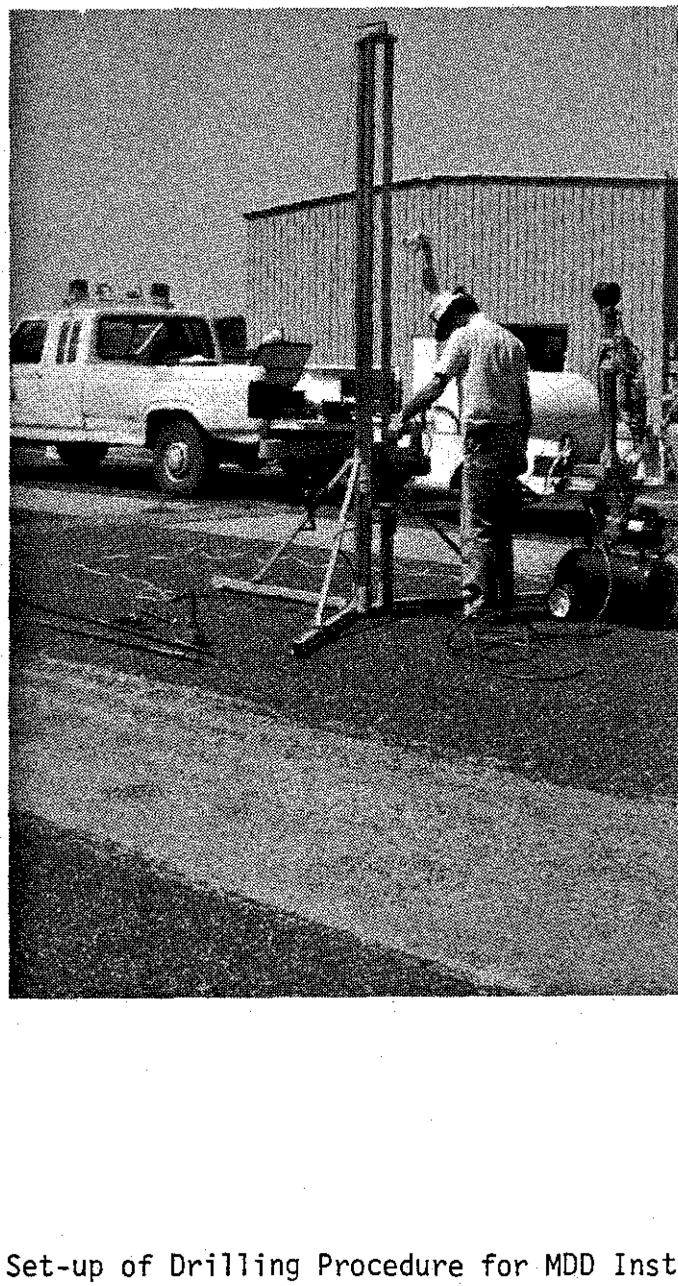


Figure 4. Set-up of Drilling Procedure for MDD Installation

following:

- the MDD should be inserted in a hole drilled vertically with a diameter of about 1.5 inches.
- the material adjacent to the hole should remain undisturbed.
- the hole must be lined so as not to dislodge material from the sidewalls when the pavement is under stress.
- the test hole must later be sealed so as not to allow the ingress of any moisture.

Among the electrical requirements to be met are the following:

- the response of the module must be insensitive to moisture in the test hole.
- LVDTs are used to measure the pavement deflections.
- the cables used to transmit data must be fixed in a protective sleeve.
- prior to operation, the LVDTs must be calibrated, so as to remove any zero error.

2.1 FIELD INSTALLATION

In order for the MDD to operate effectively, special care has to be exercised in installing the MDD unit. The test hole for instrumentation of the pavement section has to be drilled vertically. Percussion drills and a specially designed drilling rig are used for the drilling procedure (Figure 4). A 1.5 inch diameter hole is drilled to a depth of approximately 7 feet. The top one inch of the pavement is drilled with a special 2.5 inch drilling bit for installation of the top cap which is mounted flush with the surface (Figure 5). The top of the MDD has to be level with the pavement to avoid any point loading on it after installation. The hole is then lined with a 0.1 inch thick lining tube and the voids between the tube and the wall are filled with a rubber grout. The lining tube serves two purposes: viz, preventing the adjacent material from dislodging when under stress and guiding the MDD anchorpin for correct installation. The MDD anchorpin is locked in place using a fast setting cement/sand paste. This is followed by installing a pilot rod which is used to guide the MDD modules into the right position.

The modules are installed into the correct predetermined position using an installation tool especially designed for the purpose. Figure 6 shows a module being lowered into the test hole. The module is guided to the correct position

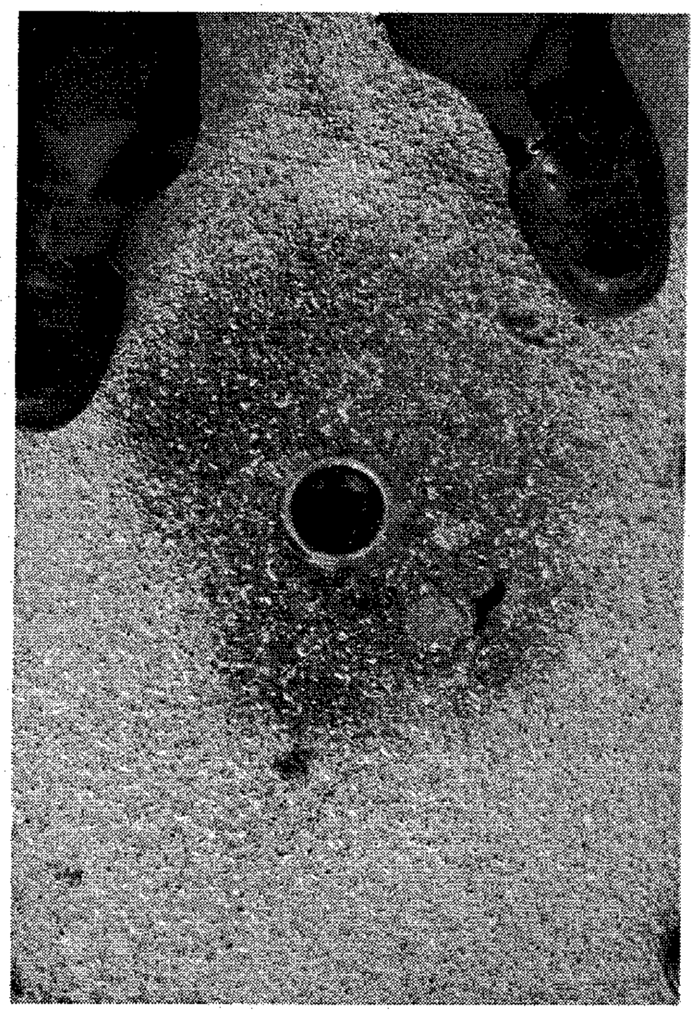


Figure 5. MDD Hole Ready for Module Installation

Figure 6. Lowering the MDD Module by Means of Snap Connector

in the test hole and secured by turning the clamping nut at the top of the MDD module. Similarly all the other modules are installed. The modules are numbered from the shallowest to the deepest in ascending order. The modules having been fixed in place, they must be calibrated before their operation. The complete installation takes approximately 1 1/2 days. The hole is drilled, lined and the anchor is installed on the first day; the rubber grout needs approximately 12 hours to set (depending on the temperature). On the second day the MDD modules are installed and calibrated.

2.2 FIELD CALIBRATION

In order to perform field calibration, a signal conditioner box unit, and a calibrator unit fitted with a dial gauge mounted on a screw adjusting mechanism are used, as shown in Figure 7. The gain pot settings on the signal conditioner are adjusted for each module to be the same as obtained from calibration in the laboratory. The MDD core is moved up and down against the modules manually to determine its mid-zero position. The calibrator unit is then placed above the MDD hole and a core is connected to it. The screw mechanism is turned until the module reads zero on the conditioner unit. The dial gauge is set to a zero reading, and the screw mechanism is turned until the dial gauge reads 0.30 inch, (for the E300 Schaevitz LVDTs). The conditioner unit should read 10 (volts). If not, it should be adjusted to read 10.00 volts on the conditioner. As a check, the dial gauge is reset to zero displacement, and the conditioner should give a zero reading. The procedure is repeated for each module installed in the MDD. Upon completion of the calibration procedure, the final pot settings are noted. Either the E300 series LVDT with a range of 0.30 inch or the E100 series LVDT with a range 0.10 inch has been used. The E100 LVDTs are recommended for deflection evaluation, whereas the E300 are preferred for long-term monitoring under traffic.

After having calibrated the MDD, it is sealed off with a brass cap which is screwed flush with the pavement surface. The surface cap is removed during a measuring operation to enable a cable to be connected from the MDD to a computerized data acquisition system. This setup was shown earlier in Figure 2.

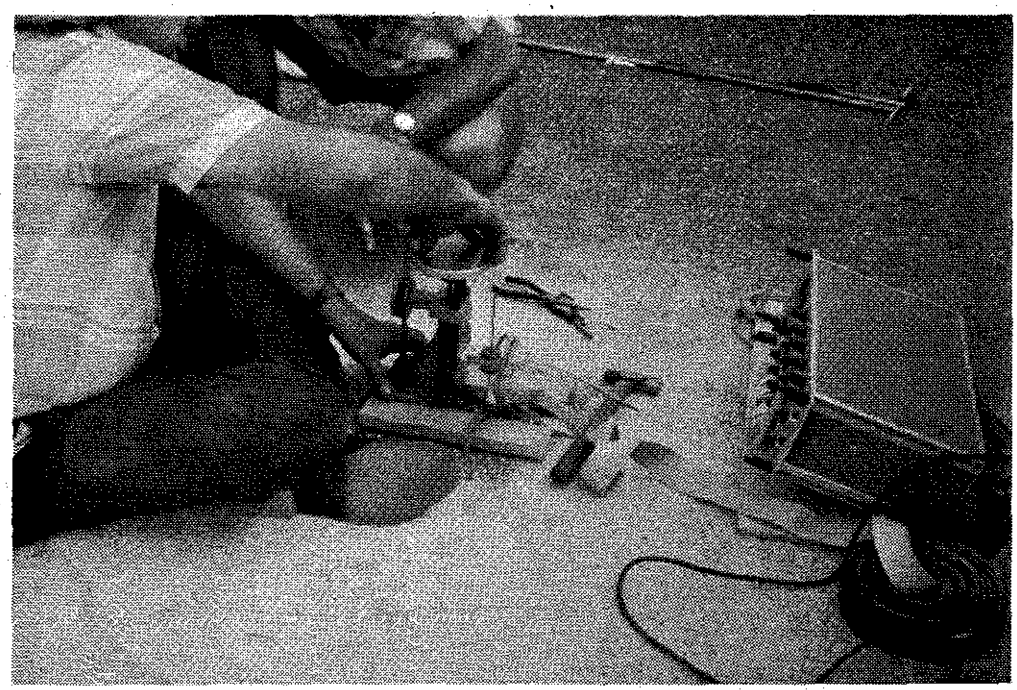


Figure 7. Field Calibration of MDD

2.3 MDD RECOVERY

One of the major advantages of the MDD is that the modules can be extracted from the hole once testing is complete. With reference to Figure 2, the only parts of the system which cannot be extracted are the anchor and hole lining. The MDD modules, center core, snap head connector and surface cap can be recovered for future use. Replacing MDD modules in an existing hole can be accomplished in one day.

SECTION 3

DATA LOGGING SYSTEM OF THE MDD

The MDD data logging system is shown schematically in Figure 8. Loads are applied to the system by either Nondestructive Testing Equipment or truck tire loadings. The LVDTs monitor the differential movement between the pavement layers and the fixed anchor. The LVDT output voltage is processed using the following hardware and software.

3.1 SIGNAL CONDITIONER BOX

The MDD voltages are first processed by a six-channel signal conditioner box which converts them into computer readable form. Each channel is set to give a calibrated output of $\pm$ 10 volts for the LVDT full range on the 100% scale. The conditioner box has several features, including a scaling switch which permits the user to select the full range scale (2%, 5%, 10%, 20%, 40%, 50% or 100%), a zero offset pot and digital output. The range setting makes the system more sensitive and permits the monitoring of small displacements. For example on the 100% scaling, 10 volts is equal to a movement of 0.30 inch, on 10% scaling, 10 volts is equal to 0.030 inch.

In the work completed, two sizes of LVDTs have been used: the E300 series which has a range 0.30 inch, and the E100 series which has a range of 0.10 inch. Typical MDD readings under FWD loading have been in the range of 0.001 to 0.020 inch. Therefore to get an acceptable range the E300 LVDTs have been recorded on the 5% scale range, whereas the E100 LVDTs have been recorded on the 20% scale range. Using the E300 series on the 5% scale introduces noise into the system which needs to be filtered out. A procedure for doing this is described below. The E300 series are easier to install and are recommended for long-term testing, which could include layer deformation. The E100 series are more accurate, produce a cleaner output signal, but are more difficult to install and more easily go out of range as the pavement deforms.

3.2 MICROCOMPUTER DATA LOGGING

The FWD load pulse is approximately 30 milliseconds in duration and the MDD

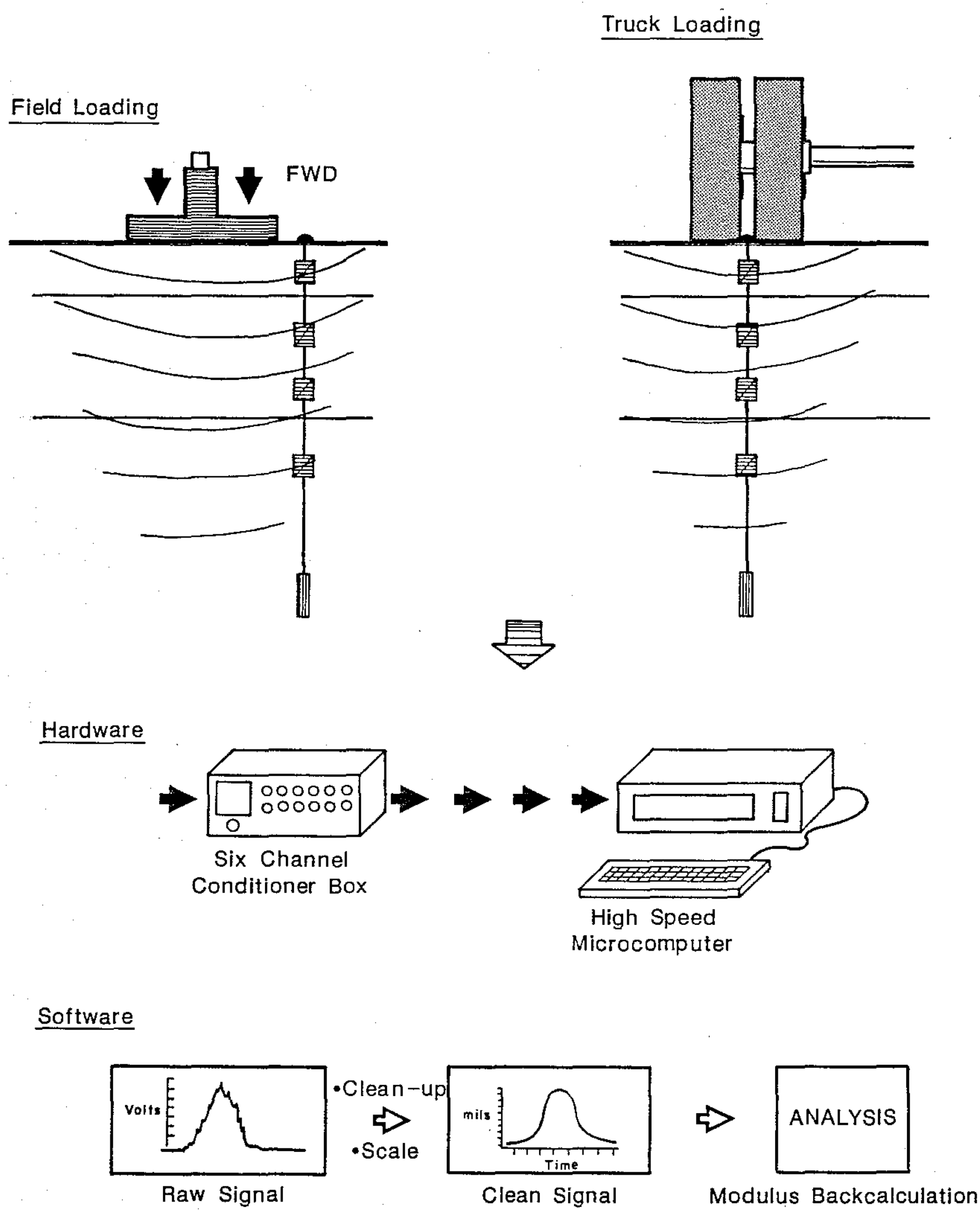


Figure 8. MDD Data Logging System

system typically records data for 60 milliseconds. Triggering of the FWD is performed by a proximity sensor activated while the load is falling. To be compatible with the MDD, the system must be able to record six channels at a high enough sampling rate. In order to capture the data, a Metrabyte DAS-16F circuit board has been installed inside the expansion slot of a portable Compaq 386/20 microcomputer. This arrangement is driven by the modified Metrabyte software with the capacity of acquiring up to 10,000 samples per second. For the MDD system, a sampling rate of 5000 readings per channel per second is used which records 300 points in the 60 millisecond recording interval. Triggering has been automated based on a response to any MDD sensor greater than a preset trigger level. The pretrigger information, 100 data points, is stored and included in the record.

In operation with the Falling Weight Deflectometer, the FWD control system is placed in manual. The "settling" drop is performed and the weights raised and held in the "up" position. The weights are dropped by the operator punching "carriage return". This manual operation permits the synchronization of FWD and MDD data collection systems.

3.3 DATA CLEANUP AND SCALING

Figure 9a shows a typical MDD trace under a FWD loading on Section 12 at the Texas A&M Research Annex. The MDD module was located 2.6 inches below the surface of the pavement, the LVDT used was the E300 series, and the conditioner scaling factor was set at 5% (i.e., 20 times amplification of the signal). As shown in Figure 9a, high frequency noise was present in the signal. The source of the noise was not detected. However, it was only observed with the E300 series LVDTs. The E100 series LVDT used a conditioner scaling of 20% (5 times amplification).

The noise was present in both truck tests and Falling Weight Deflectometer tests. It was problematic in that it made it difficult to accurately determine the true maximum deflection, particularly when low magnitude signals (<2 mils) were being analyzed. To clean up the signal, a filter program was written. This program performed a Fast Fourier Transform on the signal. In the frequency domain, it was determined that the noise was at 130 Hz. The spectrum of the signal was therefore filtered and the frequency components that were over 120 Hz were attenuated. This was followed by an inverse Fourier Transform to return the signal to the time domain. The filtered signal is shown in Figure 9b.

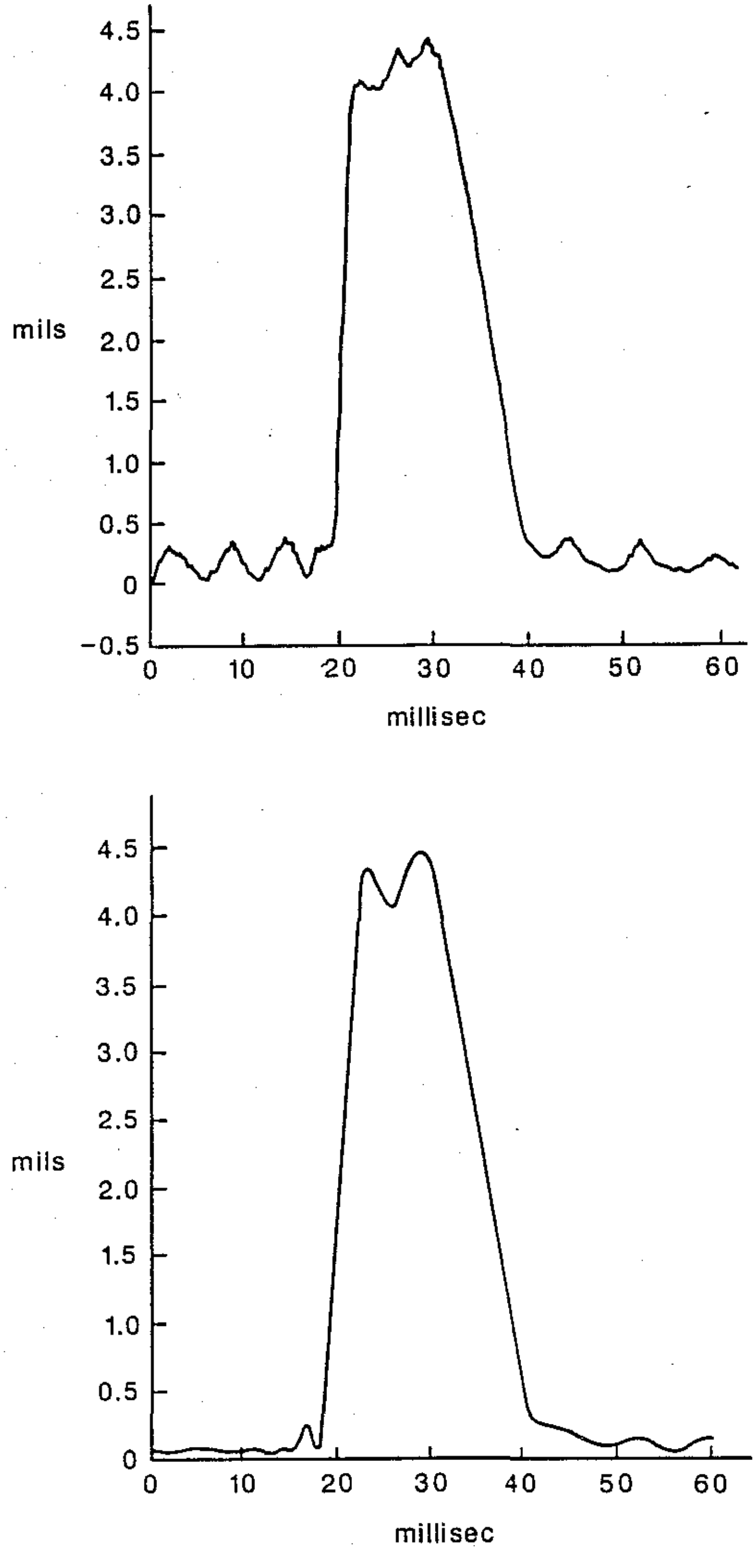


Figure 9. MDD Responses Before and After Filtering

9a) MDD Response Before Filtering

9b) MDD Response After Filtering

SECTION 4

DATA ANALYSIS

This section presents results of tests performed on the three instrumented sections at the TTI Research Annex. The layer thicknesses and MDD locations are shown in Figure 10. Sections 8 and 12 have similar layer thicknesses except that Section 8 has a cement stabilized subbase over a clay subgrade, whereas Section 12 has a crushed limestone subbase over a sandy gravel subgrade. Five MDD modules using the E300 series LVDT (0.30 inch full range) were installed in both Sections 8 and 12. The anchors for Sections 8 and 12 were located at 70 inches below the surface. Section 11 has a thin surfacing over a thick crushed limestone base over a sandy gravel subgrade; the anchor was located at 60 inches. In Section 11, two MDD modules were installed using the E100 series LVDT (0.10 inch full range).

In the remainder of this section, typical results and analyses performed will be presented. This is broken down as follows:

4.1 Typical Results Under FWD Loading

4.2 Typical Results Under Truck Loading

4.3 Moduli Backcalculation

4.1 TYPICAL RESULTS UNDER FWD LOADING

Typical MDD results from FWD loadings are shown in Figures 11 and 12. Figure 11 is data collected on Section 12 (granular base and subbase). It is noted that the maximum deflection was measured at approximately 4.4 mils and the deflection decreased with depth in the pavement. Figure 12 shows the data from Section 8 (cement stabilized subbase). Under similar FWD loading, the measured maximum deflection was 2.5 mils. The deflections in sensors 3 (bottom of base), 4 (center of CTB) and 5 (top of subgrade) were essentially the same, at approximately 1.2 mils. This demonstrates the rigid layer's ability to spread the load and minimize damage to the underlying layers.

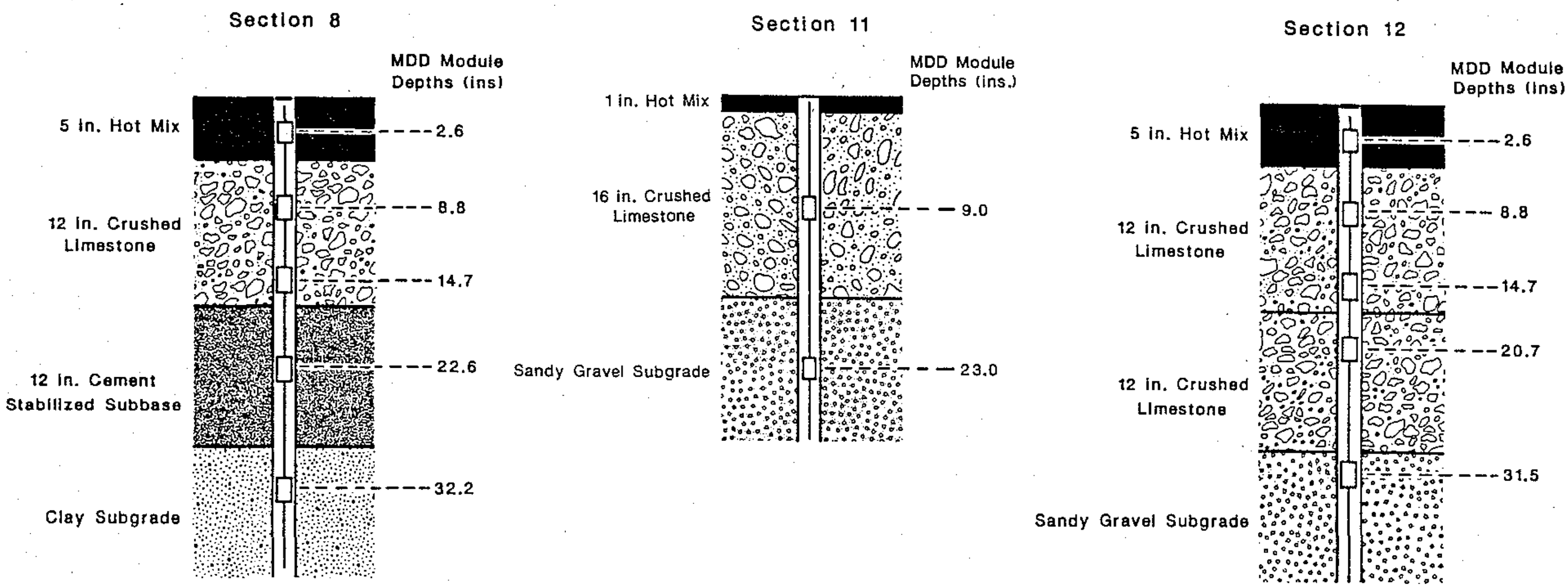


Figure 10. MDD Installations at TTI Research Annex

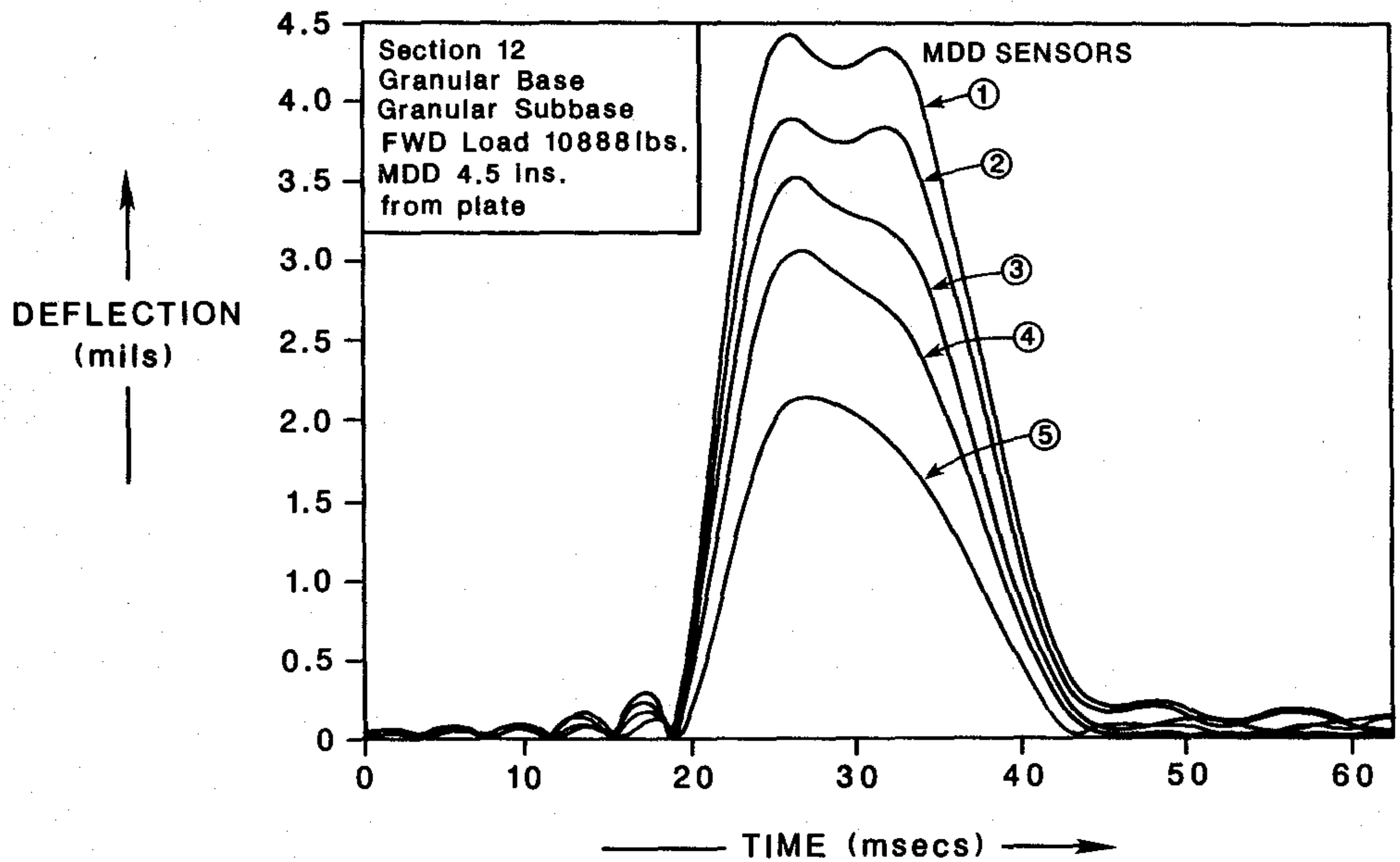


Figure 11. MDD Response Under FWD Loading (Section 12)

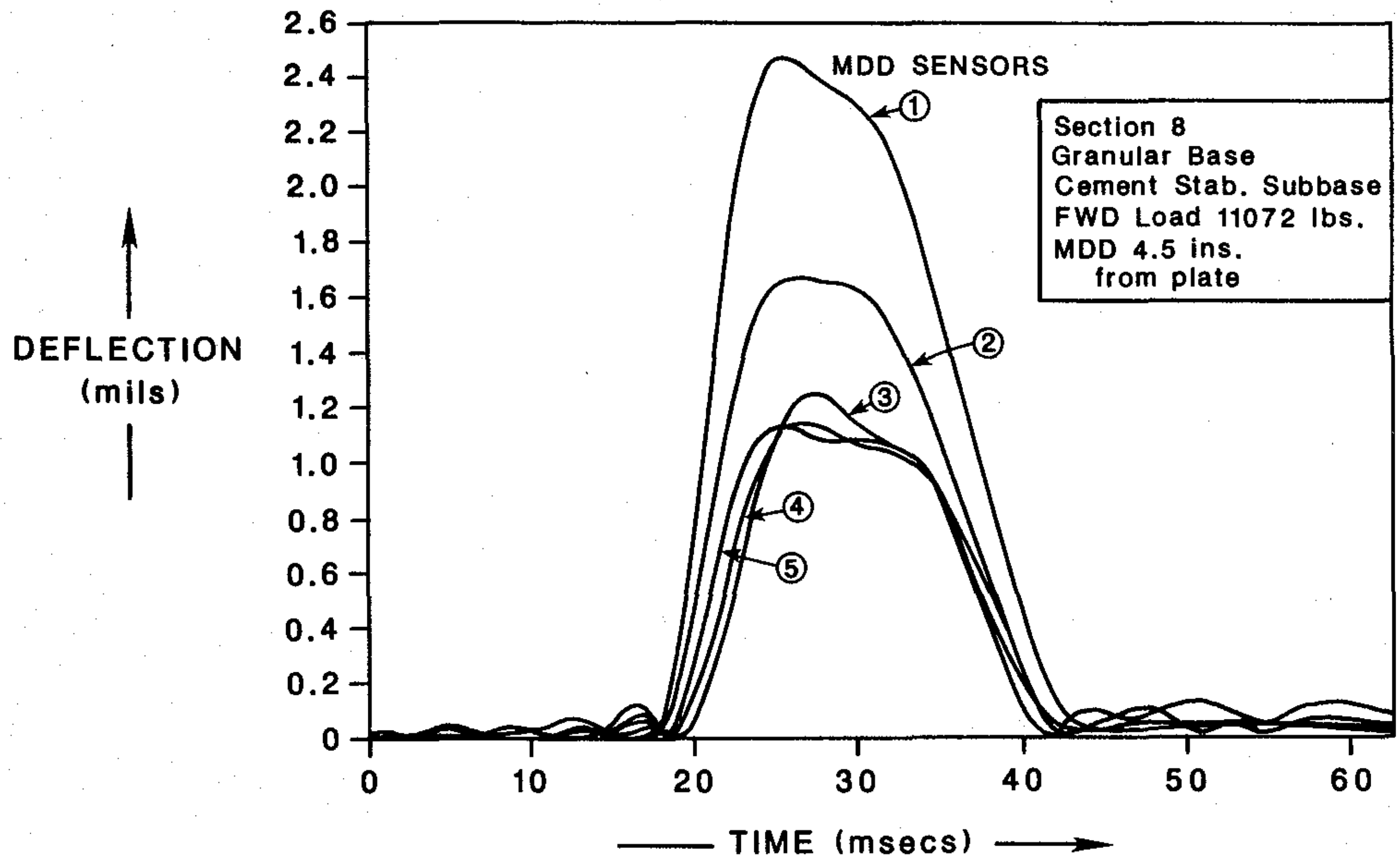


Figure 12. MDD Response Under FWD Loading

STRAIN WITHIN LAYER

The MDD measures the relative displacement between the layer and the anchor. However, the difference in MDD readings between two sensors is an indication of the strain level that is being induced in the layer. In Section 12, MDD sensors 2, 3 and 4 are in the crushed limestone base layer. Figure 11 shows that the difference between the peak deflection reading for sensors 2 and 4 is approximately 0.80 mils. With the sensors being 11.9 inches apart, this corresponds to a strain level of 67 microstrain.

The Falling Weight Deflectometer was used to test Sections 8, 11 and 12 at different load levels. The strains measured in the granular layer are shown in Figure 13. The strains in the thick pavement (Sections 8 and 12) were essentially linear with load. However, the thin pavement response was curvilinear, showing the typical stress hardening response that is observed in laboratory tests on granular materials.

REPEATABILITY MEASUREMENTS

Multiple drops of the Falling Weight Deflectometer were made on Section 11. The distance from the MDD hole and the edge of the FWD plate was fixed at two inches. At two FWD load levels (8500 lbs. and 16,000 lbs.), twelve drops were monitored. The surface and depth deflections are shown in Tables 1 and 2. The coefficient of variation was in most cases less than 1%. The Multi-Depth LVDT sensors have a similar variation as the FWD geophones at similar displacements. For example from Table 1, R3 of the FWD was recording a mean deflection of 3.07 mils and a coefficient of variance of 0.63% while D1 of the MDD was recording 4.30 miles with a coefficient of variance of 0.69%.

4.2 TYPICAL RESULTS UNDER TRUCK LOADING

The MDD was primarily designed to measure pavement response under wheel loadings. The National Institute for Transport and Road Research in South Africa has performed extensive studies in their Heavy Vehicle Simulator test program (4). The MDD testing at the Texas Transportation Institute has focused on pavement response under FWD loading; only a limited number of tests have been carried out under truck loadings. An example of a typical MDD response under a

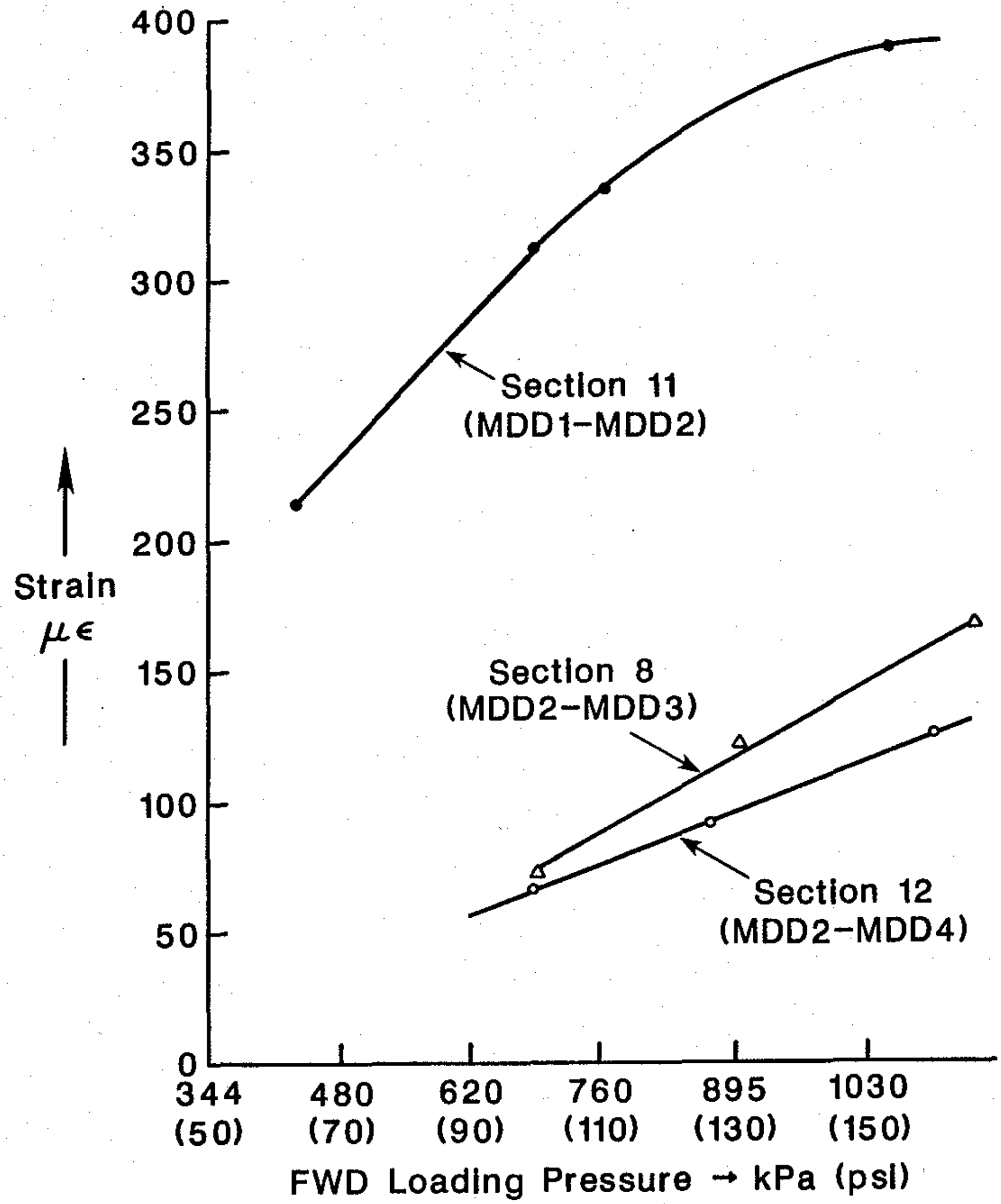


Figure 13. Vertical compressive strains measured in granular bases for different FWD loads

Table 1. Repeatibility Measurements (FWD v MDD) on Section 11 at 8500 lb. Load Level

DROP	Load (lbs)	Measured Deflection (mils) R1	R2	R3	R4	R5	R6	R7	Multi-Depth Deflectometer (mils) D1	D2
1	8,463	15.65	6.66	3.04	2.12	1.71	1.46	1.21	8.48	4.56
2	8,663	15.65	6.79	3.08	2.16	1.67	1.49	1.25	8.72	4.80
3	8,551	15.81	6.70	3.08	2.12	1.67	1.46	1.21	8.60	4.62
4	8,551	15.61	6.74	3.08	2.12	1.67	1.49	1.21	8.60	4.74
5	8,599	15.77	6.70	3.08	2.12	1.67	1.42	1.17	8.68	4.88
6	8,534	15.61	6.79	3.08	2.12	1.67	1.49	1.25	8.60	4.82
7	8,447	15.53	6.70	3.08	2.12	1.67	1.46	1.17	8.58	4.80
8	8,511	15.53	6.74	3.08	2.12	1.71	1.46	1.21	8.60	4.68
9	8,519	15.53	6.70	3.04	2.08	1.63	1.38	1.13	8.62	4.68
10	8,487	15.49	6.70	3.04	2.12	1.71	1.49	1.21	8.60	4.84
11	8,607	15.49	6.79	3.08	2.12	1.67	1.42	1.17	8.68	4.76
12	8,415	15.32	6.66	3.04	2.12	1.63	1.38	1.17	8.52	4.76
13	8,487	15.53	6.74	3.08	2.12	1.67	1.49	1.21	8.62	4.80
Mean:	8,527	15.58	6.72	3.07	2.12	1.67	1.45	1.20	8.60	4.74
Std.Dev:	67	0.13	0.05	0.02	0.02	0.03	0.04	0.03	0.06	0.08
Var.Coeff(%)	0.78	0.82	0.68	0.63	0.77	1.53	2.80	2.85	0.69	1.68

Table 2. Repeatibility Measurements (FWD v MDD) on Section 11 at 16,000 lb. Load Level.

DROP	Load (lbs)	Measured Deflection (mils) R1	R2	R3	R4	R5	R6	R7	Multi-Depth Deflectometer (mils) D1	D2
1	16,135	25.68	12.27	5.85	3.87	3.05	2.56	2.13	13.92	8.06
2	16,103	25.59	12.27	5.85	3.91	3.05	2.56	2.09	13.90	8.06
3	16,255	25.80	12.32	5.85	3.95	3.05	2.60	2.13	13.94	8.04
4	16,127	25.68	12.23	5.85	3.91	3.05	2.60	2.13	13.96	8.00
5	16,247	25.76	12.40	5.88	3.95	3.05	2.60	2.09	14.02	7.98
6	16,159	25.63	12.27	5.85	3.91	3.09	2.60	2.13	13.92	7.90
7	16,143	25.76	12.27	5.85	3.91	3.05	2.60	2.13	14.16	8.04
8	16,127	25.72	12.27	5.81	3.91	3.05	2.60	2.13	14.00	8.02
9	16,103	25.55	12.19	5.85	3.87	3.05	2.60	2.13	13.94	8.04
10	16,071	25.68	12.15	5.81	3.87	3.05	2.60	2.13	13.94	8.02
11	16,079	25.47	12.19	5.81	3.87	3.13	2.64	2.21	13.86	8.06
12	15,903	25.39	12.06	5.77	3.83	3.09	2.601	2.13	13.86	8.06
13	16,007	25.59	12.15	5.85	3.87	3.09	2.60	2.17	13.86	8.06
14	16,007	25.43	12.11	5.81	3.87	3.01	2.64	2.17	13.84	7.94
Mean:	16,105	25.62	12.22	5.83	3.89	3.06	2.60	2.14	13.94	8.02
Std.Dev:	89	0.13	0.09	0.03	0.03	0.03	0.02	0.03	0.06	0.04
Var.Coeff(%)	0.55	0.50	0.73	0.49	0.88	0.95	0.85	1.44	0.43	0.50

"dump truck" (steering axle and single axle) is shown in Figure 14. The truck was travelling at a speed of 3 mph. Figure 14 is the response of the MDD sensor located at the mid-depth of the asphalt layer (2.6 inches below the surface). Figure 15 shows the plot of deflection versus distance rather than time. The MDD registered a response over a 100-inch interval (50 inches to 150 inches on Figure 15). However, it is interesting to note that the slope of the loading curve is approximately twice that of the unloading curve (.204 mils/inch to 0.092 mils/inch), perhaps indicating a viscoelastic response of the asphalt.

As discussed earlier, the MDDs located in the base and subgrade can be used to measure the vertical strains in those layers. The MDD close to the surface can be used to measure the surface curvature of the pavement under load which many researchers have used as an indicator of the strain at the bottom of the asphalt layer. More work is planned in this area including an evaluation of tire pressure and axle type effects.

4.3 MODULUS BACKCALCULATION

The Falling Weight Deflectometer was used to test Sections 8 and 12 pavements in January, 1988. The temperature at the mid-depth of the surface and base was measured to be 49° and 54°F respectively. At both pavement sections the distance from the edge of the FWD load plate to the center for the MDD hole was fixed at 4.5 inches. At both sites the FWD was dropped at a range of load levels and both FWD maximum surface deflection and MDD depth deflections were recorded. The FWD geophones were located at 0, 12, 24, 36, 48, 60, and 72 inches from the center of the 5.91-inch diameter load plate. The MDD sensors were located as shown in Figure 10. The results of this testing are shown in Tables 3 and 4. This data will be analyzed in the remainder of this section.

ANALYSIS OF FWD AND MDD DATA

In this section the procedures to backcalculate in situ layer moduli will be discussed. These included

(1) Moduli backcalculated from MDD (Manual)

(2) Moduli backcalculated from MDD (Automatic)

(3) Moduli backcalculated from FWD (Automatic)

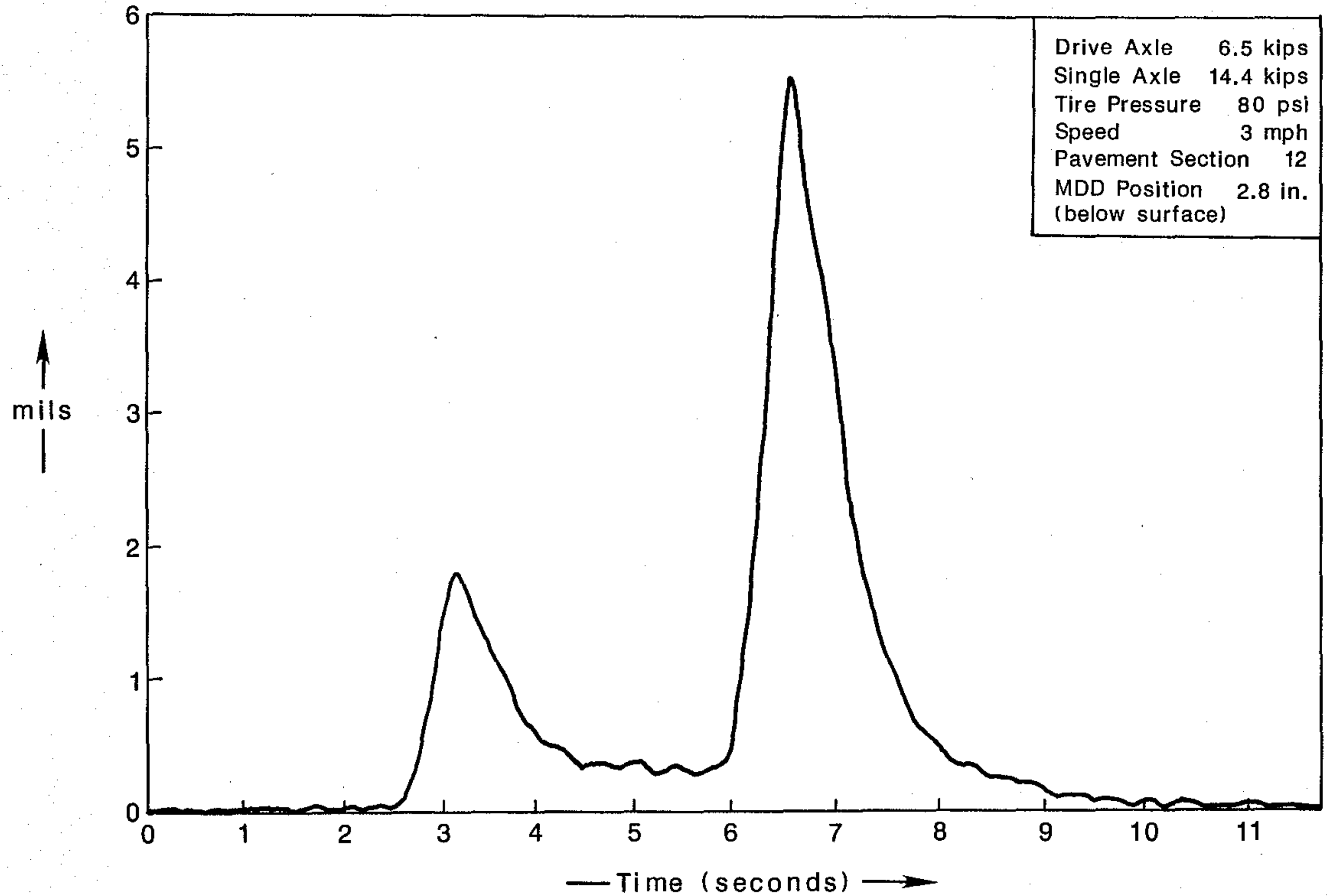


Figure 14. MDD Response to Truck Loading

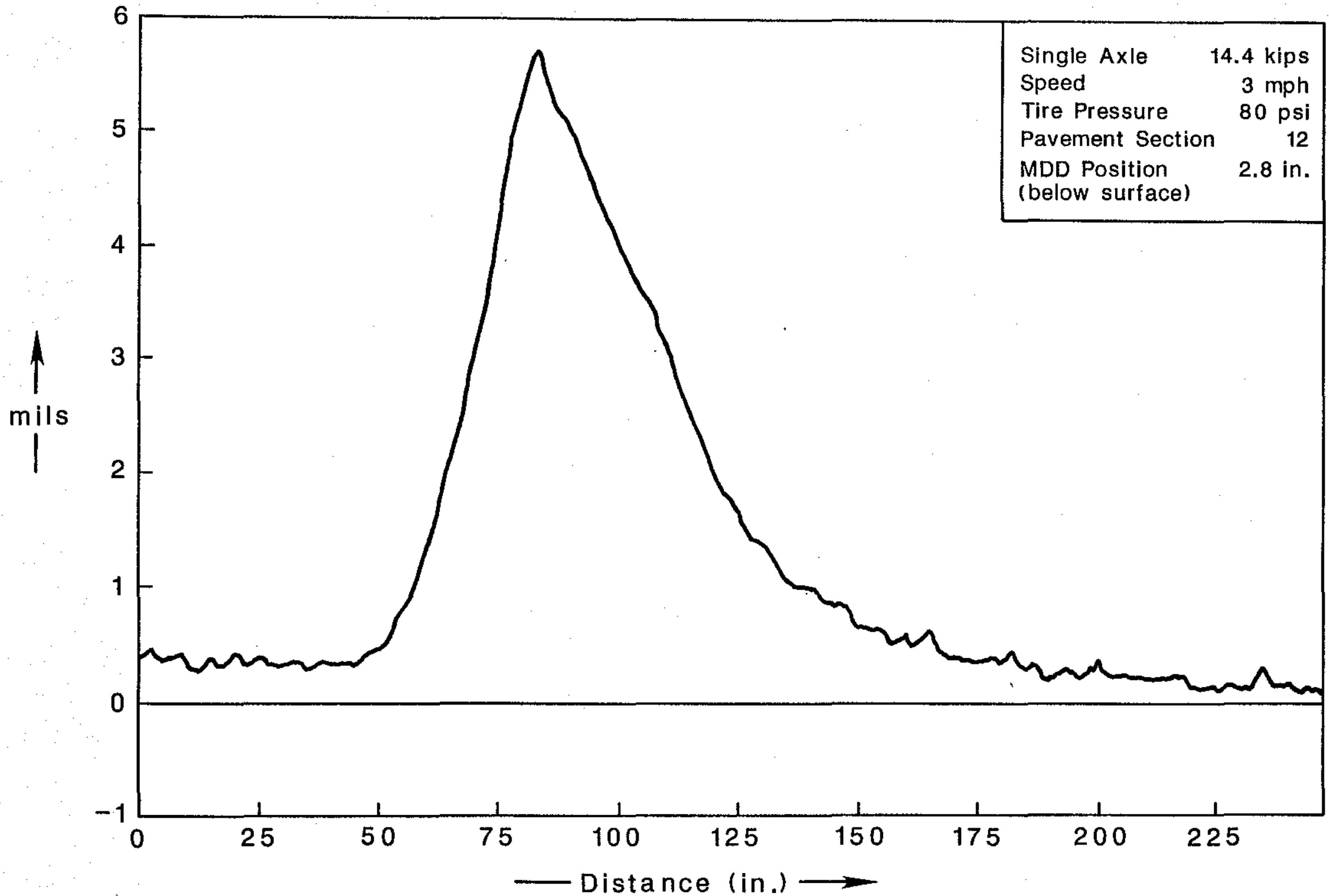


Figure 15. MDD Deflection Bowl Under Truck Loading

Table 3. FWD and MDD Maximum Deflection data for
Section 8 at TTI Research Annex

Load (Lbs)	FWD SENSORS (MILS) 1	2	3	4	5	6	7	MDD (MILS) 1	2	3	4	5
11072	6.09	4.34	2.78	2.30	1.96	1.73	1.45	2.48	1.68	1.25	1.16	1.14
14464	9.38	6.08	3.97	3.30	2.83	2.41	1.97	3.03	2.02	1.29	1.24	1.12
18352	10.48	6.99	4.58	3.77	3.25	2.74	2.29	3.21	2.07	1.07	1.15	1.06

Table 4. FWD and MDD Maximum Deflection data for Section 12 at TTI Research Annex

Load (Lbs)	FWD SENSORS (MILS)							MDD (MILS)				
	1	2	3	4	5	6	7	1	2	3	4	5
10888	8.36	6.41	3.85	2.58	1.91	1.53	1.33	4.41	3.88	3.52	3.06	2.14
13912	11.35	8.56	5.20	3.58	2.62	2.17	1.73	6.11	5.49	5.01	4.39	3.16
17704	12.88	9.96	6.14	4.13	3.08	2.49	2.05	7.46	6.78	6.08	5.29	3.75

MODULI BACKCALCULATED FROM MDD (MANUAL)

This procedure was described by Maree et al. (5) in Transportation Research Record 852. It consists of making numerous runs of a linear elastic layer program in an iterative manner to get the measured and calculated depth deflections to match. Before describing the procedure it is appropriate to refer to Figure 16, where the results of a typical analysis are plotted. It must be remembered that the MDD gives the relative movement between an anchor (at a depth of 70 inches in Section 12) and the various MDD modules located within the pavement layers. The first step in the analysis is to determine the calculated movement of the anchor point under Falling Weight loading. This was accomplished by using the BISAR layered elastic program and assuming reasonable layer moduli and a semi-infinite subgrade. With the assumed values, as shown in Figure 16, the anchor movement was calculated to be 3.69 mils. It is then possible to compare the surface and depth deflection profile in terms of:

(a) the measured MDD deflection with depth

(b) the calculated deflection with depth

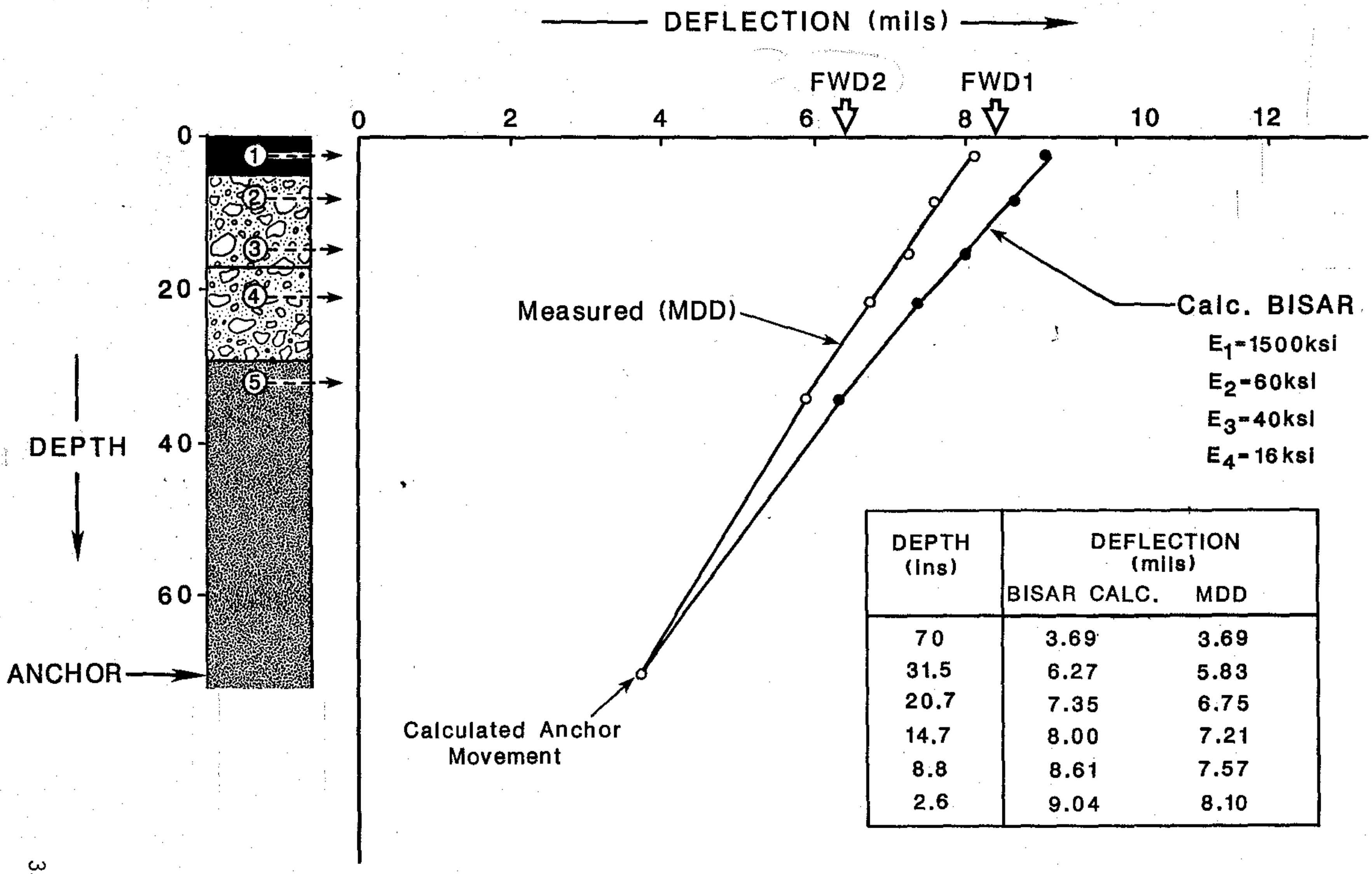
(c) the FWD surface deflections

In Figure 16, FWD1 refers to the measured surface deflection at Falling Weight Deflectometer sensor number 1. It should be noted that the MDD was located at a distance of 4.5 inches from the edge of the load plate. It is encouraging to note that the surface deflection projected from the MDD's matches the surface deflection measured by the FWD geophones. Also for the assumed layer moduli, there is reasonable agreement between the measured and calculated deflection with depth.

The iterative procedure to calculate layer moduli is illustrated in Figure 17. This manual procedure for matching measured and calculated deflections, as proposed by Maree et al. (5) is as follows:

(1) Assume a reasonable set of moduli for each pavement layer and predict vertical deflections at each MDD location and the anchor location under the applied FWD loading. In this example, shown in Figure 17, the BISAR program was used with the layer moduli being set at 1500, 60, 40, and 10 ksi.

(2) Plot predicted versus measured relative deflections as shown in Figure 17. The predicted relative deflection is that calculated at a particular depth minus that predicted at the anchor. In general, the slope



DEPTH (ins)	DEFLECTION (mils)	
	BISAR CALC.	MDD
70	3.69	3.69
31.5	6.27	5.83
20.7	7.35	6.75
14.7	8.00	7.21
8.8	8.61	7.57
2.6	9.04	8.10

Figure 16. Comparison of Measured Against Calculated Depth Deflections for Section 12 for FWD Load=10888 lbs. The FWD1 Refers to the Measured Surface Deflection on FWD Sensor 1.

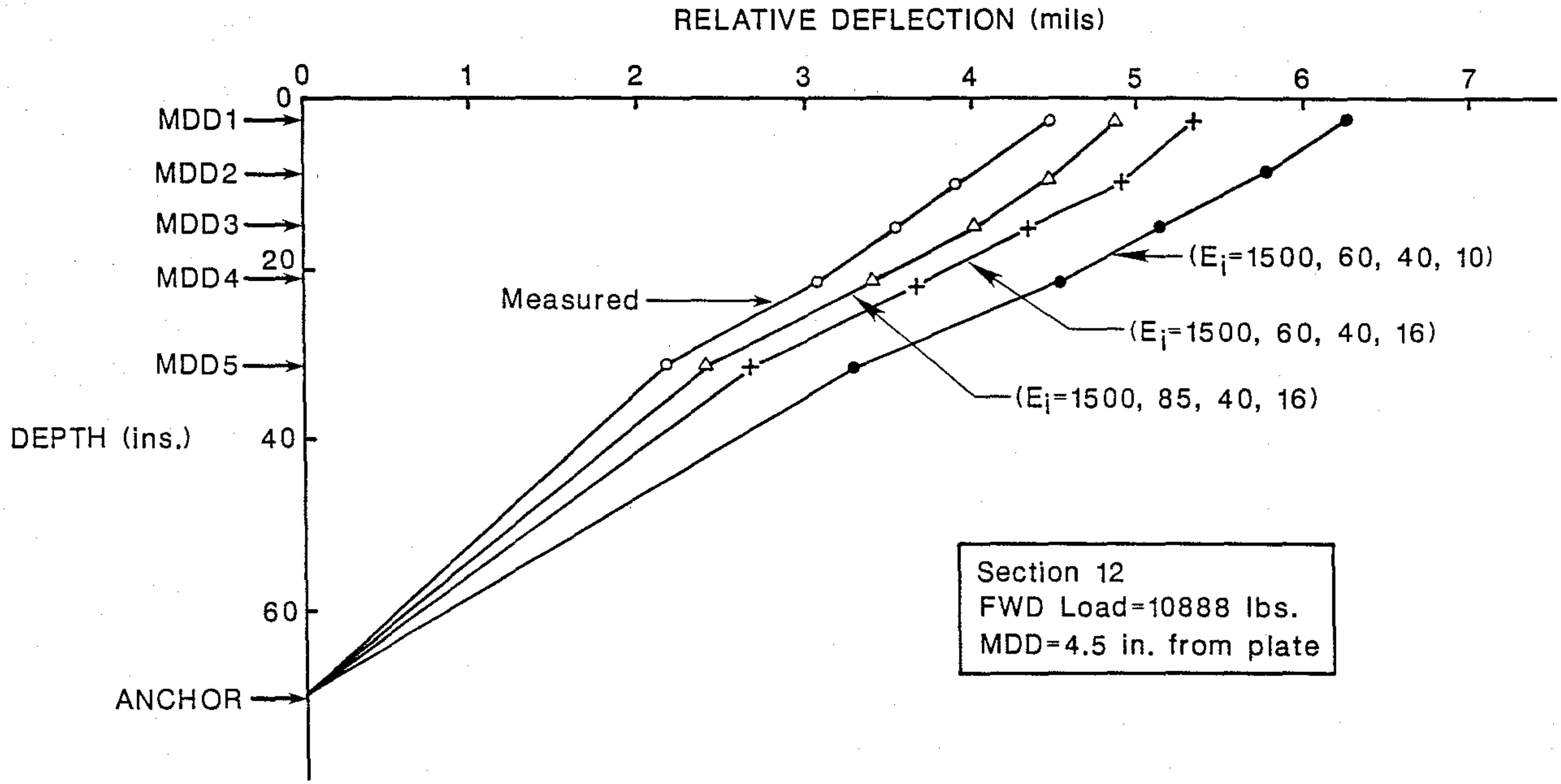


Figure 17. Manual Iterative Procedure for Matching Measured vs. Calculated Relative Depth Deflections

of the depth deflection curve at any point is an indicator of the modulus of the material at that depth. When the measured slope is steeper than the calculated one, the modulus of the material has to be increased, and vice versa. It was recommended (5) that changes be made first to the subgrade, the subbase, base and finally surfacing. By comparing the measured and the calculated (1500/60/40/10) curve it is clear that 10 ksi is too weak for the subgrade.

(3) A second BISAR run was made with the moduli values (1500/60/40/16) and as can be seen from Figure 17, there is an improved agreement between measured and calculated deflection with depth.

(4) A third BISAR run was made with the moduli values (1500, 85, 40, 16); again the measured and calculated curves moved closer together.

This process is repeated until an acceptable match is achieved. The analysis shown in Figure 17 indicated that the moduli values would be approximately 1500 ksi, 85 ksi, 40 ksi, and 16 ksi for the surfacing, base, subbase, and subgrade layers, respectively. As will be described in the next section, the best fit was computed at the moduli values of 1704, 84, 52, 18 ksi.

MODULI BACKCALCULATED FROM MDD (AUTOMATIC)

The problem of matching measured and calculated depth deflections is essentially the same as that already available for analyzing surface deflections. In these procedures the errors between measured and calculated deflections are minimized by pattern-search routines or other techniques. In order to automatically calculate layer moduli from MDD deflection data, the generalized procedure for layer moduli backcalculation developed by Uzan (6) was modified for this purpose. This procedure was originally developed to backcalculate layer moduli from surface deflection data and has been successfully implemented by the Texas SDHPT (7). This generalized procedure was modified to process the depth deflection profile rather than surface deflections.

Briefly, the procedure involves making multiple runs of a linear elastic program (BISAR) at a range of surface, base and subbase modular ratios and storing the results in a deflection data base. The exact number of runs required is computed based on the user-supplied acceptable range of layer moduli. For each run, the BISAR program calculates the absolute deflection with depth at each MDD location and at the anchor depth. The program then utilizes a sophisticated pattern search technique to minimize the error between the calculated and measured relative deflection. This system has been implemented on a microcomputer. A typical input screen is shown in Figure 18 and typical calculated results are shown in Figure 19. To perform the necessary deflection data base generation takes approximately 10 minutes on a 286-type microcomputer for a 3-layer system and 20 minutes for a 4-layer system. Once complete, it takes only about 30 seconds to find the best fit for each measured deflection bowl.

The automated procedure has the capability of specifying the depth to bedrock which is known to be significant when matching surface deflections. Tables 5a and 5b show the set of moduli values which minimizes the error between the measured and calculated depth deflections for Section 8. Table 5a assumed a semi-infinite subgrade layer, whereas in Table 5b, a rock layer was assumed to be 250 inches below the surface. The total error is the accumulative absolute percentage error between measured and calculated depth deflections. Tables 6a and 6b show the results obtained from Section 12, modeled as a 4-layer system with a 12-inch granular base and 12-inch granular subbase. Tables 7a and 7b show the results from Section 12 modeled as a 3-layer system with a 24-inch granular base course. The following conclusions can be drawn from these tables:

(1) For this particular analysis, the depth to bedrock does not appear significant when processing MDD data. Similar moduli values were obtained, particularly on Section 12.

(2) The fit on Section 8 was relatively poor. This is the section with a stiff cement-stabilized subbase. On Section 12 the total error was small, as low as 3.1%, or 0.6% per sensor reading.

(3) Using a 3-layer or 4-layer system to model Section 12 had no effect on the subgrade moduli values.

MODULI BACKCALCULATED FROM FWD (AUTOMATIC)

The surface deflection data collected on Sections 8 and 12 was shown in Tables 3 and 4. There are several procedures available to automatically process surface deflection data to generate layer moduli values (7, 8, 9). In this analysis the procedure developed by Uzan (7) was used. This procedure uses a linear-elastic program (BISAR) to generate a deflection data base to cover the range of layer moduli as supplied by the user. Once generated, a pattern search routine is used to minimize error between measured and calculated bowls.

```
    5    10   15   20   25   30   35   40   45   50   55   60   65   70   75   80
....:....:....:....:....:....:....:....:....:....:....:....:....:....:....:....:

 TITLE XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
  H1    H2      H3     H4
XXXXXX XXXXXX XXXXXX XXXXXX
 RADIUS OF PLATE   NUMBER OF LVDTS
    XXXXXXXXXX          X
 DEPTH OF LVDT'S AND WEIGHTING FACTORS                  RADIAL DIST
LVDT   No.                                              ANCE FROM
   1       2       3       4       5       6       7    PLATE EDGE
       DEPTH     OF    LVDT
XXXXXXX XXXXXXX XXXXXXX XXXXXXX XXXXXXX XXXXXXX XXXXXXX
 WEIGHTING FACTORS   OF LVDT'S                          XXXXXXXX
XXXXXXX XXXXXXX XXXXXXX XXXXXXX XXXXXXX XXXXXXX XXXXXXX
 SUBGRADE MODULUS (MOST PROBABLE VALUE IN KSI) AND POISSON'S RATIO
       XXXXXXXXX                                    XXXXX
 MODULUS OF THIRD LAYER (IN KSI)
    MINIMUM                  MAXIMUM           AND POISSON'S RATIO
   XXXXXXXXX                XXXXXXXXX               XXXXX
 MODULUS OF SECOND LAYER (IN KSI)
    MINIMUM                  MAXIMUM           AND POISSON'S RATIO
   XXXXXXXXX                XXXXXXXXX               XXXXX
 MODULUS OF FIRST LAYER (IN KSI)
    MINIMUM                  MAXIMUM           AND POISSON'S RATIO
   XXXXXXXXX                XXXXXXXXX               XXXXX
....:....:....:....:....:....:....:....:....:....:....:....:....:....:....:....:
    5    10   15   20   25   30   35   40   45   50   55   60   65   70   75   80
```

Figure 18. Input screen to MDD Analysis Program. The User fills in the X's. This information is used to supply input to BISAR to calculate the deflection data base.

```
*********************************** MULTI-DEPTH DEFLECTOMETER ANALYSIS ***********************************

                    section 12 three layer

                   DISTANCE TO EDGE OF PLATE :     4.500  (IN.)
                   RADIUS OF LOAD PLATE (IN.):     5.910         INITIAL MODULI VALUES
                                                                  MINIMUM      MAXIMUM
                   SURFACE  THICKNESS   (IN.):     5.000          100000.      2000000.
                   BASE     THICKNESS   (IN.):    24.000           30000.       150000.
                   SUBGRADE THICKNESS   (IN.):   221.000                 20000.
                        DEPTH TO SENSORS      WEIGHTING FACTORS     DEPTH TO ANCHOR
                           D1 =   2.60               1.0               70.0 INS.
                           D2 =   8.00               1.0
                           D3 =  14.70               1.0
                           D4 =  20.70               1.0
                           D5 =  31.50               1.0
------------------------------------------------------------------------------------------------------------
STATION:   2      2        D1      D2      D3      D4      D5            PLATE LOAD      (LBS):      10887
MEASURED   DEFLECTION:    4.41    3.88    3.52    3.06    2.14           PLATE PRESSURE (PSI):      99.23
CALCULATED DEFLECTION:    4.46    4.10    3.42    2.94    2.13
     % ERROR             -1.11   -5.73    2.70    4.03     .69           ABS SUM OF % ERROR:      .143E+02

LAYER:                  SURFACE     BASE  SUBGRADE                       ERROR SQUARED:           .581E-02
MODULI VALUES (PSI):   1980557.   59417.    19806.
AT OR NEAR LIMITS?        YES                                            NOTE: LOCAL MINIMUM ENCOUNTERED
                                                                               CHECK RESULTS CAREFULLY
------------------------------------------------------------------------------------------------------------
```

Figure 19. Output report from the MDD Analysis Program

Table 5a. Moduli Calculated Automatically from MDD
Section 8 Semi-Infinite Subgrade υ_i = .35, .35, .25, .45

FWD Load (lbs)		MDD DEFLECTIONS (MILS)					MODULI (KSI) E_1	E_2	E_3	E_4	TOTAL* ERROR %
11072	Measured	2.48	1.68	1.25	1.16	1.14	2000	78	2373	12	35.2
	Calculated	2.22	1.84	1.32	1.17	1.06					
14464	Measured	3.03	2.02	1.29	1.24	1.12	2000	70	2708	23	36.9
	Calculated	2.73	2.17	1.40	1.18	1.08					
18352	Measured	3.21	2.07	1.07	1.15	1.06	2000	84	5000	31	60.0
	Calculated	2.75	2.15	1.31	1.07	.96					

Table 5b. Moduli Calculated Automatically from MDD
Section 8 - Bedrock at 250 inches below surface

FWD Load (lbs)		MDD DEFLECTIONS (MILS)					MODULI (KSI) E_1	E_2	E_3	E_4	TOTAL* ERROR %
11072	Measured	2.48	1.68	1.25	1.16	1.14	2000	77	1893	16	36.0
	Calculated	2.23	1.85	1.32	1.17	1.03					
14464	Measured	3.03	2.02	1.29	1.24	1.12	2000	70	2803	23	36.7
	Calculated	2.72	2.17	1.41	1.19	1.06					
18352	Measured	3.21	2.07	1.07	1.15	1.06	2000	84	4898	33	60.1
	Calculated	2.77	2.16	1.30	1.05	0.94					

* The total error is the accumulative absolute percentage error between measured and calculated depth deflections.

Table 6a. Moduli Calculated Automatically from MDD

Section 12 - 4-Layer System Semi-Infinite Subgrade υ_i = .35, .35, .35, .45

FWD Load (lbs)		MDD DEFLECTIONS (MILS)					MODULI (KSI) E_1	E_2	E_3	E_4	TOTAL* ERROR %
10888	Measured	4.41	3.88	3.52	3.06	2.14	1746	84	51	18	6.7
	Calculated	4.33	3.99	3.52	3.02	2.15					
13912	Measured	6.11	5.49	5.01	4.39	3.16	2000	83	48	14	4.8
	Calculated	6.03	5.60	5.00	4.35	3.17					
17704	Measured	7.46	6.78	6.09	5.29	3.75	1850	84	47	16	3.1
	Calculated	7.40	6.85	6.09	5.25	3.76					

Table 6b. Moduli Calculated Automatically from MDD

Section 12 - 4-Layer System - Bedrock at 250 inches below Surface

FWD Load (lbs)		MDD DEFLECTIONS (MILS)					MODULI (KSI) E_1	E_2	E_3	E_4	TOTAL* ERROR %
10888	Measured	4.41	3.88	3.52	3.06	2.14	1705	84	52	18	6.8
	Calculated	4.33	3.99	3.51	3.02	2.15					
13912	Measured	6.11	5.49	5.01	4.39	3.16	2000	83	48	14	4.8
	Calculated	6.02	5.60	5.00	4.35	3.17					
17704	Measured	7.46	6.78	6.09	5.29	3.75	1535	88	49	16	3.3
	Calculated	7.40	6.86	6.09	5.25	3.76					

* The total error is the accumulative absolute percentage error between measured and calculated depth deflections.

Table 7a. Moduli Calculated Automatically from MDD
Section 12 - 3-Layer System - Semi-Infinite Subgrade

FWD Load (lbs)		MDD DEFLECTIONS (MILS)					MODULI (KSI) E_1	E_2	E_3	TOTAL* ERROR %
10888	Measured	4.41	3.88	3.52	3.06	2.14	1217	71	18	10.4
	Calculated	4.40	3.99	3.44	2.98	2.18				
13912	Measured	6.11	5.49	5.01	4.39	3.16	1382	68	14	8.9
	Calculated	6.14	5.61	4.89	4.30	3.22				
17704	Measured	7.46	6.78	6.08	5.29	3.75	1390	67	16	9.0
	Calculated	7.54	6.86	5.93	5.17	3.83				

Table 7b. Moduli Calculated Automatically from MDD
Section 12 - 3-Layer System Bedrock at 250 inches

FWD Load (lbs)		MDD DEFLECTIONS (MILS)					MODULI (KSI) E_1	E_2	E_3	TOTAL* ERROR %
10888	Measured	4.41	3.88	3.52	3.06	2.14	1100	72	19	10.5
	Calculated	4.40	4.00	3.44	2.98	2.19				
13912	Measured	6.11	5.49	5.01	4.39	3.16	1405	68	14	9.0
	Calculated	6.14	5.61	4.89	4.30	3.22				
17704	Measured	7.46	6.78	6.08	5.29	3.75	1337	68	16	9.1
	Calculated	7.55	6.86	5.93	5.17	3.83				

* The total error is the accumulative absolute percentage error between measured and calculated depth deflections,Table 5a

Runs were made with finite and infinite depth to bedrock. The results of this analysis are shown in Tables 8 and 9. The surface and depth deflections were measured simultaneously under the FWD load. The layer moduli values calculated using the FWD load and surface deflections are compared with those calculated using the FWD load and MDD depth deflections. In tables 8 and 9 the backcalculated layer moduli values are given together with their respective lack of fit error. This error indicates how the theoretically calculated deflection bowl matches the measured bowl.

DISCUSSION OF RESULTS

Section 8 has a 12-inch cement-stabilized subbase; this layer is very stiff, approaching the stiffness of lean concrete. The MDD data collected on this section showed that the sensors 3, 4 and 5 produced similar deflections. At the 18,352 lb. load level the deflection at sensor 4 was higher than that recorded at sensor 5, and other instances were observed where the deflections beneath the stabilized layer were higher than those measured in that layer. This inverted depth deflection profile is impossible to fit using linear-elastic theory, and the errors shown in Table 8 are relatively large (>35%). For this analysis the MDD backcalculated moduli values are not affected by varying the depth to bedrock. However, they do not match those moduli backcalculated using the surface deflection analysis.

The backcalculated moduli results from Section 12 are shown in Table 9. This is a common pavement type found on many high volume pavements in Texas. It has an asphalt surface (5-inch) over a thick granular layer (24-inch) on a natural subgrade. For this section the moduli calculated from the MDD data only, were not affected by depth to bedrock. However, the moduli obtained from the surface deflections were significantly altered. There is a reasonable match of layer moduli when the finite depth to bedrock (250 inches) is used. The base layer moduli predicted from analysis of the FWD data compare very closely to those calculated from the MDD; the maximum difference is 4 ksi, or 5%. It is worth recalling that the Corps of Engineers recommended placing a rigid layer at 20 feet when backcalculating layer moduli using linear-elastic theory (8). The results obtained on Section 12 appear to support that assumption.

Table 8. Comparing FWD and MDD Layer Moduli (ksi) for Section 8 (4-Layer System).

FWD LOAD (lbs)	SUBGRADE[1]	FWD SURFACE DEFLECTION MODULI[2]					DEPTH DEFLECTION MODULI[3]				
		E_1	E_2	E_3	E_4	Error[4] %	E_1	E_2	E_3	E_4	Error[4] %
11072	Semi-Inf	2000	58	1305	28	12.1	2000	78	2373	12	35.2
	Finite	2000	50	3771	13	9.7	2000	77	1893	16	36.0
14464	Semi-Inf	1119	71	500	27	13.2	2000	70	2708	23	36.9
	Finite	1141	61	1670	14	5.9	2000	70	2803	23	36.7
18352	Semi-Inf	1383	80	500	30	10.8	2000	84	5000	31	60.0
	Finite	1498	63	2066	15	4.0	2000	84	4898	33	61.0

1 SEMI-INF used in modeling subgrade. FINITE assumes a depth to bedrock of 250 inches.
2 Calculated using the Uzan procedure (7) with the bowls given in Tables 3 and 4.
3 From Tables 5a) and 5b).
4 Total absolute accumulative error between measured and calculated deflections. Seven sensors for the FWD and five for the MDD.

Table 9. Comparing FWD and MDD Layer Moduli (ksi) for Section 12 (3-Layer System, E_3 = Subgrade Modulus)

FWD LOAD (lbs)	SUBGRADE[1]	FWD SURFACE DEFLECTION MODULI[2]				DEPTH DEFLECTION[3] MODULUS			
		E_1	E_2	E_3	ERROR[4] %	E_1	E_2	E_3	ERROR[4] %
10888	Semi-Inf	1728	48	31	18.8	1217	71	18	10.4
	Finite	1269	69	21	34.6	1100	72	19	10.5
13912	Semi-Inf	1694	45	29	12.9	1382	68	14	8.9
	Finite	1223	66	19	27.2	1405	68	14	9.0
17704	Semi-Inf	2000	49	32	13.7	1390	67	16	9.0
	Finite	1499	72	21	28.0	1337	68	16	9.1

1 SEMI-INF used in modeling subgrade. FINITE assumes a depth to bedrock of 250 inches.

2 Calculated using the Uzan procedure (7) with the bowls given in Tables 3 and 4.

3 From Tables 6a) and 6b).

4 Total absolute accumulative error between measured and calculated deflections. Seven sensors for the FWD and five for the MDD.

SECTION 5

CONCLUSION

This report has described the installation of Multi-Depth Deflectometers in three pavement sections at the Texas A&M Research Annex. The conclusions of this investigation are as follows:

(1) The Multi-Depth Deflectometer shows considerable potential for assisting in many areas of pavement research; particularly accelerated loading testing, tire pressure studies, rutting studies and modulus backcalculation verification. The Multi-Depth Deflectometer has numerous advantages over the conventional single depth deflectometer system.

(2) The system is relatively inexpensive. The hardware for a typical installation costs less than $2,000 and the MDD units can be recovered after use. The final cost will depend on the type of LVDT chosen. In long-term testing where the units are to be installed for several months (or years), it is recommended that the hermetically sealed units be used. On extracting the MDD units from Section 8, rust was observed on the LVDT body. The hermetically-sealed LVDTs cost approximately $230 (1988 prices), compared with $35 for the regular units.

(3) Stripping an existing hole and reinstalling the MDDs may sometimes be required. In Section 12 it was observed that the center core could become locked. This is caused when one of the modules moves slightly causing the central core to "lock-up". This is easily detected and reinstallation of the hole takes approximately one day.

(4) Results gathered to date show the MDD response is repeatable under a range of Falling Weight Deflectometer loading.

(5) Efforts to match layer moduli backcalculated from both surface deflections and depth deflections were successful on Section 12 (asphalt/-granular base/subgrade) but unsuccessful on Section 8 (cement stabilized subbase). The best fit occurred when a bedrock layer was assumed at 250 inches below the surface.

Further work is underway to improve the system in three areas, these are:

(1) An experimental version of the MDD is being developed with an accelerometer (or geophone) mounted on the center core. This will permit measurement of the actual anchor movement, which can then be compared with the movement calculated using the MDD Analysis Program (Figure 19).

(2) The top cap is being redesigned so that the cables can be placed in a shallow saw cut. The connector cable will no longer be required. The MDD system will therefore be permanently installed flush with the surface. The FWD load plate can then be placed directly over the MDD hole.

(3) An evaluation is being made of using DC rather than AC LVDT's. The DC units are simpler to use and will make the system less expensive as the signal conditioner box will no longer be required. However, one concern is the durability of the DC compared with the AC units.

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