USING THE MULTIDEPTH DEFLECTOMETER TO VERIFY MODULUS BACKCALCULATION PROCEDURES

by

Tom Scullion*
Robert C. Briggs**
Robert L. Lytton***

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*Associate Research Engineer, Texas Transportation Institute, Texas A&M University.
**Eng. Assistant of Pavement Management, D18-P, State Department of Highways and Public Transportation, Texas.
***Professor of Civil Engineering and Research Engineer, Texas Transportation Institute, Texas A&M University.

ABSTRACT

This paper describes the use of a Multi-Depth Deflectometer (MDD) for determining the resilient modulus of pavement layers. The MDD's are installed in specially drilled holes, and upto six modules may be placed in a single hole. This device measures the relative deflection of each layer with respect to an anchor point located approximately 7 foot below the pavement surface. In this paper are results obtained from two instrumented pavement sections at the Texas Transportation Institute's Reseach Annex. By obtaining MDD deflections under Falling Weight Deflectometer (FWD) loadings two independent procedures are available for estimating layer moduli.

A procedure for automatically calculating layer moduli from MDD measurements is described and the results obtained are compared with those obtained from three backcalculation schemes using FWD surface deflection data. When an semi-infinite depth subgrade was specified all three procedures predicted subgrade moduli approximately 50% higher than those estimated from MDD measurements. When a finite depth was specified, a rock layer at 20 ft, all three procedures calculated subgrade moduli values very similar to the MDD values. The ELSDEF program with finite subgrade also produced comparable values for the moduli of base and subbase layers.

KEY WORDS Pavements, Non-Destructive Testing, Multi-Depth Deflectometers, Modulus Backcalculation

Using the Multidepth Deflectometer to verify Modulus Backcaclulation Procedures

Introduction

The procedure used by several investigators to verify modulus backcalculation procedures is to compare the results obtained from an appropriate theoretical analysis of Non Destructive Test (NDT) data to those obtained from laboratory testing of the pavement materials. Resilient modulus test 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 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 paper a different approach is taken to verify modulus backcalculation procedures. Two research pavement sections at the Texas Transportation Institute's Research Annex were instrumented with Multidepth Deflectometers (MDD). These devices measure the transient deflection between a particular location in the pavement and an anchor located at 86 inches below the surface. By placing MDD's 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 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.

In the next section of this paper, the MDD device and installation procedures will be described. The experimental set up at the TTI Research Annex will then be presented. This will be followed by a description of the test procedure and results obtained and details of the analysis.

Multi Depth Deflectometer

The Multidepth Deflectometer (MDD) was developed by the National Institute for Transportation and Road Research (NITRR) in South Africa (2,3). A typical set up is shown schematically in Figure 1. The measuring unit is an LVDT which is mounted inside a module which can be expanded to clamp onto the sides of the hole at the required depth. A summary of the installation procedure for the MDD is as follows:

(1) A 1.5 inch diameter hole is drilled to a depth of 86 inches. A high speed percussion drill and a specially designed drill rig is used to ensure that no major disturbances occur in the

pavement layers and that the hole remains straight.

(2) The hole is lined with a thin rubber lining to prevent moisture and loose material from damaging the transducers.

(3) An anchor is placed at the bottom of the hole, and fixed in place by cement grout.

(4) An interconnecting rod is lowered and fixed into the snap connector. The MDD modules are slid over the interconnecting rod to the desired depth and locked in place.

(5) The interconnecting rod is then replaced with a rod which contains the LVDT cores. The location of the cores can be adjusted to facilitate zeroing the LVDT's prior to the completion of installation.

When the MDD is not in use a brass surface cap, which is flush with the surface, completely seals the hole. When readings are required a reinforced connector cable is used. Once testing is complete at a site the MDD modules can be extracted and reused at another location. The only parts which cannot be reused are the anchor and rubber lining.

The MDD is an integral part of the NITRR's Heavy Vehicle Simulator Program (4). The device can measure both transient differential deflections (difference between MDD location and anchor) or accumulative permanent deformations in each of the pavement layers. A maximum of six can be placed in any hole. This makes the MDD an ideal device for long term monitoring of pavement performance. They have proven extremely durable with some installations being in operation for over 5 years. Maree (5) reported that surface deflections measured independently with a deflection beam correlated very well with the deflections measured by the MDD modules which indicates that the MDD does not significantly influence the resilient deflection of the pavement structure.

MDD Installation at TTI Research Annex

In September 1987 two pavement sections at the Texas Transportation Institute's Research Annex were instrumented with MDD's. The experimental setup is shown in Figure 2. These sections have similar layer thicknesses except that Section 8 has a cement stabilized subbase layer over a clay subgrade, whereas Section 12 has a crushed limestone subbase over a sandy gravel subgrade.

Typical MDD results from FWD loadings are shown in Figures 3 and 4. Figure 3 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 4 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 layers ability to spread the load and minimize damage to the underlying layers.

Data Collection with Falling Weight Deflectometer

The Falling Weight Deflectometer was used to test both pavements in January 1988. The temperature at the mid depth of the surface and base was measured to be 49 and 54^{o}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 load plate. The MDD sensors were located as shown in Figure 2. The results of this testing are shown in Tables 1 and 2. This data will be analyzed in the remainder of this paper.

Analysis of FWD and MDD data

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

(1) Moduli backcalculated from MDD (Manual)

(2) Moduli backcalculated from MDD (Automatic)

(3) Moduli backcalculated from FWD (Automatic)

For typical FWD backcalculation procedures it is necessary to input a "seed" modulus and a reasonable range of values. For this analysis these values are shown in Table 3.

Moduli backcalculated from MDD (Manual)

This procedure was described by Maree (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 5, 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 86 inches 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 5, the anchor movement was calculated to be 3.28 mils. It is then possible to compare three independent deflection results.

(a) the measured MDD deflection with depth

(b) the calculated deflection with depth

(c) the FWD surface deflections

In Figure 5, 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 ins. from the edge of the load plate. It is encouraging to note that the MDD surface deflections closely match those measured by the FWD and there is also close agreement between the measured and calculated deflection with depth.

The iterative procedure to calculated layer moduli is illustrated in Figure 6. This manual procedure for matching measured and calculated deflections, as proposed by Maree (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 6, the BISAR program was used with the layer moduli being set at 1500, 60, 40 and 15 ksi.

(2) Plot predicted versus measured relative deflections as shown in Figure 6. The predicted relative deflection is that calculated at a particular depth minus that predicted at the anchor. In general the slope 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 that changes be made first to the subgrade, the subbase, base and finally surfacing. By comparing the measured and the calculated (1500/60/40/15) curve it is clear that 15 ksi is too weak for the subgrade.

(3) A second BISAR run was made with the moduli values (1500/60/40/25). Comparing measured versus calculated, they compare favorably in the subgrade and subbase but diverge noticeably in the base layer.

(4) A third BISAR run was made with the moduli values (1500/80/40/25) and as can be seen from Figure 6 there is reasonable agreement between measured and calculated deflection with depth.

This process is repeated until an acceptable match is achieved. The analysis shown in Figure 6 indicated that the moduli values would be approximately 80 ksi, 40 ksi and 25 ksi for the base, subbase and subgrade layers respectively.

Moduli backcalculated from MDD (Automatic)

The problem of matching measured and calculated 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 patterned error reduction or other technidques. 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. The Uzan procedure runs on a micro computer and is described in detail in another paper to this conference.

Briefly the procedure involves making multiple runs of a linear elastic program (BISAR) at a range of surface, base and subbase modulus ratios. 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 predicted relative deflection. The results of this analysis are shown in Tables 4 and 5. To perform the necessary set up for the Uzan (6) procedure, takes approximately 10 minutes on a 286 type P.C. for a 3 layer system and 20 minutes for a 4 layer system. Once complete it takes about 30 seconds to find the best fit for each deflection bowl.

Moduli backcalculation using FWD deflection data

Three backcalculation procedures were used to analyze the FWD surface deflection data. These being

(1) BISDEF (7)

(2) ELSDEF (8)

(3) GENERALIZED MODULUS PROCEDURE (6)

In all runs the initial moduli values in Table 3 were used. The first series of runs consisted of assuming a 4-layer system with a semi-infinite subgrade. The second set, referred to as FINITE in Table 6, assumed a 5 layer system with a rock layer (E=1000 Ksi) located at a depth of 20 feet.

Discussion of Results

The MDD data collected on section 8 (Table 1) showed that the depth deflections at sensors 3, 4 and 5 were similar. This is attributed to the very stiff cement stabilized subbase slab. At the 18352 lb load level the deflection at sensor 4 was monitored to be higher than that recorded at sensor 5, and other instances have been recorded where the deflection beneath the slab was recorded to higher than that in the slab. Section 8 is a difficult pavement to analyze by either surface deflection or depth deflection analysis techniques. Analysis of the MDD data for section 8 is presented in Table 5. The results at 18352 lbs should be discounted because the inverted depth deflection profile resulted in a poor fit between measured and calculated depth deflection profiles. At the lighter load levels the modulus of the cement stabilized layer was extremely high.

The deflection data collected on section 12 is shown in Table 2. This is a fairly typical pavement section with a 5 inch hot mix over a thick granular base on a natural subgrade. The MDD data was consistent on this section and produced comparable moduli values (Table 5) at the three higher load levels. At the lower load level (5680 lbs) base and subbase moduli were significantly higher. At the three higher load levels the errors between measured and calculated depth deflection profile were small.

The results presented in Tables 4 and 5 should be compared with the results backcalculated from FWD surface deflection data shown in Table 6. The BISDEF and MODULUS programs gave comparable results although this should not be surprising as each uses BISAR. However what was unexpected was the magnitude of the effect of using a Finite as opposed to a Semi-Infinite subgrade. This change resulted in a change in a subbase stiffness by up to a factor of 3 and a change in subgrade stiffness by up to a factor of 2. No explanation is available at this time, work is continuing in this area. In the BISDEF analysis the error between measured and calculated was small, typically less than 2% on average. The ELSDEF program was less sensitive to changes in subgrade dimensions, in all cases a change of subbase and subgrade modulus of 10 to 40% occurred.

All three procedures gave similar values for subgrade stiffness. Although the semi-infinite layers were always predicted to be considerably stiffer than those obtained assuming a Finite subgrade. Comparing the MDD and FWD results for section 12 the following can be concluded. Assuming a Finite depth subgrade each of the three FWD back-calculation procedures produced a similar subgrade stiffness which was similar to that obtained from the MDD analysis, i.e. 20-24 ksi. The semi-infinite assumption resulted in an overestimate of stiffness by approximately 50%. The ELSDEF program with the Finite Subgrade assumption produced base and subbase results which were comparable with those obtained from the MDD.

Future work

The MDD provides an excellent tool for validating mechanistic models of pavements under both NDT and truck loading. The analysis performed to date is based on linear elasticity, work is underway to expand the analysis by using Finite Element techniques, non-linear material models and dynamic analysis procedures. The current data logging system is being expanded so that the MDD and FWD data capture systems trigger at the same time. This will allow MDD and FWD (load and deflection) pulses to be recorded on the same time scale, thus facilitating dynamic analysis techniques.

The data capture and analysis procedures described in this paper are currently being installed on a portable 386 microcomputer, so that complete MDD and FWD analysis can be performed in the field. Also tests are planned to monitor MDD response under truck wheel loadings, incorporating the effect of tire pressure.

Summary and Conclusions

A method of determining in situ layer moduli has been presented. The method was thought of great value in interpreting the strength of pavement layers and verifying modulus backcalculation techniques. The multidepth deflectometer functioned well, it is an inexpensive and durable device. The MDD modules can be recovered from installations and reused. This means in a large testing program the MDD material characterization could be performed at a cost comparable to the laboratory testing approach.

Acknowledgements

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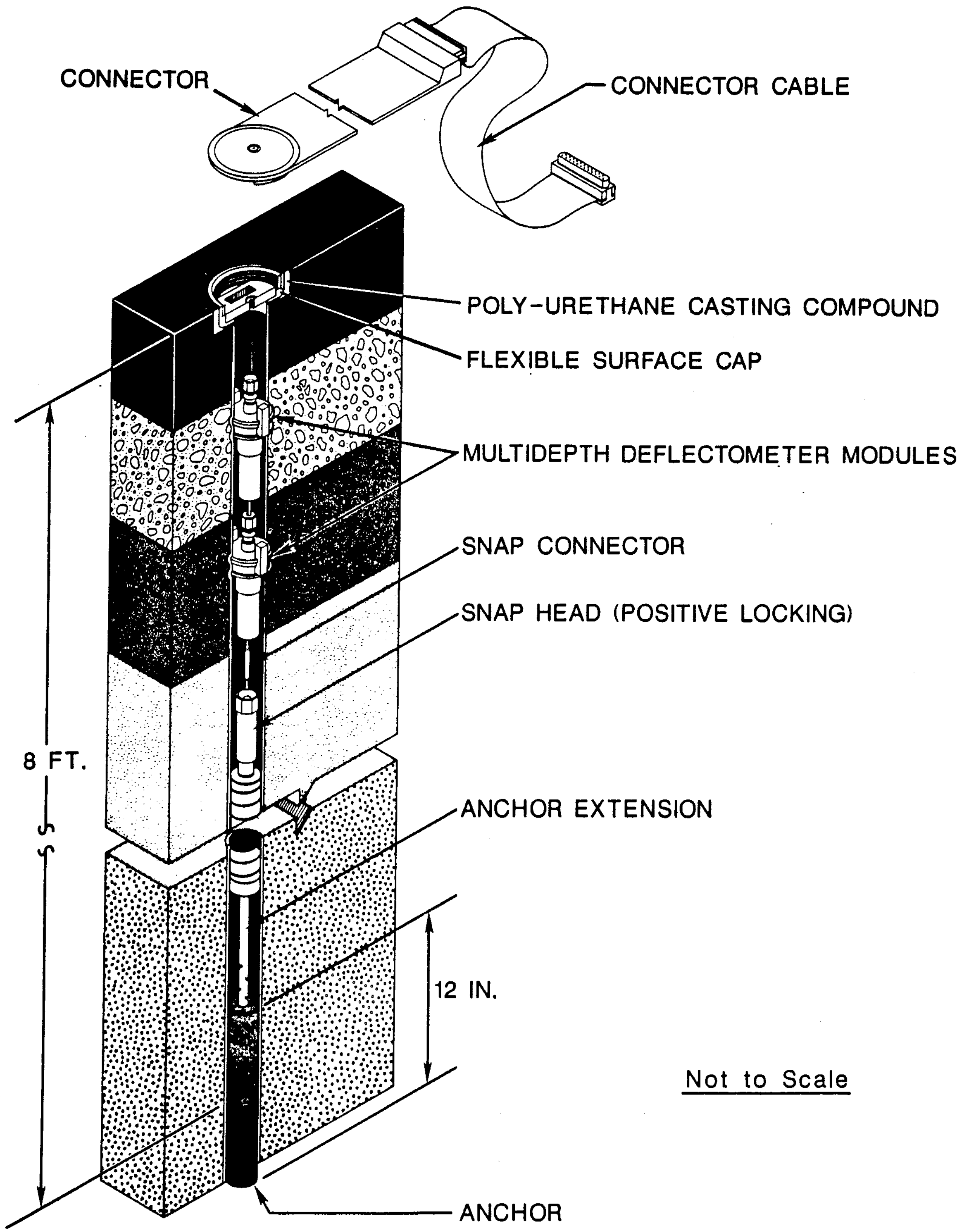


Figure 1. The MultiDepth Deflectometer

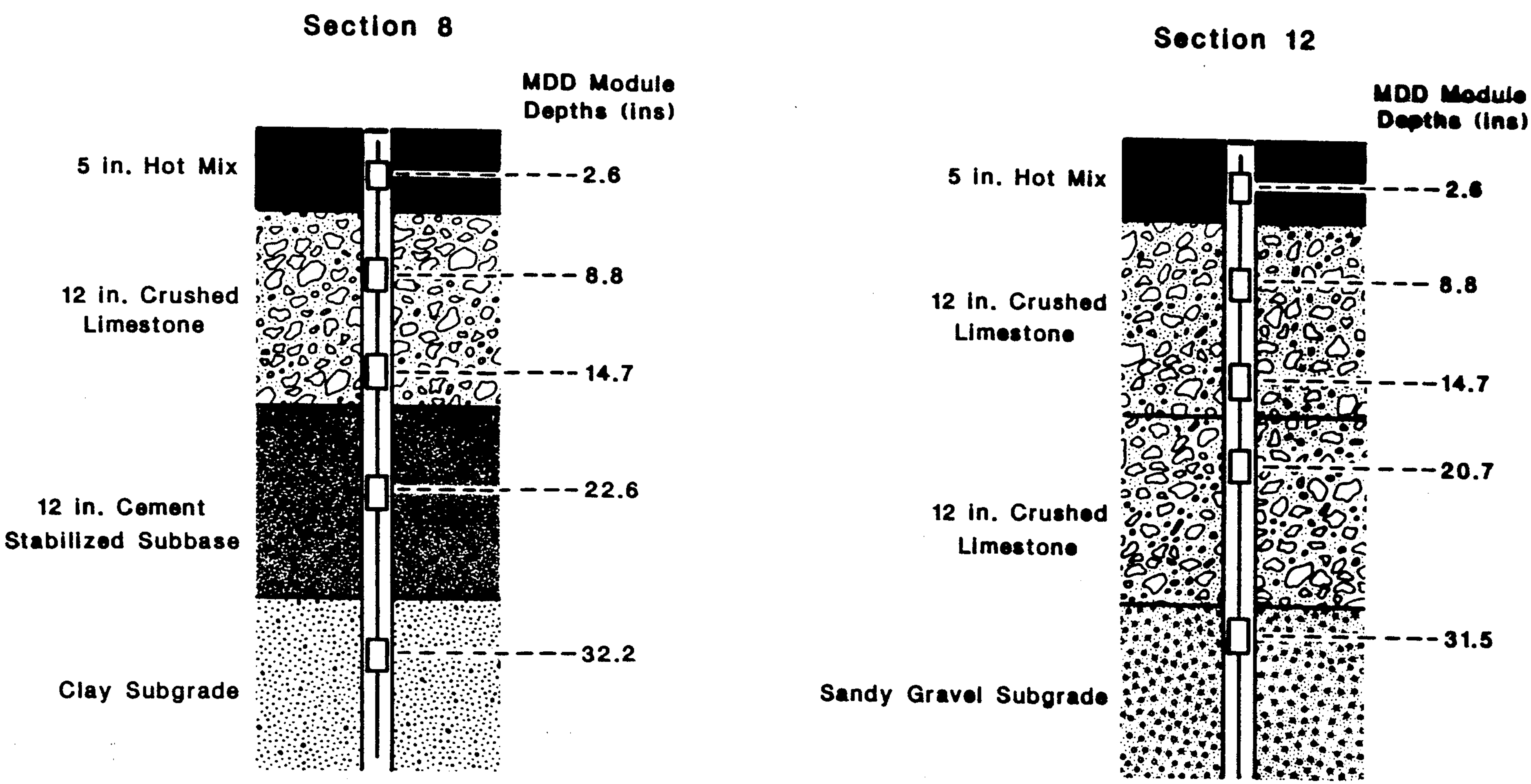


Figure 2. Details of MDD Installation at Texas Transportation Institute's Research Annex

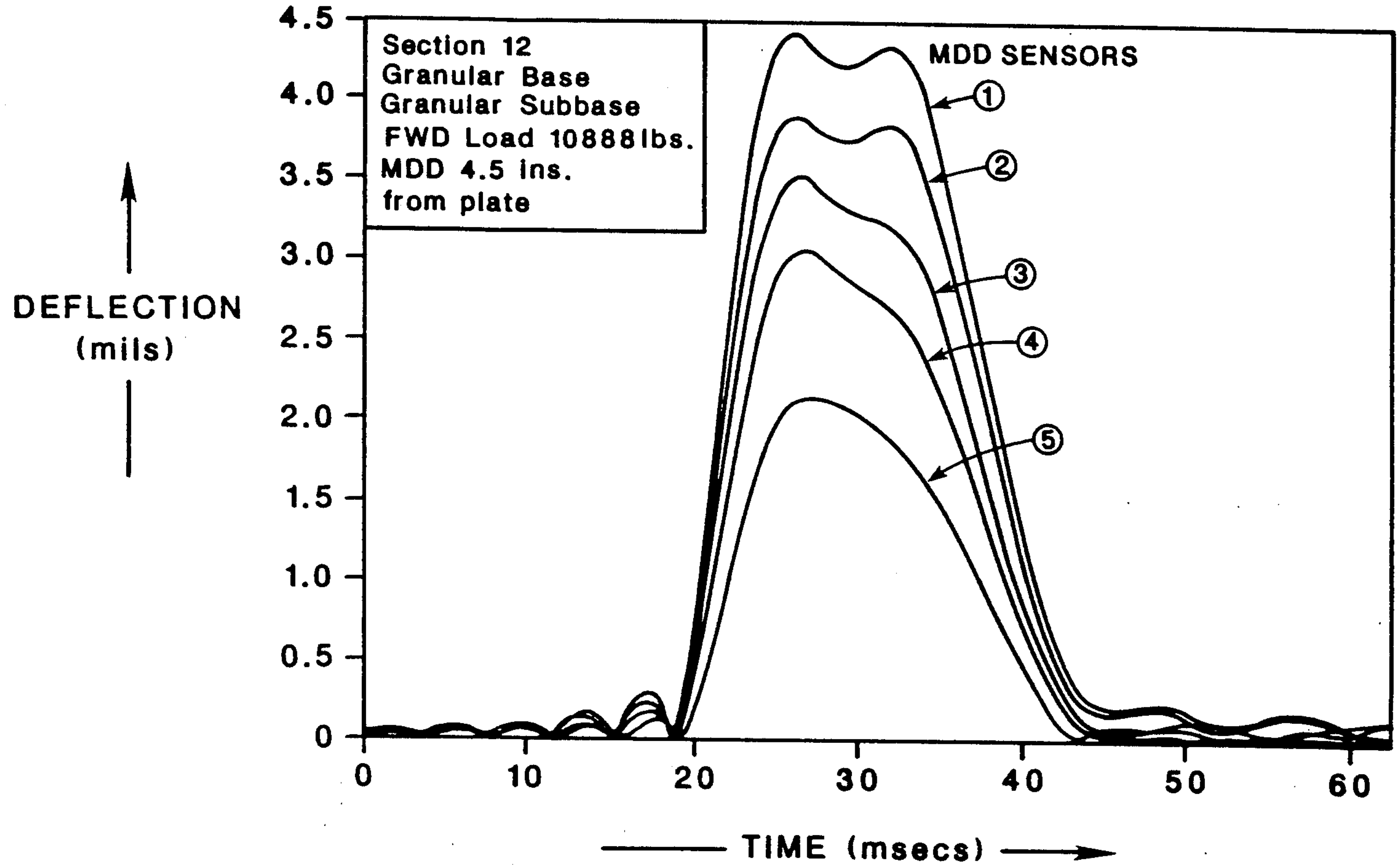


Figure 3. MDD Response Under FWD Loading (Section 12)

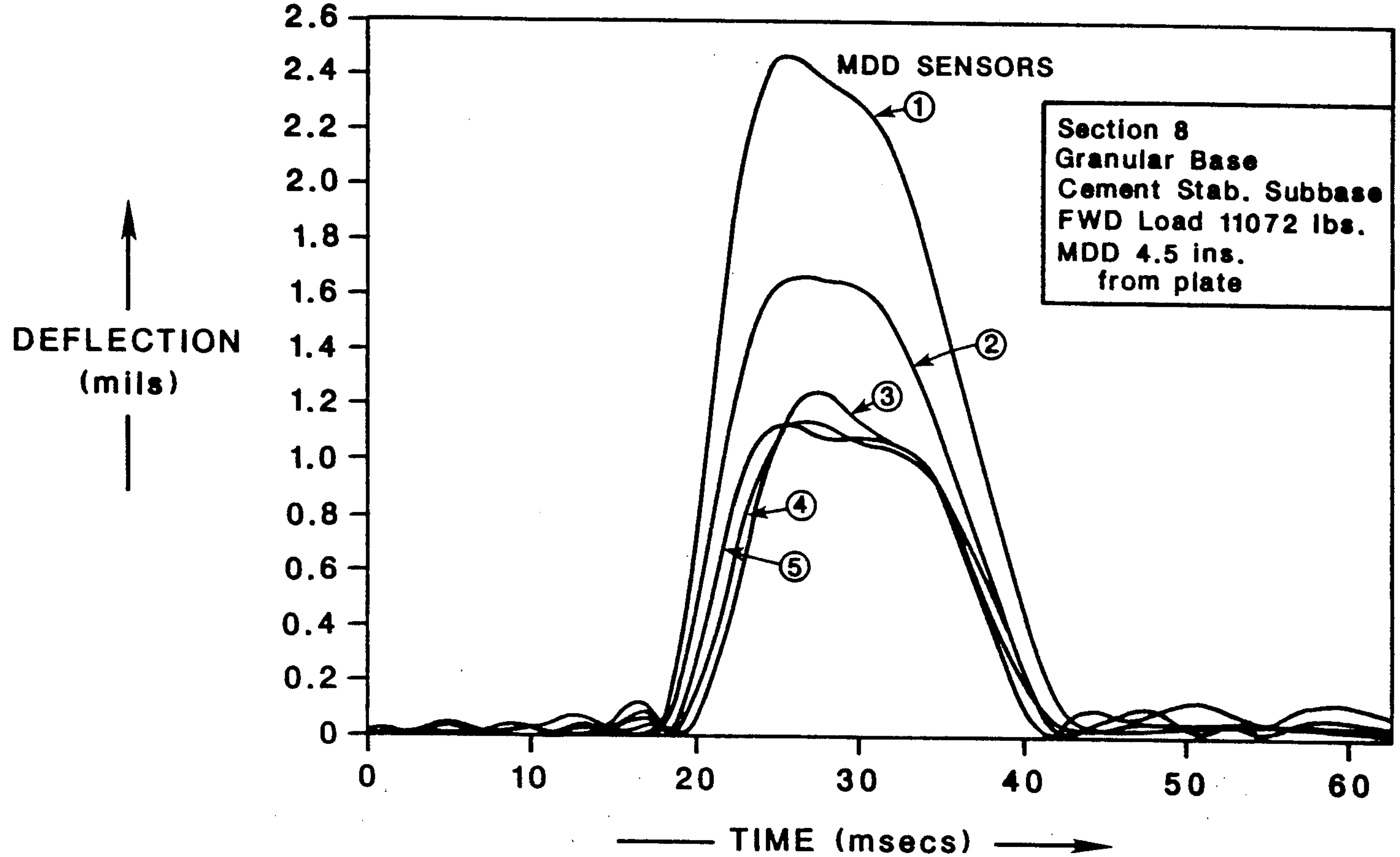
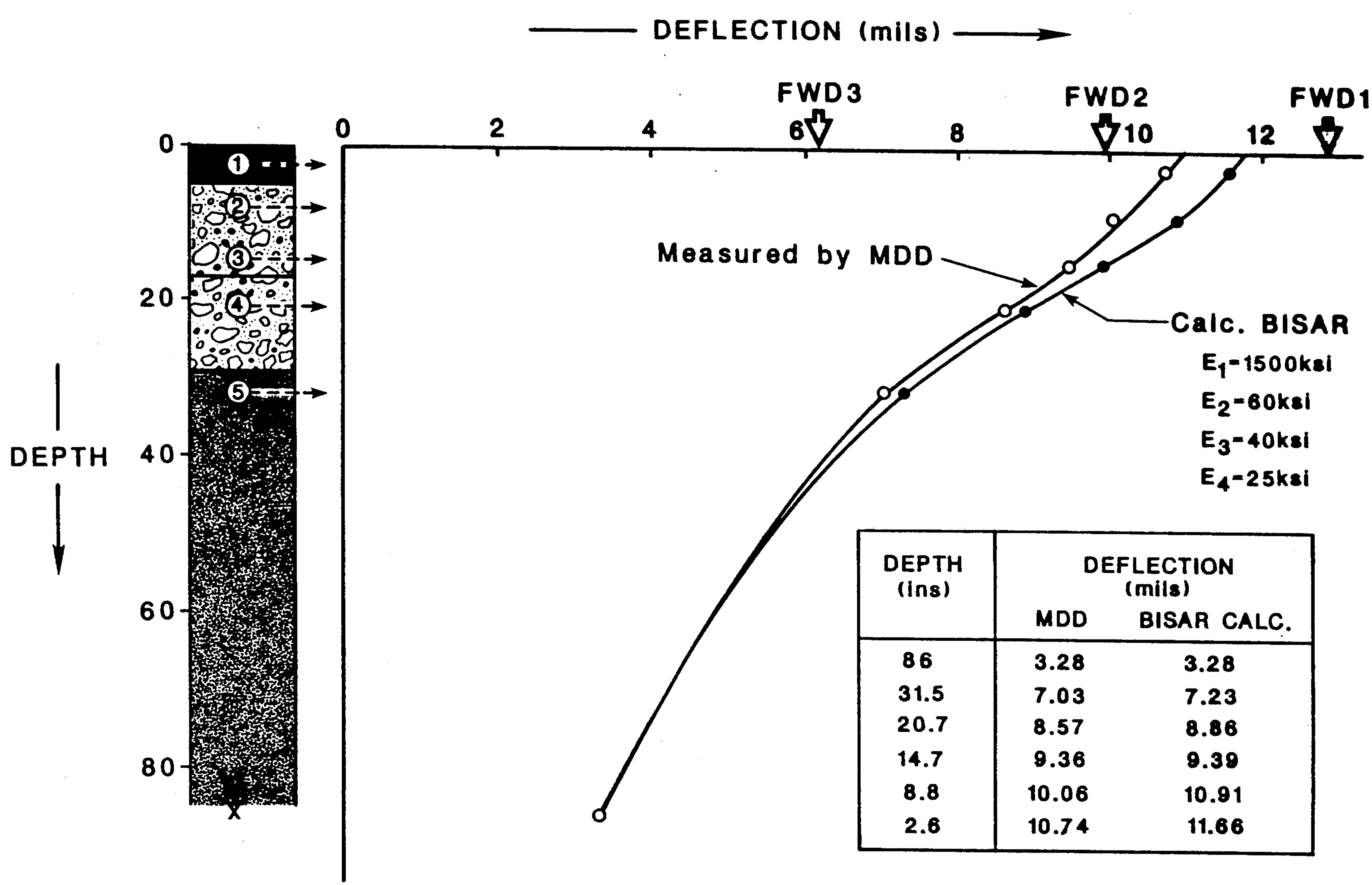


Figure 4. MDD Response Under FWD Loading



DEPTH (ins)	DEFLECTION (mils)	
	MDD	BISAR CALC.
86	3.28	3.28
31.5	7.03	7.23
20.7	8.57	8.86
14.7	9.36	9.39
8.8	10.06	10.91
2.6	10.74	11.66

Figure 5. Comparison of Measured Against Calculated Deflection with Depth for Section 12 for FWD Load=17704 lbs.

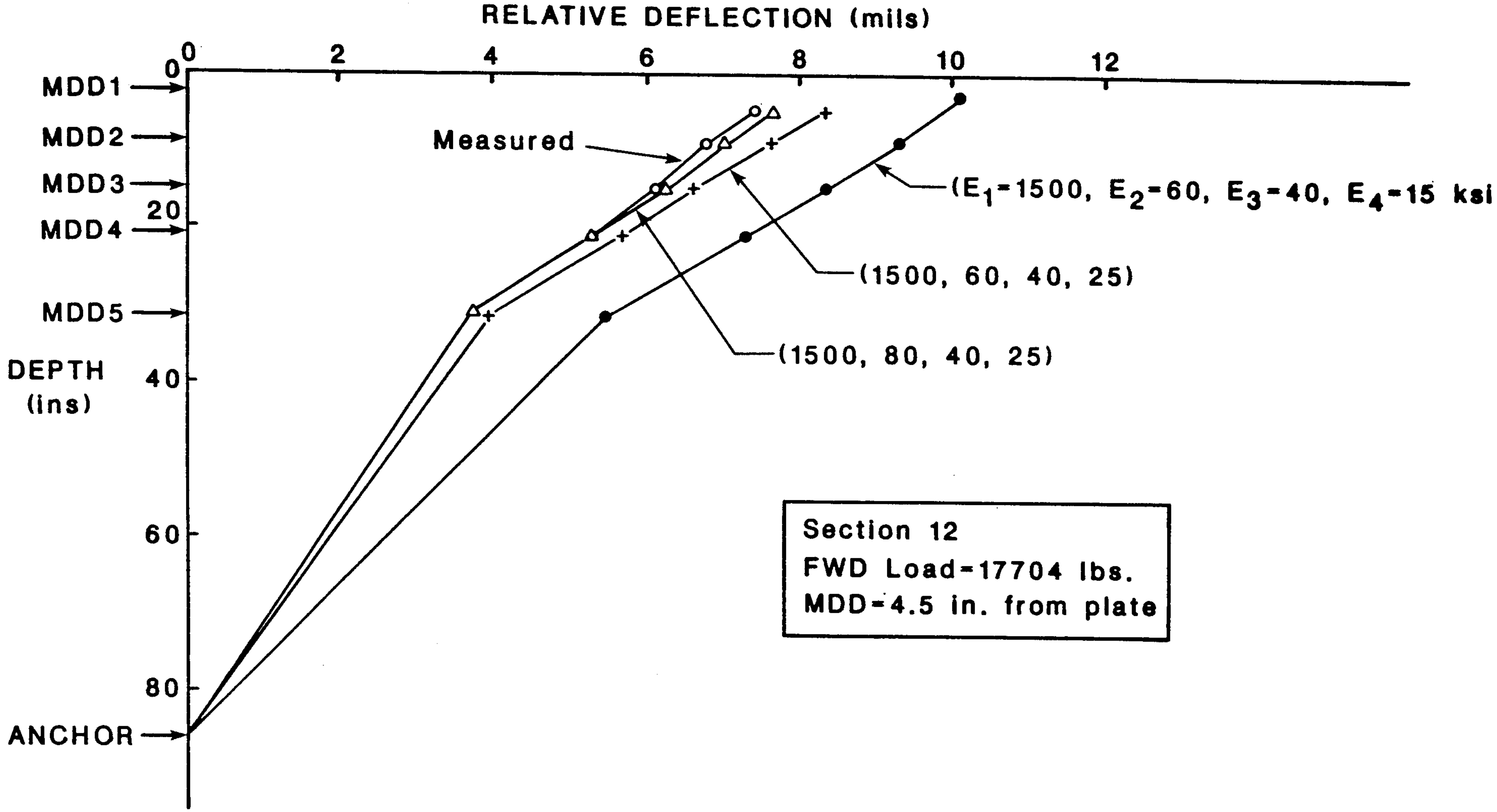


Figure 6. Comparison of Relative Deflection Measured Versus Calculated with BISAR (μ_i=0.35)

Table 1: FWD and MDD Maximum Deflection data for Section 8 at TTI Research Annex

Load (Lbs)	FWD SENSORS (MILS)							MDD (MILS)				
	1	2	3	4	5	6	7	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 2: 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
5688	3.89	3.02	1.72	1.19	0.83	0.82	0.60	1.72	1.44	1.36	1.27	0.74
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

Table 3: Initial Moduli Ranges

Layer	Material Type	Poisson Ratio	Elastic Moduli (Ksi) Seed	Low	High
Surface	Asphalt	0.35	1500	1500	1500
Base	Limestone	0.35	70	30	120
Subbase	Limestone	0.35	50	30	120
Subbase	Cement Stabilized	0.25	1000	500	3000
Subgrade	Sandy Gravel	0.35	30	10	40
Subgrade	Clay	0.40	20	10	40

[Note the asphalt layer was fixed, at a value appropriate for the test temperature].

Table 4 Moduli Calculated Automatically from MDD
Section 8

Load (lbs)		MDD DEFLECTIONS (MILS)					MODULI (KSI) E_1	E_2	E_3	E_4
11072	MEASURED	2.48	1.68	1.25	1.16	1.14	1500	82	4665	16
	CALCULATED	2.22	1.84	1.31	1.16	1.06				
14464	MEASURED	3.03	2.02	1.29	1.24	1.12	1500	76	5986	26
	CALCULATED	2.73	2.17	1.40	1.18	1.08				
18352	MEASURED	3.21	2.07	1.07	1.15	1.06	1500	93	6000	58
	CALCULATED	2.75	2.15	1.31	1.07	.96				

Table 5 Moduli Calculated Automatically from MDD
Section 12

Load (lbs)		MDD DEFLECTIONS (MILS)					MODULI (KSI) E_1	E_2	E_3	E_4
5680	MEASURED	1.72	1.44	1.36	1.27	.94	1500	140	100	25
	CALCULATED	1.64	1.53	1.38	1.23	.94				
10888	MEASURED	4.41	3.88	3.52	3.06	2.14	1500	86	48	26
	CALCULATED	4.33	3.99	3.52	3.01	2.16				
13912	MEASURED	6.11	5.49	5.01	4.39	3.16	1500	88	45	21
	CALCULATED	6.02	5.60	5.01	4.34	3.17				
17704	MEASURED	7.46	6.78	6.09	5.29	3.75	1500	87	44	24
	CALCULATED	7.40	6.86	6.10	5.23	3.76				
17704*	MEASURED	7.46	6.78	6.09	5.29	3.75	2110	82	41	23
	CALCULATED	7.40	6.85	6.11	5.24	3.76				

*The analysis performed at 17704 lbs included a calculation fixing E_1 at 1500 ksi, and another not fixing E_1.

TABLE 6 FWD BACKCALCULATED RESULTS (KSI).
E_1 Fixed at 1500 Ksi.

SECTION	LOAD (LBS)	SUBGRADE	BISDEF			ELSDEF			MODULUS		
			E_2	E_3	E_4	E_2	E_3	E_4	E_2	E_3	E_4
8	11072	SEMI-INF	83	500	29	72	1025	27	78	616	29
8	11072	FINITE	73	1618	16	100	795	17	68	2048	15
8	14464	SEMI-INF	53	970	26	55	1138	25	57	741	27
8	14464	FINITE	50	2280	14	73	946	16	52	1996	15
8	18352	SEMI-INF	69	606	28	69	1090	28	72	635	29
8	18352	FINITE	61	1825	16	90	910	17	65	1847	16
12	5688	SEMI-INF	80	43	38	63	47	37	54	68	36
12	5688	FINITE	63	116	26	*	*	*	57	113	24
12	10888	SEMI-INF	66	30	33	48	58	31	54	41	32
12	10888	FINITE	50	85	22	64	47	24	47	101	22
12	13912	SEMI-INF	60	30	31	43	58	29	55	34	30
12	13912	FINITE	44	90	20	60	49	22	43	94	20
12	17704	SEMI-INF	79	30	33	59	56	31	71	33	33
12	17704	FINITE	68	60	23	83	44	24	54	97	22

*Did not converge