# AN ABSOLUTE CALIBRATION SYSTEM FOR NONDESTRUCTIVE TESTING DEVICES

by

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and

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Research Project 913

DEVELOPMENT OF AN ABSOLUTE CALIBRATION SYSTEM FOR NONDESTRUCTIVE TESTING DEVICES

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by

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The University of Texas at El Paso

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# ABSTRACT

The Falling Weight Deflectometer (FWD) and Dynaflect devices are presently being used by highway agencies. The primary function of the FWD and Dynaflect devices is to measure a deflection basin due to a load imparted to the pavement. Deflection basins measured in the field are used in backcalculating modulus profiles of pavement sections. As such, it is critical to determine the deflection basins in the field with great accuracy. Velocity transducers (also called geophones) are used to determine the deflections, and load cells are utilized to measure applied load.

It has become increasingly important in recent years to be able to evaluate the performance of the deflection and load sensors of the Falling Weight Deflectometer or the Dynaflect devices. It has been shown that a small error in the deflections measured in the field may yield significantly erroneous modulus values. As such, a very reliable method for evaluating the accuracy of the sensors used for determining these deflections is necessary.

If geophones are used to determine deflections, the algorithm developed for calculating deflection will also become important. A geophone measures the so-called "raw" particle velocity of the pavement surface directly underneath it. Therefore, the methodology and algorithm employed to obtain the "actual" displacement must be carefully considered. Errors in the load cell measurements are not as important, but should be avoided for reliable results.

In this report the components and procedures involved in the calibration process are described. The system basically consists of two well-calibrated geophones, three load cells, a signal conditioning unit, a loading plate, and an analog-to-digital board and a computer. A software is developed to control the A/D board and to reduce the data.

A detailed procedure is also developed and is described in this report. Basically, the load cells are calibrated on a concrete pad and the geophones are evaluated on a asphaltic surface. The data are analyzed utilizing a statistical package.

KEY WORDS: Nondestructive Testing, Performance Monitoring, Geophones, Calibration, Pavement

# METRIC (SI*) CONVERSION FACTORS

## APPROXIMATE CONVERSIONS TO SI UNITS

### LENGTH

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| in | inches | 2.54 | centimetres | cm |
| 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 | centimetres squared | cm$^2$ |
| 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 |

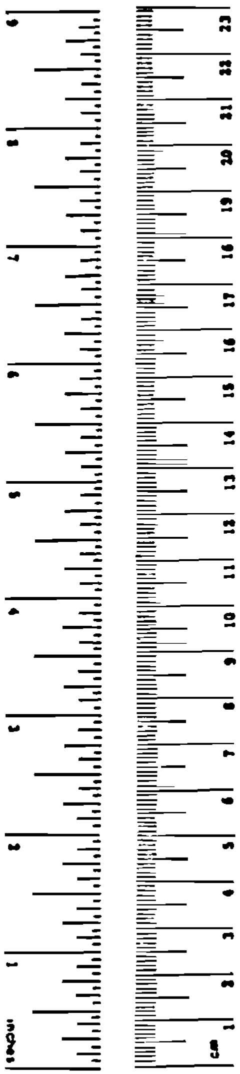
### VOLUME

| 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 |



## 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 | hectares (10 000 m$^2$) | 2.53 | acres | ac |

### MASS (weight)

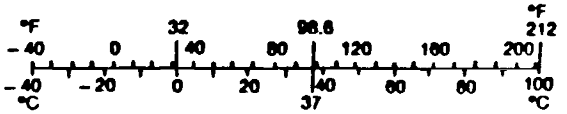
| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| g | grams | 0.0353 | ounces | oz |
| kg | kilograms | 2.205 | pounds | lb |
| Mg | megagrams (1 000 kg) | 1.103 | short tons | T |

### 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.

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* SI is the symbol for the International System of Measurements

# PREFACE

This report is the second of four reports which describes work done on Project 913, "Development of an Absolute Calibration System for Nondestructive Testing Devices." The study is being conducted at the Center for Geotechnical and Highway Materials Research, the University of Texas at El Paso with the cooperation of the Texas State Department of Highways and Public Transportation.

Many people have contributed their help towards the completion of this report. Thanks are extended to Mr. Amin Solehjou for excellent work in preparing the electronic parts, and to all the secretaries in the Department of Civil Engineering for their help and efforts.

Invaluable comments and support were provided by Mr. Robert Briggs, Richard Rogers and all other personnel of SDHPT.

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August, 1990

# LIST OF REPORTS

Research Report 913-1F, Volume 1, "Comprehensive Evaluation of Five Sensors Used for Pavement Monitoring," by Vivek Tandon and Soheil Nazarian, presents an extensive testing program to evaluate the accuracy and precision of five deflection sensing transducers used in pavement engineering, for use by Texas State Department of Highways and Public Transportation, August, 1990.

Research Report 913-1F, Volume 2, "An Absolute Calibration System for Nondestructive Testing Devices," by Vivek Tandon and Soheil Nazarian, presents a system developed for the absolute calibration system of the FWD and Dynaflect devices, for use by the Texas State Department of Highways and Public Transportation, August, 1990.

Research Report 913-1F, Volume 3, "User's Manual to Computer Program Calibrat," by Vivek Tandon and Soheil Nazarian, contains a user's manual for a computer program called CALIBRAT, for use by the Texas State Department of Highways and Public Transportation, August, 1990.

Research Report 913-1F, Volume 4, "Appendices and Supporting Data," by Vivek Tandon and Soheil Nazarian, for use by the Texas State Department of Highways and Public Transportation, August, 1990.

# SUMMARY

An system is developed for the absolute calibration of the FWD and Dynaflect devices. The calibration system consists of two well-calibrated geophones and three load cells with calibration constants traceable to the National Bureau of Standards. A Signal Conditioning Unit (SCU) is also developed for preconditioning of the signals. The SCU consists of antialising filters and a triggering mechanism. For collection and reduction of data a computer algorigthm is coded.

The calibration of the FWD device can be done by using the calibration system. For each drop height, the data is collected from the load cells and geophones. The collected data is reduced to obtain the deflections and loads. A calibration factor is developed on the basis of linear regression between data collected by the calibration system and those reported by the FWD device.

# IMPLEMENTATION STATEMENT

The developed system should be implemented as soon as possible. All components are tested and developed and a user's manual describing the process has been prepared.

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# CHAPTER ONE

# ABSOLUTE CALIBRATION SYSTEM FOR NONDESTRUCTIVE TESTING DEVICES

## 1.1 INTRODUCTION

The system developed for an absolute calibration of nondestructive testing devices is presented herein. This system consists of a load calibration component and a deflection calibration component. A block diagram describing the different components of the calibration system is included in Figure 1.1

The load calibration component consists of three load cells and an aluminum plate. The deflection calibration component consists of two well-calibrated geophones and a signal conditioning unit (SCU). A data acquisition system and a computer are also utilized. Through a sophisticated computer algorithm, all the components are controlled and all collected data are reduced and presented. All the components of calibration system are shown in Figure 1.2. The overall setup and different components are described in this chapter.

## 1.2 LOAD CALIBRATION COMPONENTS

### 1.2.1 ALUMINUM PLATE

The FWD device imparts a load to the pavement by dropping a weight from different heights. This load is transferred to the pavement through a PVC plate. An aluminum plate with the same thickness and diameter of the FWD PVC plate was fabricated (Figure 1.3). Six different holes were drilled in the plate for fastening the load cells to the plate. Three holes, which were 120 degrees apart, were located half-way between the three screws used for connecting the aluminum plate to the FWD device. The other three holes were made along a straight line. The first three holes can be used for calibration purposes and the other three are used to study the variation of load along the diameter of the FWD plate. All the holes had grooves for load cell output cable. The plate also had three small holes for fastening the aluminum plate to the FWD device.

### 1.2.2 LOAD CELLS

Three load cells Model 200B20 manufactured by PCB Piezotronics, Inc. were utilized. The characteristics of these load cells are given in Appendix A. The calibration curves of the load cells, provided by the manufacturer are traceable to the National Bureau of Standards (NBS). The calibration factor for Load Cell 1, Load Cell 2, and Load Cell 3 were 0.277, 0.241, 0.237 mv/lbs respectively. Load Cell 2 encased in a mounting mechanism similar to those provided on the calibration plate was recalibrated in the laboratory (Section 2.4) to ensure that the aluminum plate does not affect the calibration factor of the load cell. The results of this calibration are reported in Research Report 913-1.

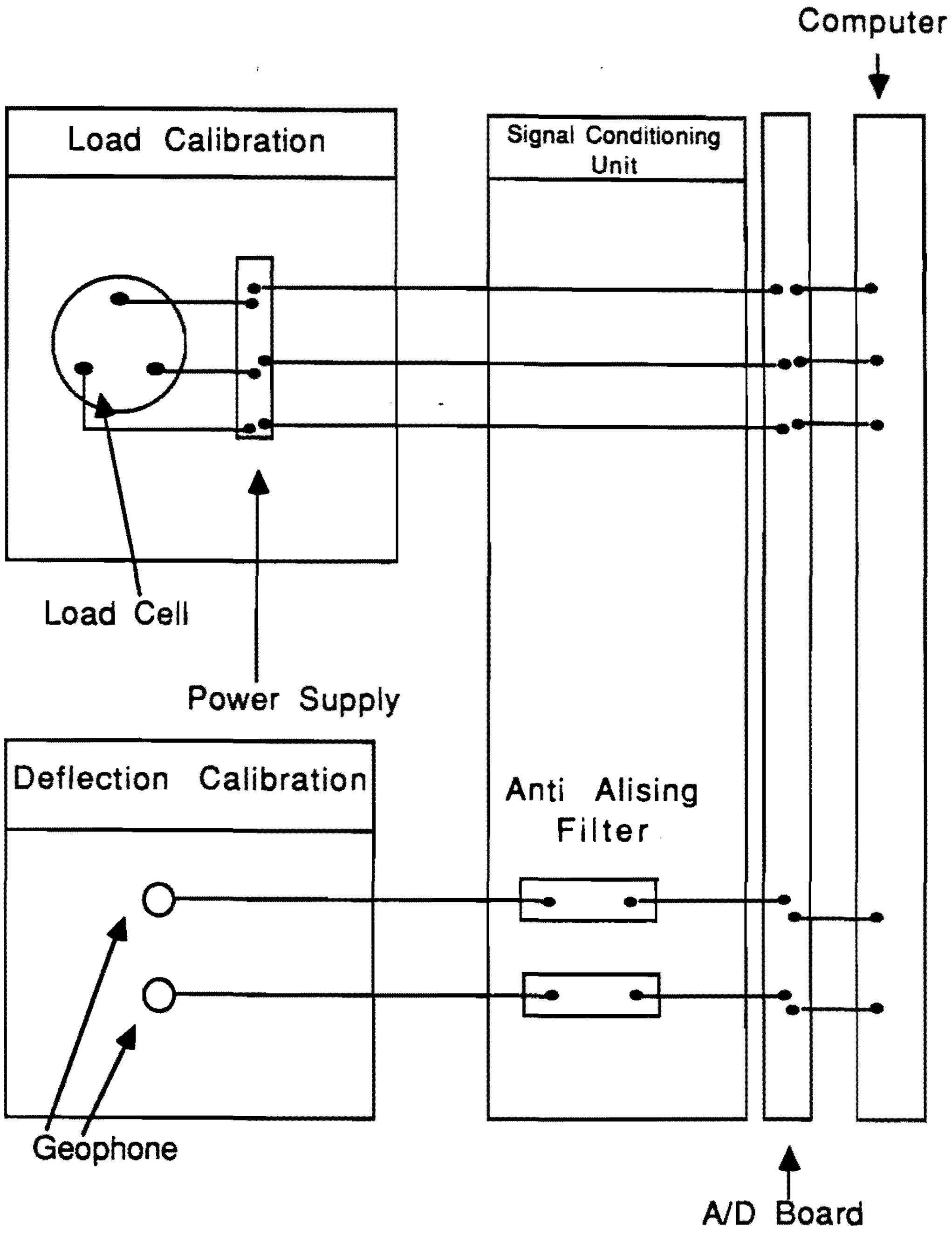
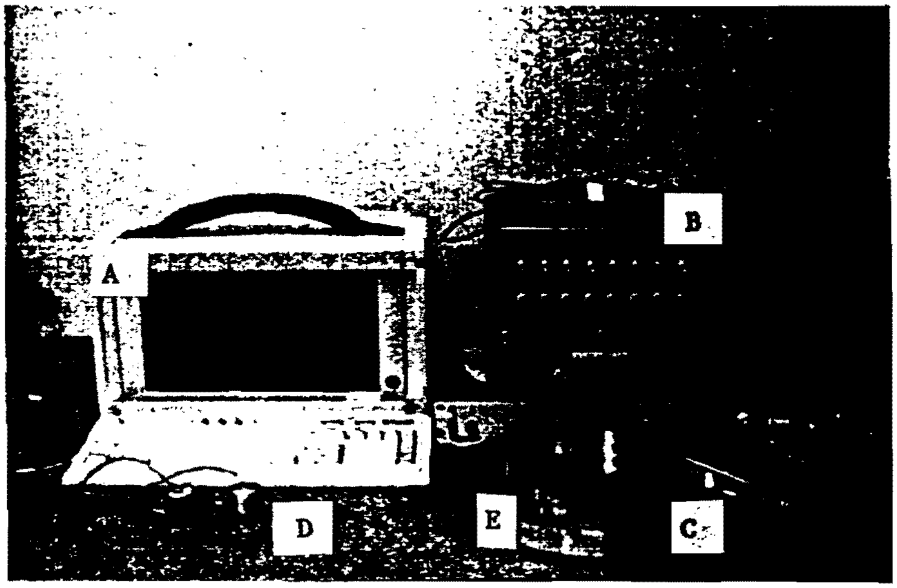
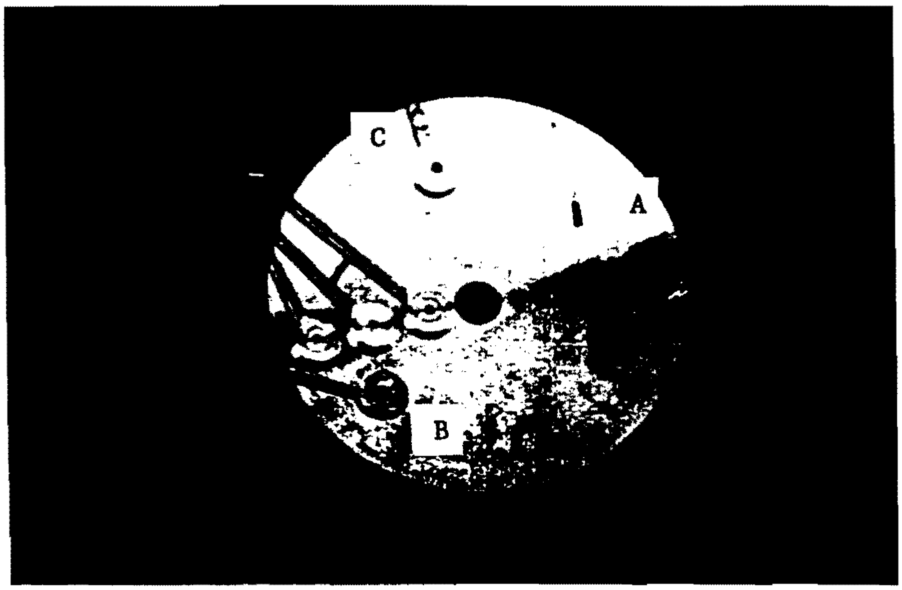


Figure 1.1 Block Diagram of Different Components Used in Calibration System



A - Computer
B - Signal Conditioning Unit
C - Geophones
D - Load Cell

Figure 1.2 Components of Calibration System



A - Aluminum Plate
B - Hole for Load Cell
C - Slot Provided for Load

Figure 1.3 Aluminum Plate Developed for Calibration System

## 1.3 DEFLECTION CALIBRATION COMPONENTS

### 1.3.1 DEFLECTION SENSORS

The two geophones, used in the calibration system, were named Geophone 1 and Geophone 2. Geophone 1 had a natural frequency of 4.53 Hz and damping ratio 78 percent and a gain factor of 0.788 Volts/in/Sec; while Geophone 2 had a natural frequency of 4.77 Hz and a damping ratio of 69 percent and a gain factor of 0.599 Volts/in./Sec.

### 1.3.2 SIGNAL CONDITIONING UNIT (SCU)

The SCU consists of an eight-channel analog filter, and a triggering mechanism as depicted in Figure 1.4. The filter is a fourth order low-pass filter with a cut-off frequency of 250 Hz. The unit is placed between the sensors and the analog-to-digital convertor board. As shown in Figure 1.4, each load or displacement sensor is connected to one channel of the unit. The signal can either be filtered and output to the A/D board or the filter can be bypassed and the output can be directly output to the board. Each channel is equipped with a switch for directing or bypassing the signal through the filter. The SCU had eight BNC connectors for connecting the input signals. The output signals from the SCU were directed to the A/D board through a 50-pin connector. In addition to filtering, the unit had provisions for activating the A/D board through an external triggering circuitry. The triggering sensor is a proxy sensor.

## 1.4 ANALOG TO DIGITAL (A/D) CONVERSION BOARD

The output of SCU can be connected to the input port of the A/D board. The basic function of the A/D board is to convert the analog data obtained from the SCU to a digital form. The specifications of the board used in the calibration system are included in Appendix A.

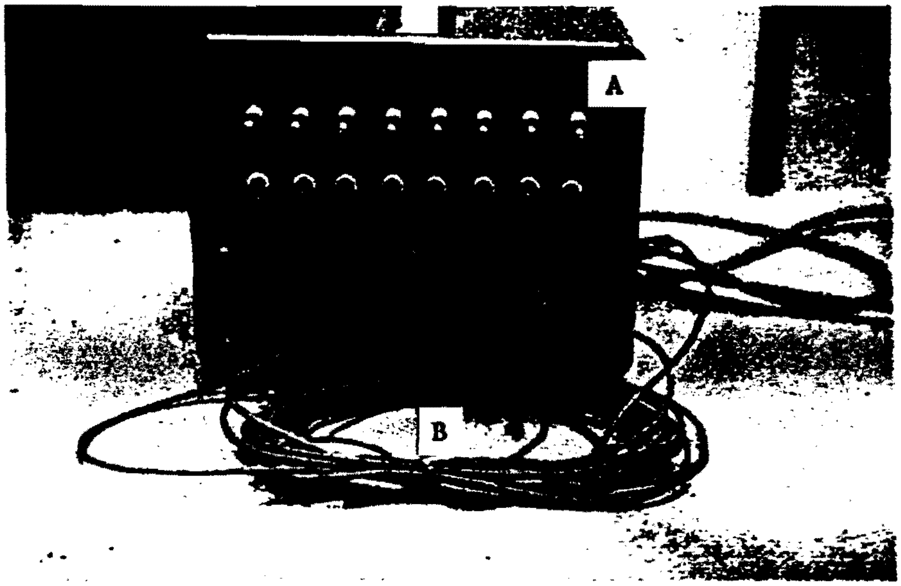
The board is initialized and controlled by a computer software. The main features of the software are discussed in Section 1.7.

## 1.5 COMPUTER

The calibration system consists of a Compaq Portable 386$^{TM}$, manufactured by Compaq Computer Corporation. The compaq computer was selected because it is IBM compatible and is rugged enough for field work. The A/D board is installed inside an external box that can be connected to the computer.

## 1.6 SOFTWARE

A computer program was developed to: 1) control the acquisition and retrieval of the analog data captured by the sensors; 2) reduce the collected data and 3) to display and analyze the raw and reduced data. The program provides software-controlled initialization



A - Signal Conditioning Unit
B - Proxi Switch

Figure 1.4 Signal Conditioning Unit

and identification of the A/D board and facilitates the collection of data using Direct Memory Access (DMA). The acquired data is stored in a file for further processing. The block diagram of the program is shown in Figure 1.5.

The program can be used in two modes: 1) the data are collected through the board and processed or 2) previously collected data are reduced.

The software is preprogrammed for calibration of either the dynaflect or the FWD device. In order to make the system flexible, a third option is provided. With this option, any other type of sensor under either a steady-state sinusoidal load or an impulse load can be calibrated. If this option is selected, a table containing variables that can be varied as well as default values for these variables will appear on the screen for collection and reduction of data. The variables consist of the number of channels used for collection of data, the type of sensor used with each channel, the calibration properties of each sensors, the time span for collection of data and number of data points per channel. The default values can also be read from a file previously saved. The program saves this information in a file and collects data. After collecting data from the board, the load obtained from each load cell and deflections measured with geophones are reduced and plotted.

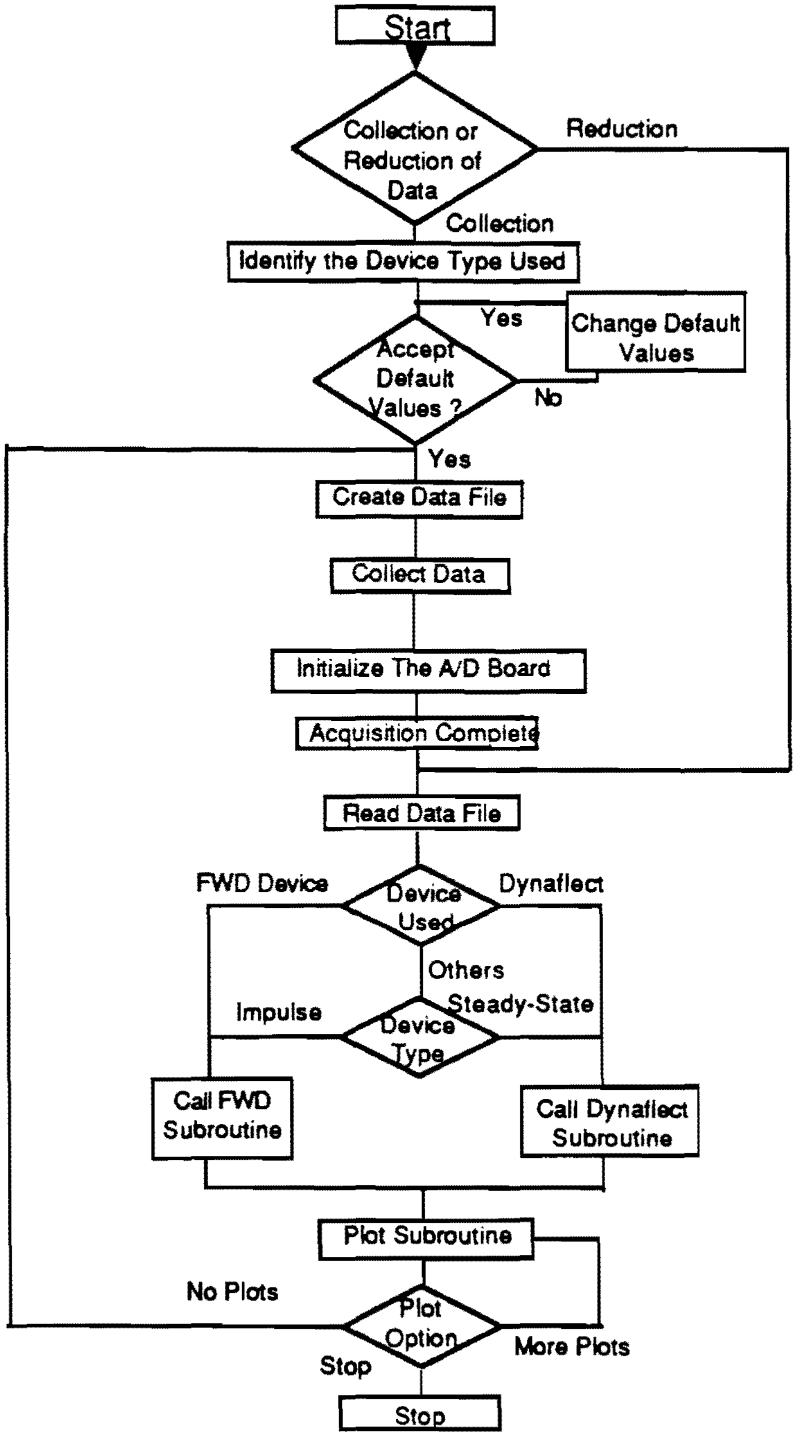


Figure 1.5 Block Diagram of Computer Program

# CHAPTER TWO

# CALIBRATION PROCESS FOR FALLING WEIGHT DEFLECTOMETER

## 2.1 INTRODUCTION

For calibration of the FWD device, the setup described in Chapter One was utilized. Deflection and load data were collected with the FWD device and the calibration system, concurrently. Tests were repeated on a concrete site and an asphalt site. In this chapter, data collection process and results obtained from calibration of one FWD device are presented and discussed.

## 2.2 DESCRIPTION OF DATA COLLECTED

In order to evaluate the FWD device several parameters were considered. The parameters studied for load measuring system were the type of pavement material, the effects of padding below the FWD plate, the effects of the drop height, and the effects of rotation of the calibration plate. For deflection measuring components, only the effects of the drop height were investigated. In each study, the FWD plate was placed on the pavement surface and the weight was dropped ten times. In addition, a second series of tests was carried out where the FWD plate was lifted and placed back on the pavement and then the weight was dropped. This process was repeated ten times as well. In this manner, the effects of placement of the loading plate on calibration process could be evaluated. Hereafter, the first ten drops, where the plate was not removed between drops, will be called a repetition and the ten drops with the removal and placement of the load plate will be named a wrap.

### 2.2.1 CONCRETE PAVEMENT

A set of data was collected on a concrete pavement section to evaluate the loading mechanism of the FWD device. This site was particularly suitable for load measurement because the site consisted of more than four feet of concrete overlaying a stiff base. As such, the amount of loss of energy is minimal. The maximum deflection measured at this site was roughly 0.3 mils. In a separate test, it was found that the background electrical noise associated with the FWD device was approximately 0.2 mils. Therefore, the deflection measurements on the concrete pavement were of little value.

Several factors were studied at this site. Tests were repeated with and without rubber padding to investigate the effects of the rubber padding below the FWD load plate on the loads measured.

The next parameter considered was the drop height. Test were carried out at four drop heights. In ascending order, the drop heights correspond to nominal loads of 6, 9, 11, and 16 kips, respectively.

As indicated in Chapter One, three load cells were used in the calibration system. To consider the effect of the order of placing the load cells, with plate the calibration plate was rotated 120 degree three times and identical tests were conducted. For Drop Height 4, the plate was not rotated because of time limitations.

### 2.2.2 ASPHALT PAVEMENT

On the asphalt section, both deflection and load measurements were carried out. The effects of drop height were considered for deflection measurements. Tests were performed at two different sites. At one site data was collected only for Drop Height 2 while data for Drop Heights 1, 3, and 4 was collected at a different site.

For load measurements, the effect of rotation of plate was not considered due to lack of time. However, the effects of drop height and the rubber padding under the load pad were considered. Tests were carried out at Drop Heights 1 and 4 only.

## 2.3 DATA COLLECTION PROCEDURE

As discussed in previous section, a set of data was collected for determining the accuracy and precision of the load cell and geophones used in the FWD device. The FWD device is equipped with one load cell and seven geophones. The calibration system utilizes three load cells and two geophones at a time. Loads from three different load cells are summed to find the total load applied to the pavement. This data is then compared with the load registered by the FWD device. Only two sensors of the FWD devices can be evaluated at one time, because only two well-calibrated geophones were used in this study. Each time, two geophones of the FWD device were compared with Geophone 1 and Geophone 2 of the calibration system. Sensor 1 of the FWD device was not evaluated because of time limitations.

### 2.3.1 LOAD CELLS

The load cell of the FWD device was evaluated on a concrete and an asphalt pavement section. The same field procedure was followed to collect data at both sites. Three load cells were fastened to the aluminum plate fabricated for calibration purposes (See Section 1.3). The original PVC plate of the FWD was replaced with this aluminum plate. The load cells were connected to the SCU with BNC coaxial cables. In turn the SCU was connected to the Computer (via an A/D Board). The FWD device loading mechanism was raised and dropped from four different heights.

Two sets of experiments were carried out for each drop height. First, the loading plate was securely placed on the pavement and the drop weight was released ten times without moving the plate. Secondly, after each test, the loading plate was removed and repositioned on the pavement.

After these tests were completed, the aluminum plate was rotated 120 degree and the process was repeated again. For all cases, data were collected with and without rubber padding below the aluminum plate.

Each time data were collected with the FWD device load cell and the three load cells of the calibration system. The sum of the loads registered with the three load cells was then compared with the load reported by the FWD device. The load from each load cell was obtained by calculating the difference between the base and peak value of each record. An example of the load time history of a load cell is shown in Figure 2.1 where the process of determining load is clearly marked.

### 2.3.2 DEFLECTION SENSORS

The set up for deflection calibration was identical to that used for load calibration. Two geophones of the calibration system were placed as close as possible to the two geophones (for example, Sensors 7 and 6) of the FWD device. The two calibration geophones were attached securely to the pavement using modelling clay. The well-calibrated geophones were connected to the A/D board through the Signal Conditioning Unit (SCU). Tests were carried out in two phases. In phase one, the load plate of the FWD was placed securely on the pavement and the FWD weight was dropped ten times. In the second phase, the loading mechanism of FWD system was lifted and seated after each drop. This procedure was also repeated ten times.

The geophone records captured by the calibration system was reduced following the procedure explained in Appendix D. An example of raw data collected with the geophone of the calibration system and final reduced results are shown in Figure 2.2. The deflection is basically the difference between the base value and the first peak as shown in the figure.

## 2.4 COMPARISON OF LOAD AND DEFLECTION MEASUREMENTS

The data collection methodologies for load and deflection are discussed in Section 2.3. The data reduction process for each geophone and load cell are discussed in Appendix D and Section 2.3.1, respectively. In the present section, the load and deflection data obtained following the procedures described in Section 2.3 are analyzed.

### 2.4.1 LOAD MEASUREMENT

An example of load data collected at one position is shown in Table 2.1. All data collected for evaluating the FWD load cell is shown in Appendix O. As indicated before, first the load plate was placed on the pavement and the load was dropped ten times. The results of this experiment are shown in Table 2.1a. In the table, the outcome of each load cell as well as the summation of loads from the three load cells are included. The output of the FWD from the same drop are reflected in the table also. For each drop, the difference between the loads from the calibration system and the FWD is included in the last column. The averages and the coefficient of variations were calculated and reported in the table as well. These values are used in the evaluation of the device (next section) and for determining the calibration values for the FWD sensors (Chapter Three). In Table 2.1b, similar information is furnished but for the case when the loading plate was raised and

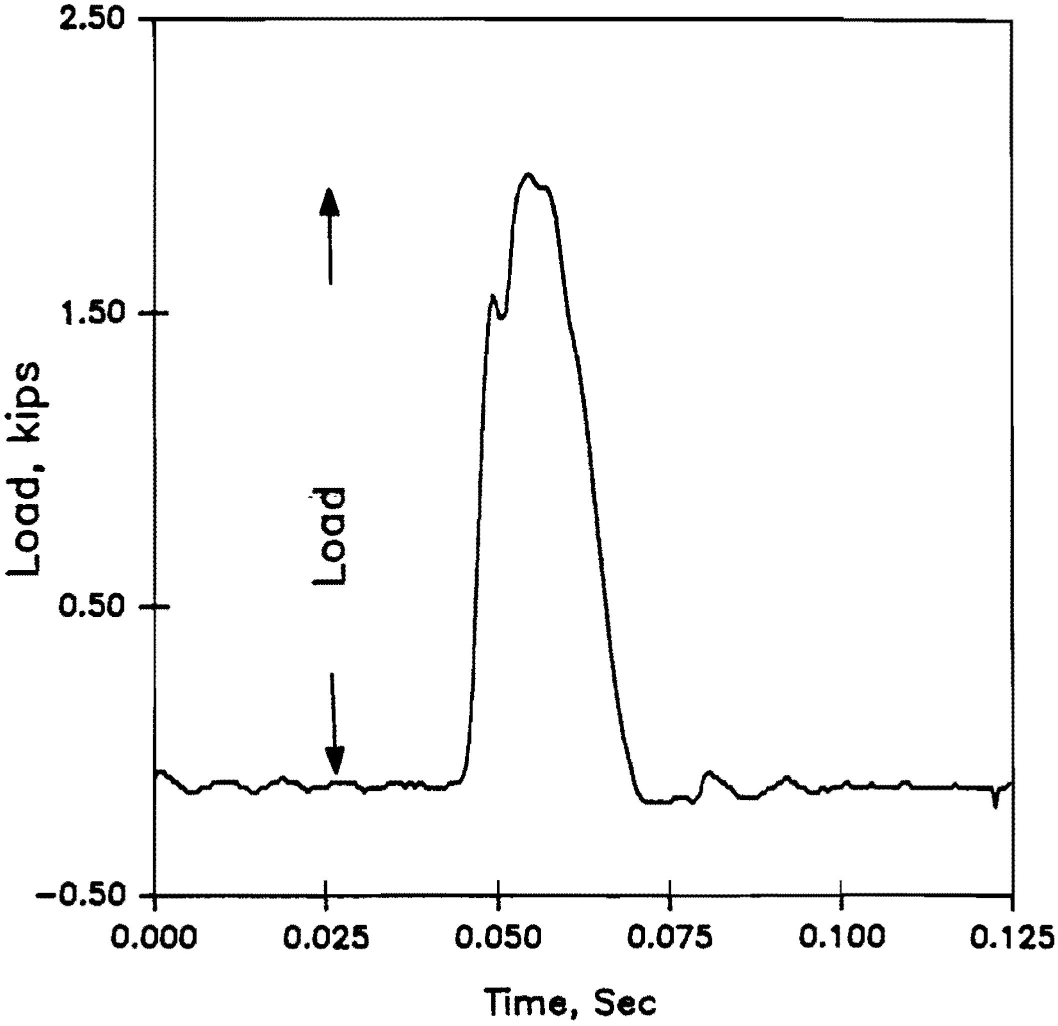
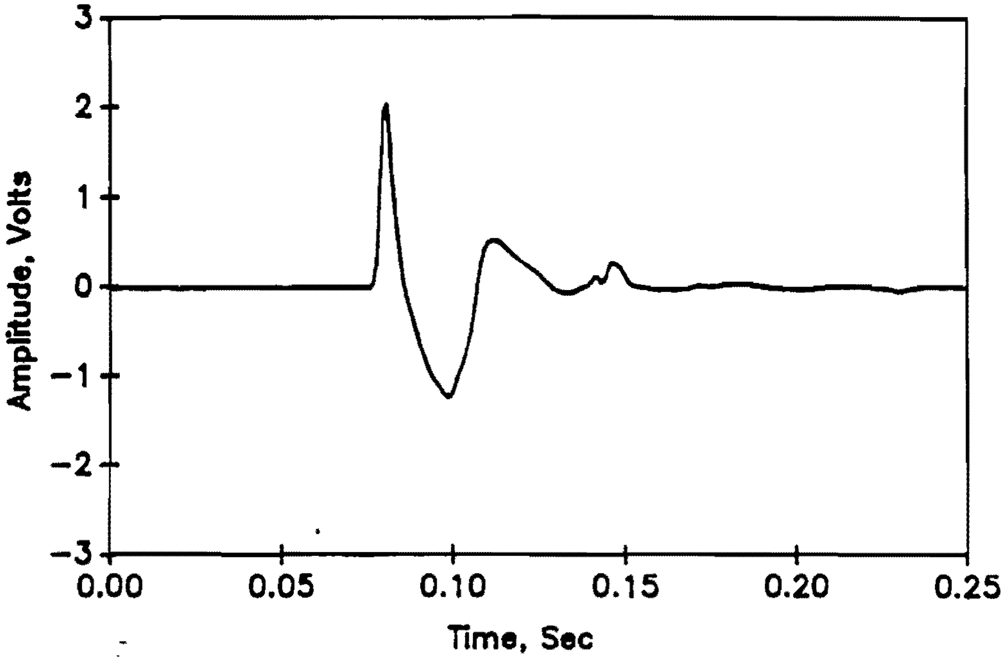
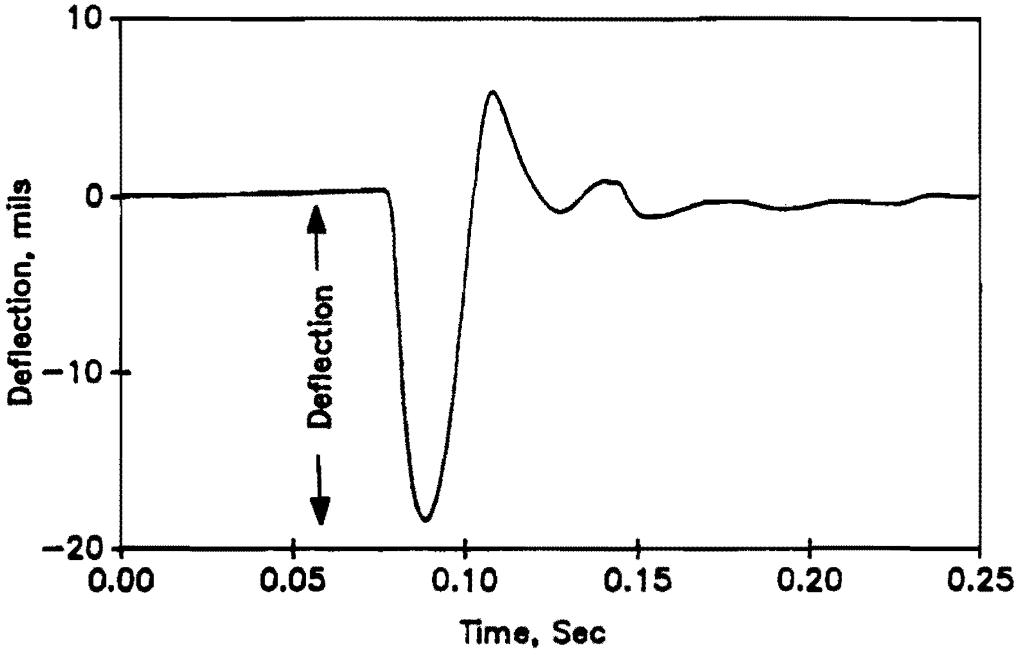


Figure 2.1 An Example of Load Time History Measured by the Calibration System



a) Raw Votlage Output



b) Deflection Time History

Figure 2.2 An example of Deflection Time History Measured by the Calibration System

**Table 2.1** Comparison of Loads Obtained with Calibration System and FWD Device

a) Results of Repetitions

| Test | Load from Calibration System (kips) | | | | | Load from FWD | Difference[+] |
|---|---|---|---|---|---|---|---|
| No. | Load Cell 1 | Load Cell 2 | Load Cell 3 | Average | Total | (Kips) | (percent) |
| 1 | 2.09 | 1.77 | 2.24 | 2.03 | 6.10 | 6.51 | 6.37 |
| 2 | 2.13 | 1.77 | 2.23 | 2.04 | 6.13 | 6.56 | 6.62 |
| 3 | 2.09 | 1.76 | 2.26 | 2.03 | 6.10 | 6.52 | 6.37 |
| 4 | 2.09 | 1.79 | 2.27 | 2.05 | 6.15 | 6.54 | 5.91 |
| 5 | 2.07 | 1.79 | 2.26 | 2.04 | 6.13 | 6.56 | 6.62 |
| 6 | 2.06 | 1.76 | 2.27 | 2.03 | 6.09 | 6.50 | 6.38 |
| 7 | 2.08 | 1.77 | 2.25 | 2.03 | 6.10 | 6.50 | 6.13 |
| 8 | 2.07 | 1.78 | 2.26 | 2.04 | 6.11 | 6.54 | 6.53 |
| 9 | 2.10 | 1.78 | 2.25 | 2.04 | 6.13 | 6.54 | 6.36 |
| 10 | 2.07 | 1.78 | 2.26 | 2.04 | 6.12 | 6.59 | 7.18 |
| Average | | | | | 6.11 | 6.53 | 6.44 |
| Coefficient of Variation (percent) | | | | | 0.28 | 0.43 | |

b) Results of Wraps

| Test | Load from Calibration System (kips) | | | | | Load from FWD | Difference[+] |
|---|---|---|---|---|---|---|---|
| No. | Load Cell 1 | Load Cell 2 | Load Cell 3 | Average | Total | (Kips) | (percent) |
| 1 | 2.11 | 1.76 | 2.22 | 2.03 | 6.10 | 6.46 | 5.70 |
| 2 | 2.08 | 1.78 | 2.28 | 2.05 | 6.14 | 6.50 | 5.61 |
| 3 | 2.06 | 1.78 | 2.29 | 2.04 | 6.13 | 6.50 | 5.81 |
| 4 | 2.11 | 1.80 | 2.28 | 2.06 | 6.19 | 6.55 | 5.56 |
| 5 | 2.10 | 1.82 | 2.28 | 2.07 | 6.20 | 6.59 | 5.99 |
| 6 | 2.05 | 1.79 | 2.30 | 2.05 | 6.14 | 6.56 | 6.45 |
| 7 | 2.09 | 1.81 | 2.25 | 2.05 | 6.15 | 6.53 | 5.81 |
| 8 | 2.06 | 1.79 | 2.28 | 2.04 | 6.13 | 6.56 | 6.52 |
| 9 | 2.08 | 1.79 | 2.25 | 2.04 | 6.11 | 6.51 | 6.14 |
| 10 | 2.06 | 1.80 | 2.29 | 2.05 | 6.16 | 6.55 | 6.04 |
| Average | | | | | 6.14 | 6.53 | 5.96 |
| Coefficient of Variation(percent) | | | | | 0.48 | 0.54 | |

[+] Difference= {Load from FWD - Load from Calibration System}*100/{Load from FWD} lowered after each drop.

In the following sections, the effects of parameters investigated on the loads measured are discussed.

#### 2.4.1.1 CONCRETE PAVEMENT

The effects of parameters such as the rotation of the loading plate on the total load obtained, drop height, use or lack of rubber padding are discussed in the following sections.

##### 2.4.1.1.1 ROTATION OF PLATE

The data obtained from the rotation of the loading plate is shown in Table 2.2 and Table 2.3 for the cases when the pad was placed and removed, respectively. Zero degree of rotation was arbitrary selected. To obtain data for 120 and 240 degrees of rotation, the plate was rotated twice clockwise.

The average values of load obtained for Drop Heights 1, 2, and 3 are 6.25, 8.70 and 10.96 kips respectively. For Drop Height 1 and at a 120 degree rotation, the load is 6.53 kips which is higher as compared to zero or 240 degree rotation. But it can be seen that the load obtained from the load cell of the FWD device is also higher. Therefore, the variation is due to the variation in load imparted by the FWD device.

In general, the coefficient of variation is within 1.5 percent except for the Drop Height 1 (without rubber padding). Therefore, the rotation of plate only slightly affects the total load obtained from the calibration system.

##### 2.4.1.1.2 COMPARISON OF TOTAL LOADS

The total loads obtained from the FWD device and the calibration system are shown in Table 2.4 for the case when no rubber padding was used under the aluminum plate. The total load obtained from the calibration system is always less than that of the FWD device. This difference may be due to the fact that the load cells from the calibration system are mounted at different places. The load cell of the FWD device seems to be mounted on a rigid frame. Therefore, it may not consider the interaction between the loading mechanism and the pavement. While the load measured by the calibration system considers this interaction. It can be seen from Table 2.5 that the difference between loads measured with the FWD and calibration system is less than 7 percent and it decreases as the drop height increases. The coefficient of variation is always less than 1 percent indicating repeatability of tests.

The data obtained from the FWD load cell and the calibration system are shown in Table 2.5 when rubber padding was used below aluminum plate. The load obtained from calibration system is always less than that of FWD device. The difference is at the most 14 percent and it also decreases with the increase in drop height. The coefficient of

Table 2.2 Average Load Obtained from three Load Cells of Calibration System (without rubber padding).

| Drop Height | Load, kips | | | | Coefficient of Variation (percent) |
|---|---|---|---|---|---|
| | Roation, degree* | | | Average | |
| | 0 | 120 | 240 | | |
| 1 | 6.11<br>(6.54) | 6.53<br>(7.00) | 6.12<br>(6.66) | 6.25<br>(6.73) | 3.84<br>(3.54) |
| 2 | 8.65<br>(9.29) | 8.76<br>(9.27) | 8.69<br>(9.15) | 8.7<br>(9.24) | 0.64<br>(0.82) |
| 3 | 10.89<br>(11.11) | 11.13<br>(11.88) | 10.86<br>(11.19) | 10.96<br>(11.39) | 1.35<br>(3.72) |

*Numbers in parantheses correspond to loads measured with the FWD.

Table 2.3 Average Load Obtained from Three Load cells of Calibration System (with Rubber Padding)

| Drop Height | Load, kips | | | | Coefficient of Variation (percent) |
|---|---|---|---|---|---|
| | Roation, degree* | | | Average | |
| | 0 | 120 | 240 | | |
| 1 | 5.99<br>(6.98) | 5.91<br>(6.751) | 6.09<br>(6.75) | 6.00<br>(6.83) | 1.5<br>(1.94) |
| 2 | 8.10<br>(9.20) | 8.33<br>(9.15) | 8.17<br>(8.98) | 8.2<br>(9.11) | 1.43<br>(1.27) |
| 3 | 10.41<br>(11.47) | 10.57<br>(11.44) | 9.87<br>(11.17) | 10.28<br>(11.36) | 0.37<br>(1.45) |

*Numbers in parantheses correspond to loads measured with the FWD.

Table 2.4 Average Load Values Obtained from Calibration System and FWD Device (without Rubber Padding)

| Drop Height | Average | | Difference (percent) | Coefficient of | |
|---|---|---|---|---|---|
| | C.S* | FWD | | C.S* | FWD |
| 1 | 6.11 | 6.54 | 6.44 | 0.28 | 0.43 |
| 2 | 8.65 | 9.29 | 6.86 | 0.84 | 0.55 |
| 3 | 10.89 | 11.11 | 2.04 | 0.41 | 0.3 |
| 4 | 15.88 | 16.00 | 0.77 | 0.55 | 0.82 |

* C.S indicates the Calibration System

Table 2.5 Average Load Values Obtained from Calibration System and FWD Device (with Rubber Padding)

| Drop Height | Average | | Difference (percent) | Coefficient of | |
|---|---|---|---|---|---|
| | C.S* | FWD | | C.S* | FWD |
| 1 | 5.99 | 6.98 | 14.17 | 1.18 | 1.24 |
| 2 | 8.10 | 9.20 | 12.05 | 0.99 | 0.35 |
| 3 | 10.41 | 11.47 | 9.36 | 1.87 | 0.80 |
| 4 | 14.85 | 16.43 | 9.60 | 0.94 | 0.54 |

* C.S indicates the Calibration System

variation for the load data is less than 2 percent. But it has also increased by 1 percent as compared to the loads obtained when no rubber padding was used.

It can be seen from Tables 2.4 and 2.5 that the use of the rubber padding significantly decreases the loads obtained from the calibration system and slightly affects the values obtained from FWD device. This matter implies that perhaps the load cell of the FWD device may not be located at a proper place because the loading mechanism pavement interaction is not included in the FWD load cell's readings.

### 2.4.1.1.3 DROP HEIGHT

The effect of the drop height for different conditions was also considered while comparing the loads obtained from calibration system and FWD device. It can be seen that as the drop height increases from 1 to 4 , the difference between the loads measured from the two devices decreases from 6.5 to 0.7 percent and 14.2 to 9.7 percent for without rubber padding and with rubber padding conditions, respectively. The coefficient of variation is below 1 percent and below 2 percent for without rubber padding and with rubber padding conditions, respectively. The rubber padding below the aluminum base plate increases the difference in loads to almost 8 percent and it also increases the coefficient of variations. The reasons for this matter was explained in Section 2.4.1.1.1.

### 2.4.1.1.4 EFFECT OF RUBBER PADDING

The use of rubber padding affects the rigidity of the system. The difference between loads measured with the FWD device and the calibration system always increases when the rubber padding was used as shown in Figure 2.3. In the Figure 2.3, the average loads measured with pad and without pad are compared. For the FWD device, the existence of the padding has a minimal effect on the load measured. However, for the calibration system, the installation of the padding results in a significant reduction in the measured loads. In order to investigate the causes of this loss of energy, the load-deformation characteristics of the load cell encased in the aluminum casing (see Figure 2.3) were determined with and without the pad. The load cell configuration was placed in an MTS device, loads were applied in increments of 500 lbs, and deformation corresponding to each load was registered. The two load-displacement curves are depicted in Figure 2.4.

The area under each curve at a given load and displacement is proportional to the strain energy stored (per unit volume) in the plate. The strain energy can be defined as:

$$E = \int_0^{\varepsilon} \sigma \, d\varepsilon \qquad (2.1)$$

where $\sigma$ and $\varepsilon$ are the applied stress and strain respectively. Equation 2.1 can be written in terms of load and displacement as:
where P and $\delta$ are the applied load and deformation, respectively. Symbols A and L denote area and length, respectively. As indicated before the area of the circular casing was 6.15 in$^2$. (diameter of 2.8 in.) and the length of the casing was 1 in. In order to

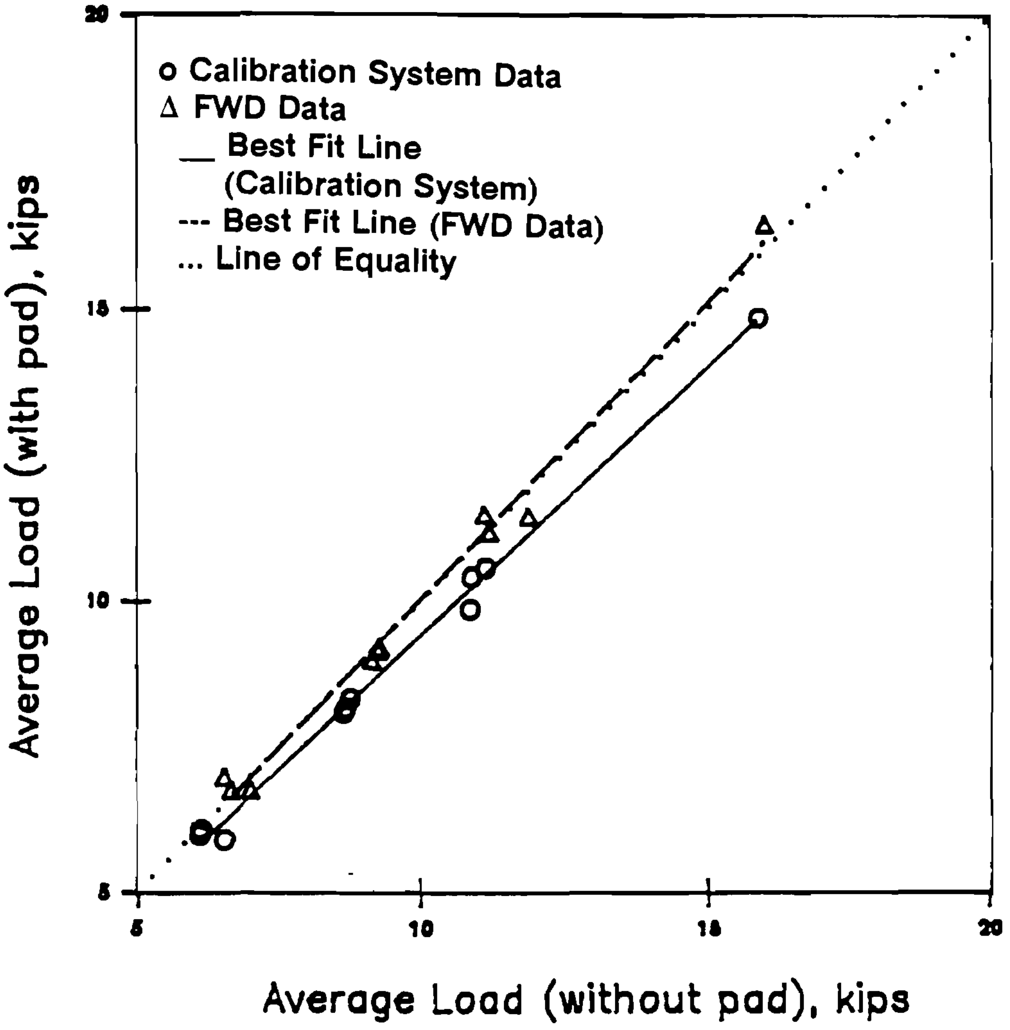


Figure 2.3 Comparison of Loads Obtained with and without Loading Pad

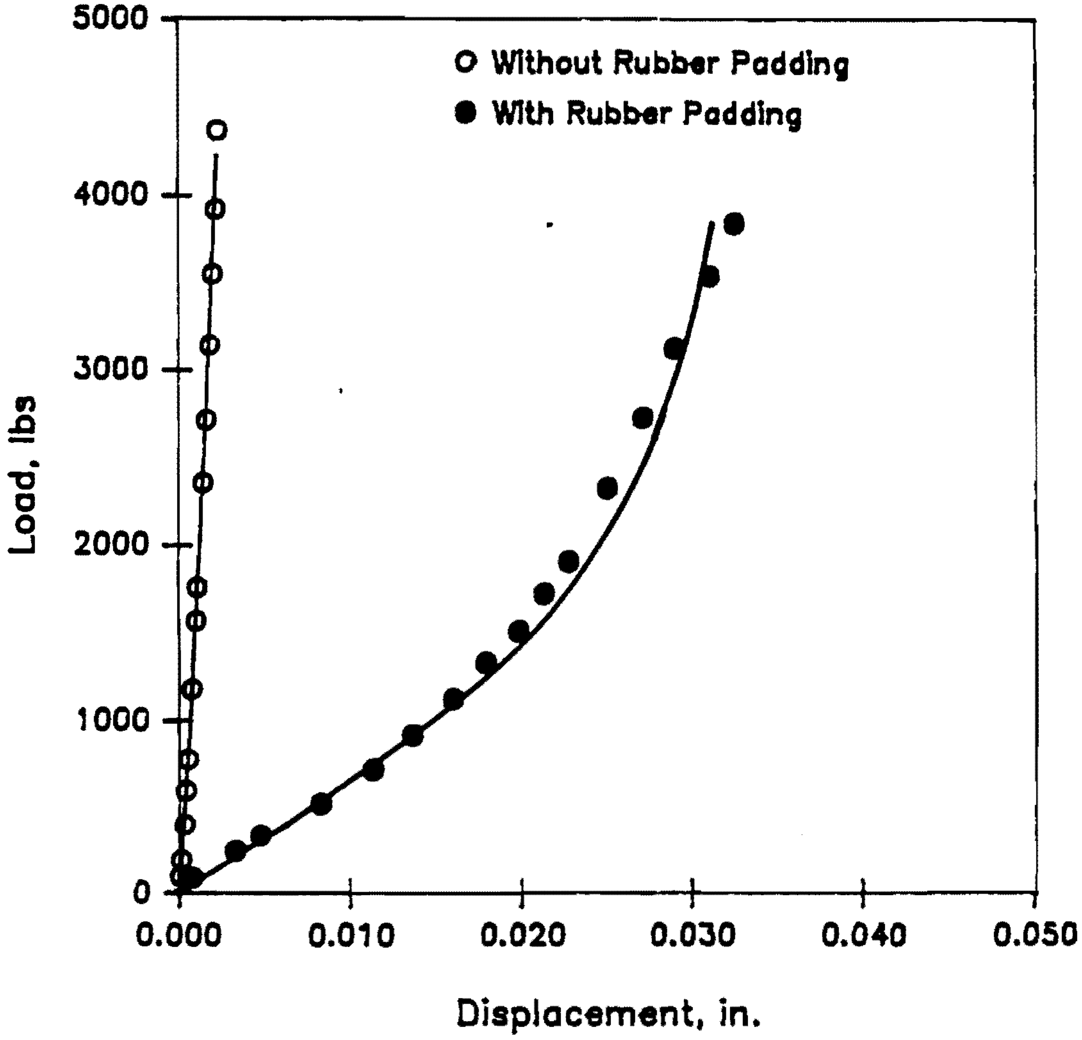


Figure 2.4 Comparison of Displacement Obtained for Different loads Applied (with and without Rubber Padding)

$$E - \frac{1}{AL}\int_0^{\delta} P\,d\delta \tag{2.2}$$

calculate the total energy absorbed in the plate, the value obtained from Equation 2.2 was multiplied the area and thickness of the FWD loading plate. Based upon this methodology, the loss of load due to the absorption of strain energy in the loading system was calculated. Shown in Figure 2.5 are the loss of applied load to the pavement as a function of load imparted by the FWD device for the cases when the padding was and was not utilized under the FWD loading pad. The difference between the curves, corresponding to the energy loss due to the padding, is included in the Figure 2.6. In Figure 2.5, the abscissa corresponds to the load per load cell. In order to determine the loss due to the FWD load, the abscissa was multiplied by a factor of 3 (3 load cells of calibration system). The ordinate of Figure 2.6 is simply the difference between the two curves in Figure 2.5 and corresponds to loss of energy due to installation of rubber padding. Also shown in the figure are the difference between loads measured with and without padding. The numbers obtained from this simplified theoretical exercise and those obtained from the actual field tests *(see Tables 2.5 and 2.6)* do not agree completely. However, the trends closely follow each other.

### 2.4.1.2 ASPHALT

For the asphalt pavement, the effect of rotation was not taken into consideration because of time limitations and because it was quite small for the concrete pavement (section 2.4.1.1.1). Only tests with Drop Heights 1 and 4 with and without rubber padding were carried out. The data collected are included in Appendix O and summarized in Table 2.6.

### 2.4.1.2.1 DROP HEIGHT

From Table 2.6, it can be seen that the difference between loads obtained from the calibration system and the FWD device decreases with the increase of drop height from 1 to 4. However, the effect of drop height is not as pronounced compared to the difference obtained on concrete. The differences are within 1 percent for change in drop height from 1 to 4 and are independent of the use of rubber padding. The coefficient of variation decreases with the increase in drop height with or without rubber padding. The coefficient of variation is always less than 0.5 percent for all cases (except 1).

### 2.4.1.2.2 RUBBER PADDING

The use of the rubber padding below the aluminum plate does not have as a significant effect on the calibration values as on concrete pavement. The loads obtained for the cases when the with rubber padding was used are lower than that when no rubber padding was used. For example, the total load obtained from calibration system was 6.29 and that of FWD was 6.73 when no rubber padding was used. However, when the rubber padding was used, the total load obtained from the calibration system was 6.15 and that of FWD was 6.64. The coefficient of variation is always less than 0.5 percent for all cases.

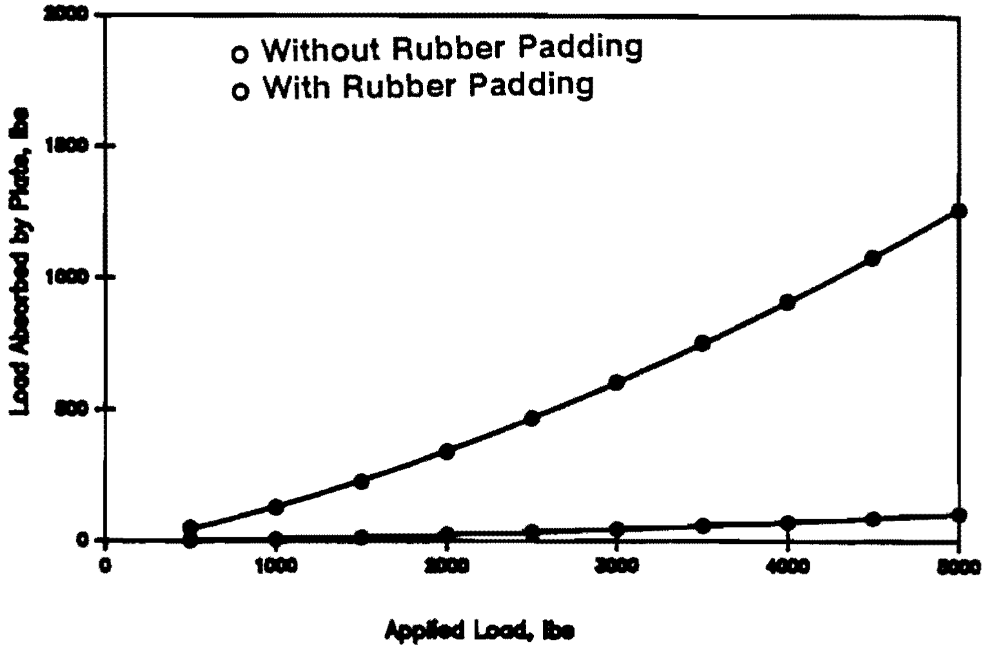


Figure 2.5 Estimation of Loss of Load Due to Rubber padding

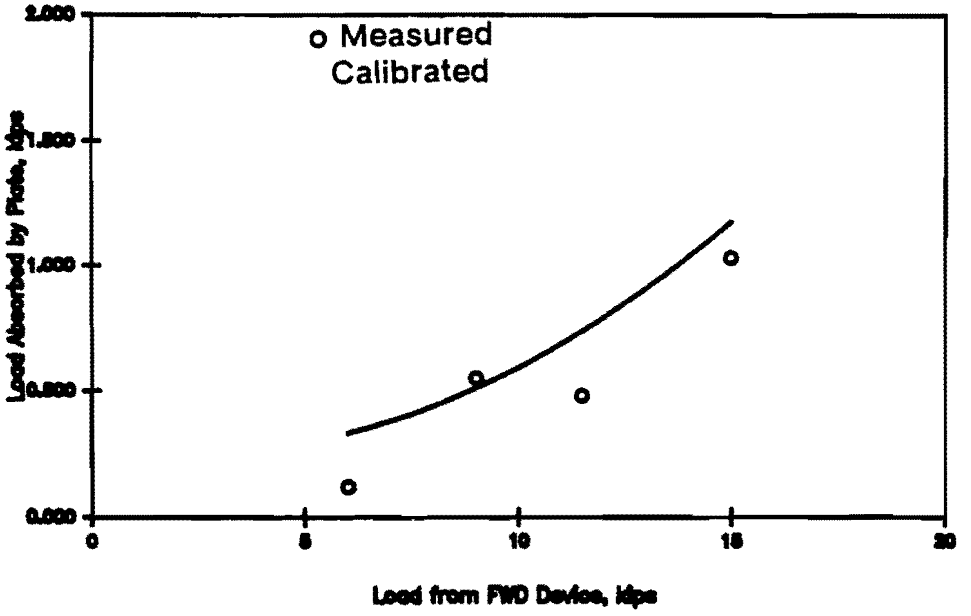


Figure 2.6 Comparison of Theoretical and Measured Load Due to Installation of Rubber Padding

**Table 2.6** Comparison of Loads Obtained from the FWD and Calibration System on Asphalt System

a) From Repetitions

| Drop Height | Padding | Load, kips | | Difference (percent) | Coefficient of Variation (percent) | |
|---|---|---|---|---|---|---|
| | | C.S* | FWD | | C.S* | FWD |
| 1 | No | 6.29 | 6.73 | 6.6 | 0.46 | 0.52 |
| 4 | No | 15.00 | 15.85 | 5.4 | 0.29 | 0.27 |
| 1 | Yes | 6.15 | 6.64 | 7.3 | 0.49 | 0.37 |
| 4 | Yes | 14.56 | 15.59 | 6.7 | 0.32 | 0.27 |

b) From Wraps

| Drop Height | Padding | Load, kips | | Difference (percent) | Coefficient of Variation (percent) | |
|---|---|---|---|---|---|---|
| | | C.S* | FWD | | C.S* | FWD |
| 1 | No | 6.32 | 6.76 | 6.6 | 0.38 | 0.43 |
| 4 | No | 14.95 | 15.80 | 5.4 | 0.41 | 0.46 |
| 1 | Yes | 6.16 | 6.60 | 6.8 | 0.93 | 1.04 |
| 4 | Yes | 14.71 | 15.58 | 5.4 | 0.54 | 3.41 |

It can be concluded that the effect of using rubber padding below aluminum plate on asphaltic section is small. This matter requires further study.

### 2.4.1.3 CONCRETE PAVEMENT VS ASPHALT PAVEMENT

The FWD and calibration system show the same trends for both materials. For example, with the increase in drop height the difference in loads measured with the two systems decreases. However, the decrease in differences is not as significant for the asphalt section compared to the concrete section.

The concrete pavements show the effect of rubber padding below the aluminum plate. The use of rubber padding increases the difference in loads measured with the two systems. However, the effect is not as significant for the case of asphalt as compared to concrete. Therefore, it can be concluded that for the concrete pavements the effect of rubber padding is significantly higher than for asphalt material.

### 2.4.2 DEFLECTION MEASUREMENT

The parameter considered for evaluation of the sensors of the FWD device is discussed in the next section. The data collected is included in Appendix P. Deflection measurement, were carried out only on the asphalt section and the basic parameter considered was the drop height. An example of testing sequence is shown in Table 2.7.

As indicated before, first the two well-calibrated geophones were placed on the pavement very close to the FWD sensors. Deflections from the FWD device and the calibration system were then compared. The results of this experiment are shown in Table 2.7a. In the table, deflections obtained from FWD and calibration system sensors are included. For each drop, the difference between the deflections obtained from the calibration system and the FWD is included in the adjacent column. The averages and the coefficient of variations for the ten drops were calculated and reported in the table as well. These values are used in the evaluation of the device (next section) and for calibration adjustments (Chapter Three) for the FWD. In Table 2.7b, similar information is furnished but for the case when the loading plate was raised and lowered after each test.

Table 2.8 contains deflections obtained for Sensors 2 through 7 of the FWD device for Drop Heights 1 through 4, respectively. Included in these tables are values obtained from the FWD and calibration system. For each sensor, the difference between deflections obtained from the two systems is also included. The difference between deflections obtained from the two systems for Sensor 2 is around 10 percent except for Drop Height of 3 where the difference is about 3 percent.

For Sensors 3 through 7, the difference between deflections varies from a minimum of less than 1 percent to more than 15 percent. However, for a variation of 15 percent the absolute difference between deflections is within background noise level. In general, the differences are within 3 to 4 percent. Both systems are quite precise. The coefficient of variation is about 1 percent with the extreme case where the coefficient of variation is

**Table 2.7** Comparison of Deflections Obtained with Calibration System and FWD Device

a) Results of Repetitions

| | Sensor 3 | | | Sensor 2 | | |
|---|---|---|---|---|---|---|
| Test | Deflection (mils) | | Difference[+] | Deflection (mils) | | Difference[+] |
| No. | Calibration | FWD | (percent) | Calibration | FWD | (percent) |
| 1 | 4.35 | 4.50 | -3.33 | 10.56 | 11.86 | -10.96 |
| 2 | 4.37 | 4.42 | -1.13 | 10.57 | 11.78 | -10.27 |
| 3 | 4.37 | 4.46 | -2.02 | 10.57 | 11.82 | -10.58 |
| 4 | 4.37 | 4.50 | -2.89 | 10.60 | 11.86 | -10.62 |
| 5 | 4.40 | 4.46 | -1.35 | 10.60 | 11.82 | -10.32 |
| 6 | 4.39 | 4.46 | -1.57 | 10.60 | 11.82 | -10.32 |
| 7 | 4.36 | 4.46 | -2.24 | 10.48 | 11.74 | -10.73 |
| 8 | 4.36 | 4.46 | -2.24 | 10.57 | 11.74 | -9.97 |
| 9 | 4.38 | 4.46 | -1.79 | 10.60 | 11.82 | -10.32 |
| 10 | 4.38 | 4.50 | -2.67 | 10.57 | 11.82 | -10.58 |
| AVG[*] | 4.37 | 4.46 | -2.12 | 10.57 | 11.81 | -10.46 |
| COF[#] | 0.32 | 0.54 | | 0.32 | 0.34 | |

b) Results of Wraps

| | Sensor 3 | | | Sensor 2 | | |
|---|---|---|---|---|---|---|
| Test | Deflection (mils) | | Difference[+] | Deflection (mils) | | Difference[+] |
| No. | Calibration | FWD | (percent) | Calibration | FWD | (percent) |
| 1 | 4.38 | 4.46 | -1.79 | 10.56 | 11.74 | -10.05 |
| 2 | 4.34 | 4.46 | -2.69 | 10.54 | 11.70 | -9.91 |
| 3 | 4.38 | 4.50 | -2.67 | 10.65 | 11.74 | -9.28 |
| 4 | 4.40 | 4.54 | -3.08 | 10.65 | 11.86 | -10.20 |
| 5 | 4.41 | 4.50 | -2.00 | 10.71 | 11.78 | -9.08 |
| 6 | 4.40 | 4.50 | -2.22 | 10.70 | 11.78 | -9.17 |
| 7 | 4.40 | 4.50 | -2.22 | 10.63 | 11.74 | -9.45 |
| 8 | 4.35 | 4.46 | -2.47 | 10.61 | 11.74 | -9.63 |
| 9 | 4.38 | 4.50 | -2.67 | 10.71 | 11.78 | -9.08 |
| 10 | 4.36 | 4.46 | -2.24 | 10.55 | 11.74 | -10.14 |
| AVG[*] | 4.38 | 4.49 | -2.12 | 10.63 | 11.76 | -9.60 |
| COF[#] | 0.51 | 0.57 | | 0.58 | 0.35 | |

[+] Difference={Calibration System Geophone - FWD Geophone}*100/{FWD Geophone}

[#] COF : Coefficient of Variation (percent)

[*] AVG : Average

**Table 2.8** Average Deflection Obtained from Calibration System and FWD device.

a) Drop Height of 1

| Geophone No. | Avearge Deflection, mils | | Difference (percent) | Coefficient of Variation (percent) | |
|---|---|---|---|---|---|
| | C.S* | FWD | | C.S* | FWD |
| 2 | 10.57 | 11.81 | -10.46 | 0.32 | 0.34 |
| 3 | 4.37 | 4.47 | -2.12 | 0.32 | 0.54 |
| 4 | 2.44 | 2.57 | -4.98 | 0.68 | 0.70 |
| 5 | 1.82 | 1.85 | -1.66 | 0.76 | 1.45 |
| 6 | 1.35 | 1.4 | -3.84 | 0.45 | 1.14 |
| 7 | 1.17 | 1.18 | -1.42 | 0.79 | 1.55 |

* C.S indicates the Calibration System

b) Drop Height of 2

| Geophone No. | Avearge Deflection, mils | | Difference (percent) | Coefficient of Variation (percent) | |
|---|---|---|---|---|---|
| | C.S* | FWD | | C.S* | FWD |
| 2 | 18.30 | 20.09 | -8.92 | 0.44 | 0.38 |
| 3 | 6.45 | 6.44 | -.06 | 0.60 | 0.50 |
| 4 | 3.53 | 3.74 | -5.8 | 0.93 | 0.64 |
| 5 | 2.45 | 2.51 | -2.46 | 0.77 | 1.02 |
| 6 | 1.91 | 1.99 | -4.06 | 1.37 | 1.35 |
| 7 | 1.40 | 1.64 | -15.03 | 3.09 | 1.02 |

* C.S indicates the Calibration System

Table 2.8 Cont'd. Average Deflection Obtained from Calibration System and FWD device.

c) Drop Height of 3

| Geophone No. | Avearge Deflection, mils | | Difference (percent) | Coefficient of Variation (percent) | |
|---|---|---|---|---|---|
| | C.S* | FWD | | C.S* | FWD |
| 2 | 18.48 | 18.97 | -2.60 | 0.16 | 0.21 |
| 3 | 7.73 | 7.64 | 1.20 | 0.23 | 0.21 |
| 4 | 4.40 | 4.52 | -2.61 | 0.28 | 0.44 |
| 5 | 3.13 | 3.18 | 1.37 | 0.35 | 0.91 |
| 6 | 2.40 | 2.45 | 2.24 | 0.38 | 0.00 |
| 7 | 2.07 | 2.09 | 1.05 | 0.36 | 0.00 |

*C.S indicates Calibartion System

d) Drop Height of 4

| Geophone No. | Avearge Deflection, mils | | Difference (percent) | Coefficient of Variation (percent) | |
|---|---|---|---|---|---|
| | C.S* | FWD | | C.S* | FWD |
| 2 | 27.06 | 30.60 | -11.57 | 0.14 | 0.16 |
| 3 | 11.94 | 12.23 | -2.382 | 1.87 | 0.23 |
| 4 | 6.59 | 6.87 | -4.16 | 0.11 | 0.17 |
| 5 | 4.54 | 4.68 | 3.01 | 0.17 | 0.42 |
| 6 | 3.77 | 3.53 | -6.45 | 0.28 | 0.45 |
| 7 | 2.77 | 2.89 | -4.09 | 0.22 | 0.42 |

*C.S indicates Calibartion System

about 3 percent.

To analyze the effect of variation in loads on the variation in deflections, the measured deflections were normalized. For normalization, the average load obtained from the ten drops was calculated. For each drop, the deflection obtained from both devices was then multiplied by the average load calculated and divided by the load obtained for that particular drop. The load used to normalize the displacement was the load measured with the calibration system. The normalized deflection obtained from this method is shown in Table 2.9. Upon comparison of Tables 2.8 one can conclude that the variability in the deflection cannot be described by the variability in the load. As a matter of fact, in most cases, the coefficient of variation increases as the deflections are normalized. Therefore, the variation in deflections from successive drops is inherent in the deflection data and is not due to variation in the drop height.

Table 2.9 Normalized Deflection Obtained from Calibration System and FWD Device, for Drop Height 2.

| Geophone No. | Normalized Deflection, mils | | Difference (percent) | Coefficient of Variation (percent) | |
|---|---|---|---|---|---|
| | C.S* | FWD | | C.S* | FWD |
| 2 | 18.29 | 20.08 | 8.90 | 0.68 | 0.53 |
| 3 | 6.45 | 6.44 | 0.16 | 0.53 | 0.60 |
| 4 | 3.58 | 3.79 | 5.54 | 1.63 | 1.76 |
| 5 | 2.49 | 2.55 | 2.35 | 1.44 | 2.10 |
| 6 | 1.88 | 1.97 | 4.57 | 1.70 | 1.40 |
| 7 | 1.38 | 1.63 | 15.33 | 3.09 | 0.97 |

* C.S indicates the Calibration System

# CHAPTER THREE

# RECOMMENDED CALIBRATION PROCESS

## 3.1 INTRODUCTION

Based upon, the evaluation process discussed in Chapter Two, and utilizing the set up discussed in Chapter One, a calibration process is recommended herein. The recommended process is clarified through an illustrative example employing the data presented in Chapter Two and Appendices O & P.

## 3.2 LOAD CALIBRATION

The recommended process for calibrating the FWD load cell is as follows. Firstly, an appropriate site should be identified. The site should consist of a thick rigid pavement section. The thickness of concrete in excess of 18 in. is recommended. Also, the site should be reasonably flat. Based upon results presented in Chapter Two, an asphaltic pavement section is not appropriate for load calibration.

Secondly, the PVC loading plate of the FWD should be replaced by the aluminum plate encasing the calibration load cells. The use of a rubber padding between the loading plate and the pavement is not recommended because the pad will absorb part of the energy imparted by the drop weight to the FWD system. As indicated before, the effect of rotating the plate is minimal and the load cells can be placed in any arbitrary position.

The drop weight should be dropped at a minimum ten times and loads registered by the FWD device and the calibration system should be registered after each drop. The average standard deviation and the coefficient of variation of all drops should be calculated from the results obtained from the FWD and the calibration system. A student's test on the two samples (i.e. the FWD and calibration system loads) should be carried out to determine whether the two means are statistically different. This process should be repeated for four different drop heights. The drop heights should be selected so that the range of loads of interest in the pavement evaluation is covered.

In the next step, the data from the four drop heights should be plotted using the FWD loads as the dependent and the calibration system loads as independent variables. A linear regression process should then follow to determine the least-square best-fit regression line through the data. The upper and lower bounds corresponding to a degree of confidence level of 95 percent should be included on the same plot also. Should the 95 percent interval confidence level enclose the line of equality, no action should be taken. Otherwise, the calibration of the sensors should be adjusted.

This process should be carried out in two phases. In the first phase, the loading pad is seated on the pavement and is not removed between drops (designated as a repetition). In the second phase, the load pad is removed and placed after each drop (designated as a wrap). In this manner, the effects of loading mechanism on the calibration of the load cell can be determined.

Should the coefficient of variation measured with a sensor be larger than 4 percent, the calibration process should be terminated. In this case, possibly some other factors such as mounting mechanism or bad electric connection are interfering with the proper behavior of the sensors.

## 3.3 DEFLECTION CALIBRATION

The calibration process to be followed for the deflection sensors is similar to that of the loads. An appropriate site for calibrating the FWD sensors is a flexible pavement site. It is recommended that for the sensors close to the loading plate, deflections in excess of 25 mils should be considered. Tests on concrete sites are not recommended because of small values of deflections measured on rigid pavements.

The well-calibrated geophones are placed close to the FWD sensors. Also the load cells are connected as well. The drop weight is dropped and the deflections are measured with both the FWD and the calibration system. The load imparted to the pavement is measured with the calibration system also. The measured loads are used to normalize the deflection as described in Chapter Two. This process is repeated ten times at a minimum. The average, standard deviation and the coefficient of variation of deflections measured with the two devices and the load measured with the calibration system are calculated. Deflection are normalized following the procedure described in Chapter Two. A student's t test on the two samples should then be carried out to ensure that the means of the two samples are statistically the same.

This process is repeated for four representative drop heights. The results from the four drop heights are plotted. The dependent variable will be the deflections measured with the FWD and the independent one will be the deflections measured with the calibration system. The least-square best-fit line as well as the upper and lower bounds of a 95 percent confidence interval should be plotted. Should the line of equality be enclosed within the lines of a 95 percent confidence interval no change is necessary. Otherwise, the calibration values should be revised.

Should the coefficient of variation measured with a sensor be larger than 4 percent, the calibration process should be terminated. In this case, possibly some other factors such as mounting mechanism or bad electric connection are interfering with the proper behavior of the sensors.

## 3.4 CALIBRATION EXAMPLE

An illustrative example is included herein to clarify different steps involved in the calibration of an FWD. The data used in this example were collected with an FWD device and is presented in Appendix P and summarized in Chapter Two.

Shown in Figure 3.1 is a calibration curve for the load cell of a FWD device. In the figure,

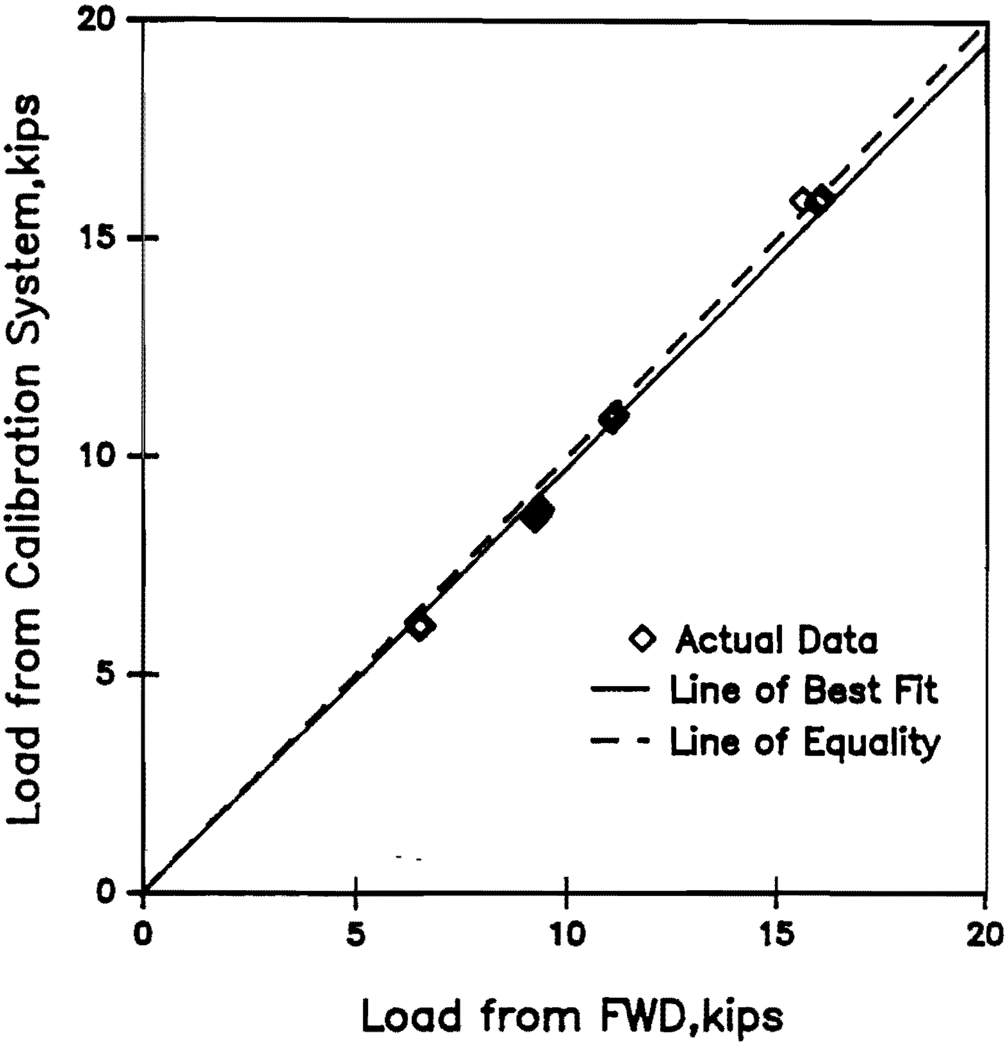


Figure 3.1 Calibration Curve for the FWD Load Cell

40 data points corresponding to the 10 drops per drop height are included. The data is clustered in four groups corresponding to the four drop heights used. Shown in the Figure 3.1 is the best-fit line and the line of equality. The two lines are quite close to one another indicating the closeness of the calibration value to unity. In actuality, the slope of the line (the calibration value) is equal to 0.97.

The upper and lower bound of the data corresponding to a confidence interval of 95 percent and the line of equality is shown in Figure 3.2. Based on this figure, the correction of the calibration value is necessary.

Shown in Figure 3.3 is the calibration curve for Deflection Sensor 2. As for the case of the load cell data, the data is clustered in three groups. The best-fit line and the line of equality are also shown in the figure. The best-fit line, line of equality and upper and lower bounds of the 95 percent confidence interval are included in Figure 3.4. Obviously, a significant difference exists between the two sensors. There is no doubt that the calibration of this sensor should be revised.

The calibration factors from all sensors are summarized in Table 3.1. The calibration factors for both the wraps and repetitions are included. It can be seen that the effect of removing the loading pad after each drop on the calibration factors is quite small.

For each drop height and each sensor, the student's t distribution (William, 1989) was utilized to determine whether the means obtained from the calibration system and the FWD device are significantly different. The results are presented in Table 3.2. To obtain the values reported in Table 3.2, the null hypothesis selected was that the means of the two processes are from the same population. The alternative hypothesis was that the means of the two systems are not from the same population. A computer software named STATPLAN III ( Version 1.4, 1987) was used to calculate the t scores and to analyze the hypothesis.

In all cases, the two means are significantly different. The reason, for this matter can be that both systems are quite precise (i.e. the standard deviations are quite small).

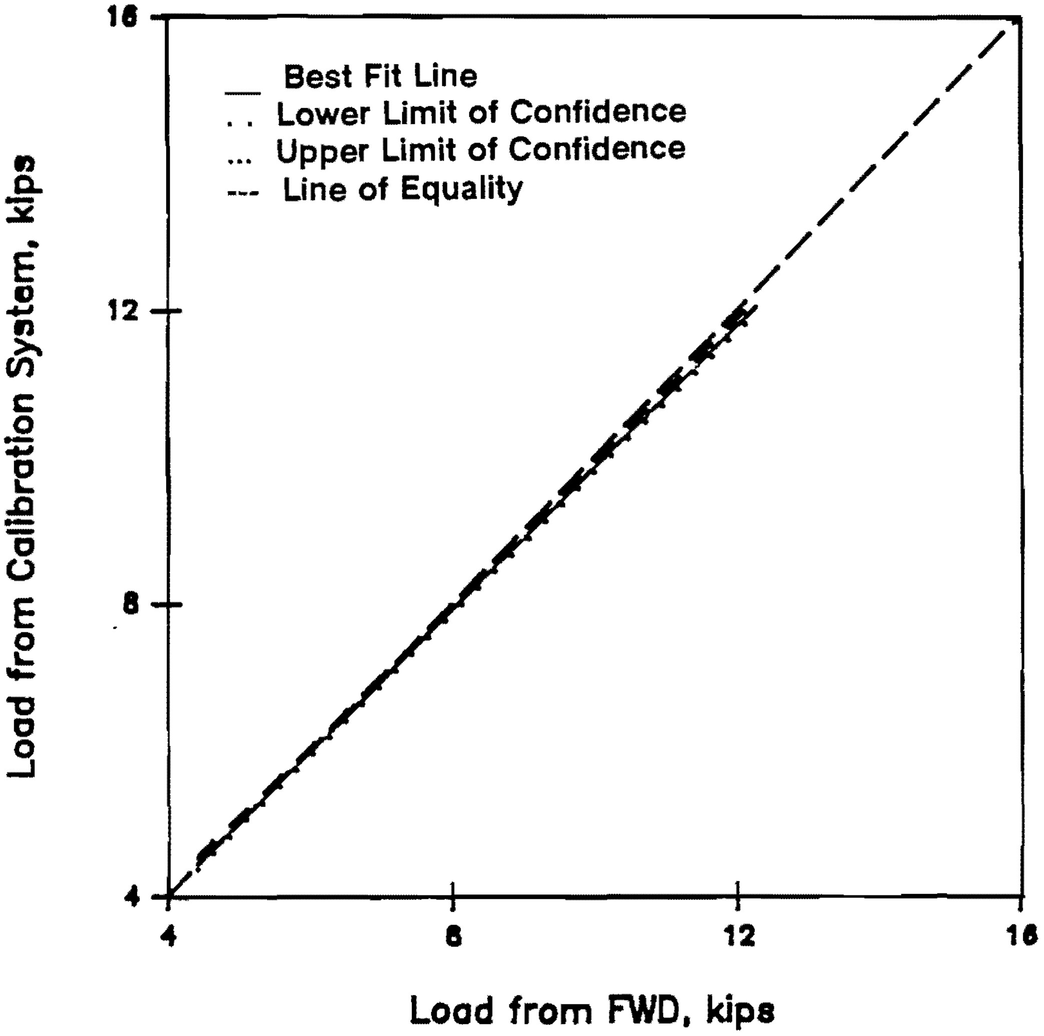


Figure 3.2 95 Percent Confidence Interval Obtained from Load Measurements

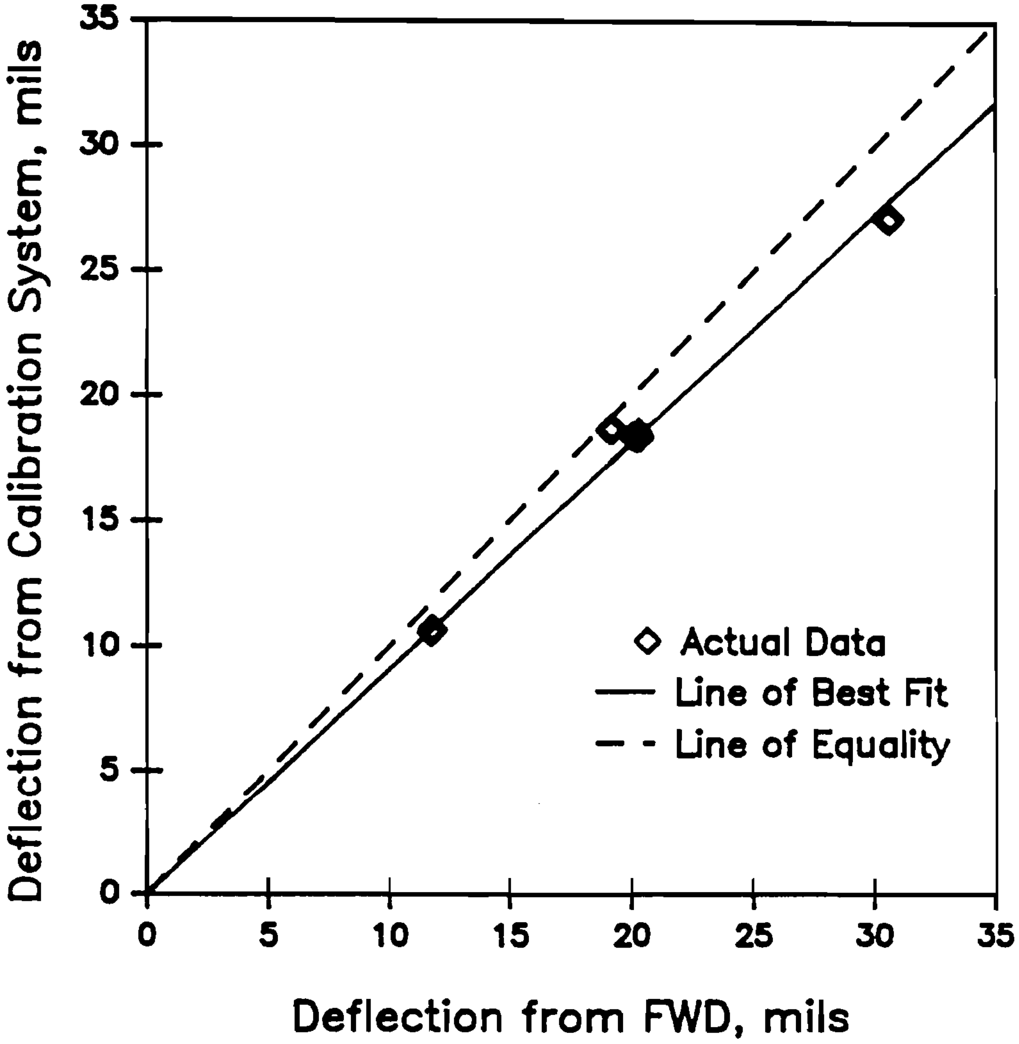


Figure 3.3 Calibration Curve for Sensor 2 of FWD

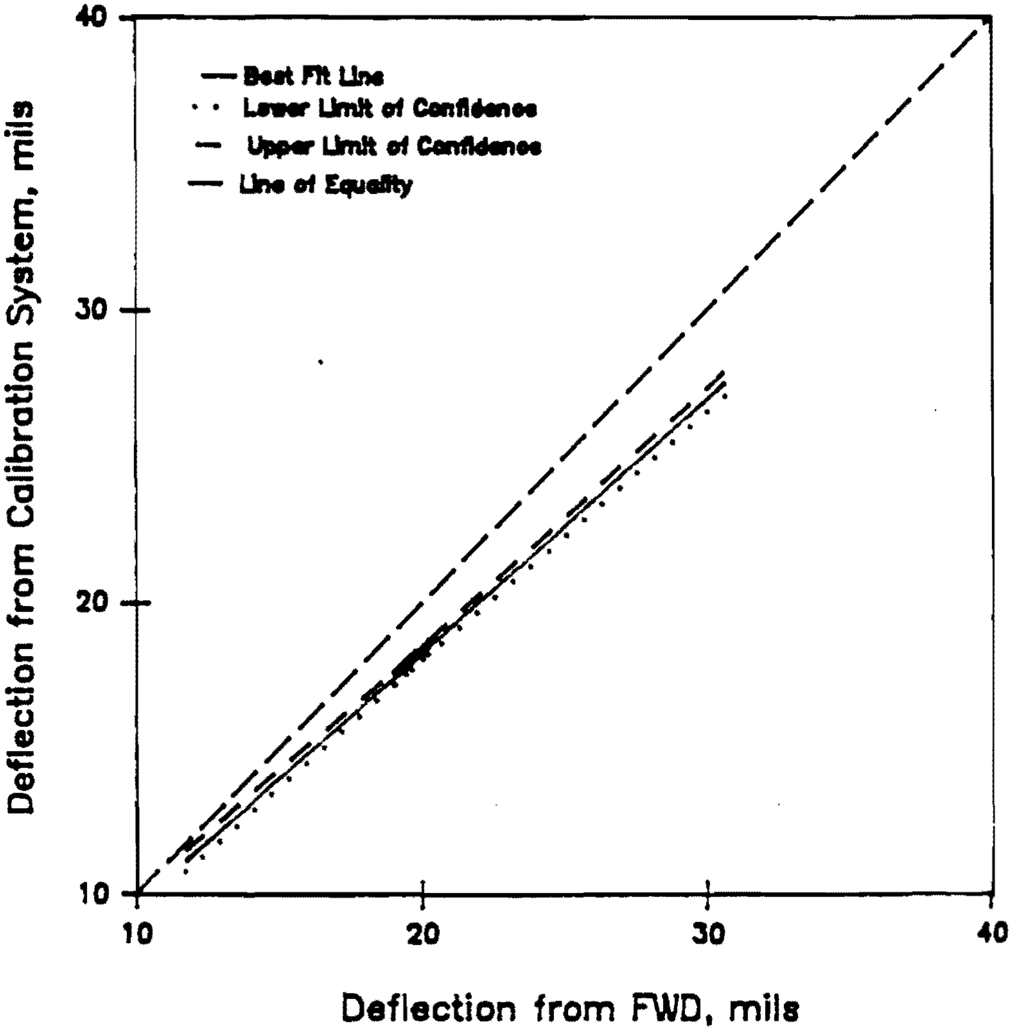


Figure 3.4 95 Percent Confidence Interval for Sensor 2

Table 3.1 Calibration Factors For FWD Sensors

| Sensor | Calibration Factor | |
|---|---|---|
| | Repetition | Wraps |
| Load Cell | 0.97 | 0.97 |
| Geophone 2 | 0.91 | 0.91 |
| Geophone 3 | 0.99 | 0.99 |
| Geophone 4 | 0.96 | 0.96 |
| Geophone 5 | 0.98 | 0.98 |
| Geophone 6 | 0.95 | 0.95 |
| Geophone 7 | 0.95 | 0.95 |

Table 3.2 Probability Analysis of Data Collected with the FWD and Calibration System

a) Load Cell

| Drop Height | Probability | Degree of | t score |
|---|---|---|---|
| 1 | 1.00 | 18 | -38.20 |
| 2 | 1.00 | 18 | -21.51 |
| 3 | 1.00 | 18 | -12.1 |
| 4 | 0.97 | 18 | -2.41 |

b) Geophone 2

| Drop Height | Probability | Degree of Freedom | t score |
|---|---|---|---|
| 1 | 1.00 | 18 | -70.17 |
| 2 | 1.00 | 18 | -48.40 |
| 3 | 1.00 | 18 | -29.50 |
| 4 | 1.00 | 18 | -174.62 |

c) Geophone 3

| Drop Height | Probability | Degree of Freedom | t score |
|---|---|---|---|
| 1 | 1.00 | 18 | -10.22 |
| 2 | 0.19 | 18 | -0.24 |
| 3 | 1.00 | 18 | -11.56 |
| 4 | 0.99 | 18 | -3.88 |

**Table 3.2 Cont'd.** Probability Analysis of Data Collected with the FWD and Calibration System

d) Geophone 4

| Drop Height | Probability | Degree of Freedom | t score |
|---|---|---|---|
| 1 | 1.00 | 18 | -15.73 |
| 2 | 1.00 | 18 | -16.07 |
| 3 | 1.00 | 18 | -15.01 |
| 4 | 1.00 | 18 | -60.67 |

e) Geophone 5

| Drop Height | Probability | Degree of Freedom | t score |
|---|---|---|---|
| 1 | 0.99 | 18 | -3.08 |
| 2 | 1.00 | 18 | -5.84 |
| 3 | 1.00 | 18 | -4.26 |
| 4 | 1.00 | 18 | -20.05 |

f) Geophone 6

| Drop Height | Probability | Degree of Freedom | t score |
|---|---|---|---|
| 1 | 1.00 | 18 | -9.48 |
| 2 | 1.00 | 18 | -6.52 |
| 3 | 1.00 | 18 | -17.90 |
| 4 | 1.00 | 18 | -37.10 |

Table 3.2 Cont'd. Probability Analysis of Data Collected with the FWD and Calibration System

g) Geophone 7

| Drop Height | Probability | Degree of Freedom | t score |
|---|---|---|---|
| 1 | 0.97 | 18 | -2.49 |
| 2 | 1.00 | 18 | -16.0 |
| 3 | 1.00 | 18 | -8.82 |
| 4 | 1.00 | 18 | -26.39 |

# CHAPTER FOUR

# CONCLUSIONS

A system is developed for the absolute calibration of the FWD and Dynaflect devices. The calibration system consists of two well-calibrated geophones and three load cells with calibration constants traceable to the National Bureau of Standards. A Signal Conditioning Unit (SCU) is also developed for preconditioning of the signals. The SCU consists of anti-alising filters and a triggering mechanism. For collection and reduction of data a computer algorithm is coded.

The calibration of the FWD device can be done by using the calibration system. For each drop height, the data is collected from the load cells and geophones. The collected data is reduced to obtain the deflections and loads. A calibration factor is developed on the basis of linear regression between data collected by the calibration system and those reported by the FWD device.

Based upon field and laboratory investigations, the following conclusions are drawn:

1) The calibration of all the FWD devices used by the highway agencies is necessary.
2) Geophones are viable sensors for use in the calibration.
3) For the calibration of load cell a concrete overlay should be used while the deflection sensors should be calibrated on an asphalt section.
4) Rubber padding should not be used under the aluminum loading plate during testing.
5) Tests should be carried out for each drop height and the weight should be dropped at least ten times.