# Development of an Absolute Calibration System for Nondestructive Testing Devices

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Many highway agencies use falling weight deflectometers (FWDs) for pavement evaluation. The primary function of the FWD is to measure a deflection basin due to a load imparted to the pavement. Deflection basins measured in the field are used to back-calculate modulus profiles of pavement sections. Accurate determination of deflection basins in the field is critical. Velocity transducers (geophones) are used to determine the deflections, and load cells are used to measure the applied loads. The accuracy of deflections and loads obtained from these devices is of much concern, and a system is needed to calibrate them. A recently developed absolute calibration system is described. The system consists of two well-calibrated geophones, three load cells, a signal-conditioning unit, a loading plate, an analog-to-digital (A/D) board, and a computer. Software was developed to control the A/D board and to reduce the data. Geophones were selected for the calibration of the FWD sensors after an evaluation of the accuracy and precision of five candidate sensors. An aluminum loading plate was constructed to allow mounting of the load cells in line with and below the FWD load cell. The calibration curves of all load cells were traceable to the National Bureau of Standards. The effects on the calibration factors of load cells of using the aluminum plate were small. The signal-conditioning unit was developed to condition the signals before acquisition. The system was used to calibrate an FWD device. The system was effective. A calibration process is proposed on the basis of an analysis of the data collected. The calibration system is cost-effective, accurate, and rugged, and it can be used by highway agencies to calibrate their FWD devices.

It has become increasingly important in recent years to evaluate the performance of deflection and load sensors of falling weight deflectometer (FWD) devices. A small error in deflections measured in the field may yield significantly erroneous modulus values (*1*). A reliable method for evaluating the accuracy of the sensors used for determining these deflections is necessary. An absolute calibration system is required for this purpose.

An absolute calibration consists of determining the accuracy with which the deflections and loads are measured by using an independent system. Such a system has been proposed by Richter and Irwin (*2*). At a minimum, the following criteria should be met: (*a*) the calibration of the load and deflection sensors should be traceable to the National Bureau of Standards, and (*b*) all sensors should be calibrated in place. In this manner, the decoupling of the loading and sensing mechanisms and the coupling of the sensing mechanism to the pavement can be verified. The device recommended by Richter and Irwin provided a good start, but it does not satisfy the two criteria. Low cost and portability are other desirable characteristics.

The development of an absolute calibration system and the procedure used to calibrate an FWD device are described. To identify the most accurate and practical sensors for the system, five commercially available sensors were investigated. Different types of motion were used to compare the performance of each sensor. The evaluation procedures, selection criteria, and recommendations regarding the most suitable sensor type are included.

The selected sensors were used to develop an absolute calibration system. The components of the calibration system are described in detail. A computer algorithm developed to collect and reduce the data obtained from the sensors is also described.

The data obtained from the calibration system were compared and analyzed with the data obtained simultaneously from an FWD device. The effects of different parameters, such as drop height and pavement type, on the deflections and loads obtained from both devices are discussed. On the basis of an evaluation of the data collected with the calibration system and the FWD device, a calibration process is proposed.

## SELECTION OF SENSORS

The calibration system consists of several deflection sensors and load cells. The selection of proper sensors for each of the components was critical. Five deflection-measuring devices were evaluated, including an accelerometer, a linear variable differential transformer (LVDT), a proximeter probe, a laser optocator, and a geophone. These devices were selected because of their commercial availability and their effectiveness in deflection measurement (*3*).

Sensor characteristics considered in the evaluation were accuracy, precision, field worthiness, cost, and mounting. Amplitude of vibration, type of excitation, and frequency content of vibration were studied over a wide range to evaluate fully the five candidates. Tests were carried out in the laboratory so these variables could more closely be controlled. The setup used for the evaluation of accuracy and precision of each sensor type is shown in Figure 1.

A detailed account of the testing procedure and results is given by Tandon (*3*). In summary, the amplitude of vibration

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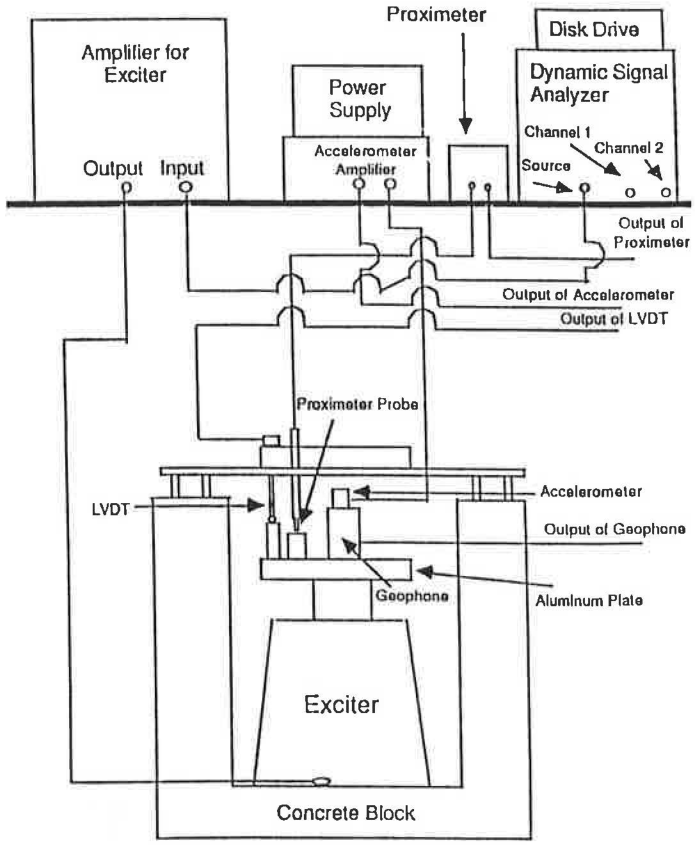


**FIGURE 1 Schematic of setup used for evaluation of five sensors.**

varied between 1 and 25 mils. Such a broad range was studied to ensure proper response of the sensors to small as well as large amplitudes. Different types of excitation were investigated to determine the appropriateness of each sensor type for use in calibrating the various types of nondestructive testing devices. Types of excitation included impulse (transient) motions and steady-state vibrations. Three type of impulses—half-sine, triangular, and square—were used. For the impulse tests, the duration impulse varied between 12.5 and 175 msec to cover the frequency ranges of interest in nondestructive testing methods. For the steady-state tests, the frequency of vibration varied between 5 and 100 Hz.

The accuracy of the sensor types was determined by comparing deflections measured with each device against those measured with a proximeter probe (Figures 2b and 3b). The proximeter is an accurate and precise deflection-measuring device in the laboratory because of its noncontact nature.

As an example, data obtained from a geophone and an LVDT under half-sine impulse motion are shown in Figures 2 and 3, respectively. The LVDT used was similar to that suggested by Richter and Irwin (*2*). The variances as a function of impulse width and deflection level are shown in Figures 2a and 3a. Each experiment was repeated 10 times to determine the variances. In all but a few cases, the variance was less than 0.5 percent, and it never exceeded 1.5 percent. Such a small variation can be attributed to background noise. The accuracy of geophones under steady-state motion, compared with the proximeter, is typically within 2.5 percent.

The advantages and disadvantages of all the sensors and their direct and indirect costs are given in Table 1, which indicates that geophones are the most practical of the sensors evaluated. They are rugged enough for the field testing, cost less than other sensors, and do not need a special type of mounting fixture because they can be attached to the pavement with the help of modeling clay. Tests indicate that the use of clay does not affect the response of the geophone in the frequency range of interest for FWD testing. No post- or preamplification or signal conditioning is needed for collection of data, resulting in large cost savings. The cost of calibration of each device is approximately the same.

The load-measuring sensor was selected on the basis of commercial availability and calibration curves traceable to the National Bureau of Standards. However, one of the load cells was calibrated in the laboratory to confirm the calibration factor.

## DESCRIPTION OF CALIBRATION SYSTEM

The system developed consists of a load calibration component and a deflection calibration component. Figure 4 shows a block diagram of the fundamental components.

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

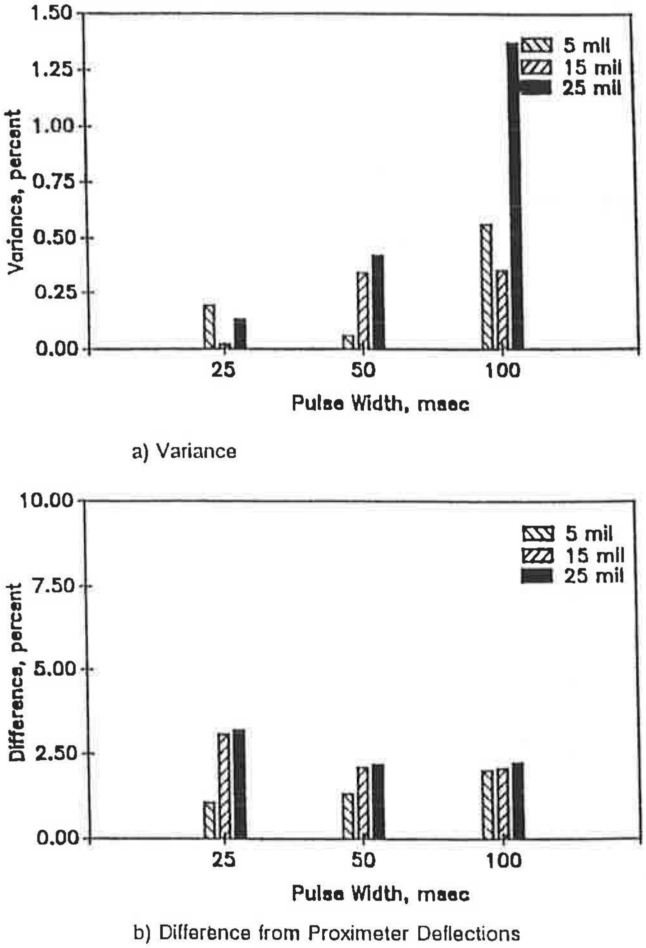


**FIGURE 2 Evaluation of a geophone under half-sine impulse motion.**

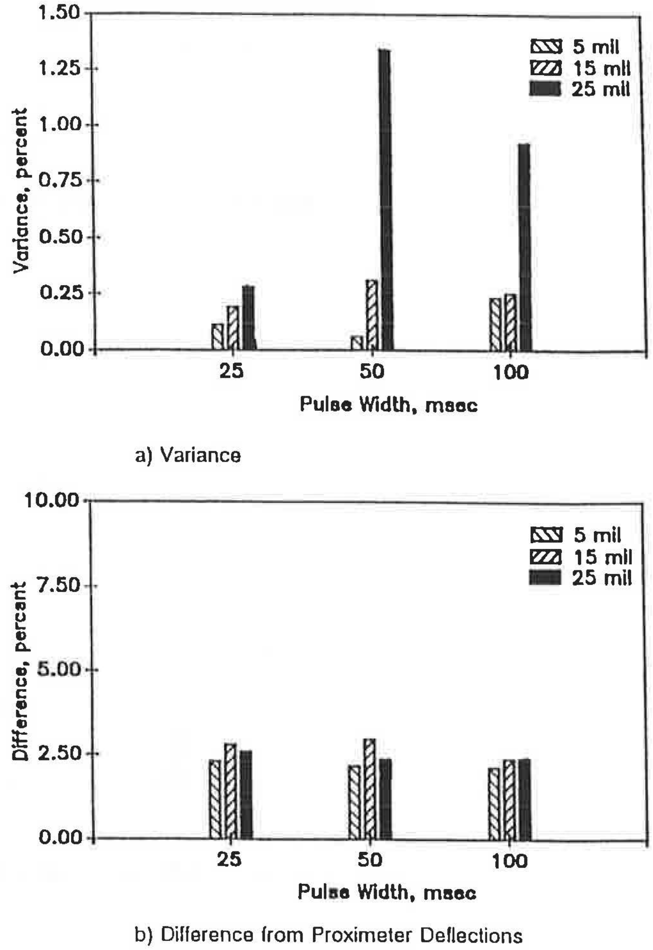


**FIGURE 3 Evaluation of an LVDT under half-sine impulse motion.**

TABLE 1 COMPARISON OF CHARACTERISTICS OF FIVE DEFLECTION SENSORS

| | Sensor | | | | |
|---|---|---|---|---|---|
| Characteristic | Accelerometer | LVDT | Geophone | Proximeter | Laser |
| Cost ($) | 350 | 350 | 40 | 400 | >10,000 |
| Supporting devices | Power amplifier ($300) | Power supply ($400) | – | Power supply ($400) | – |
| Precision, steady state | Moderate | Good | Good | Very good | Excellent |
| Precision, impulse | Poor | Good | Good | Very good | Good |
| Accuracy, steady state | Moderate | Good | Good | Excellent | Excellent |
| Accuracy, impulse | Poor | Good | Good | Good | Good |
| Field worthiness | Good | Moderate | Very good | Moderate | Poor |
| Mounting | Very easy | Difficult | Very easy | Difficult | Difficult |

computer are also used. The components are controlled and all collected data are reduced and presented through a computer algorithm. Figure 5 shows the entire system.

The FWD device imparts a load to the pavement by dropping a weight from different heights. The load is transferred to the pavement through a polyvinyl chloride (PVC) plate. An aluminum plate with the same thickness and diameter as the PVC plate was fabricated (Figure 6). A PVC plate cannot be used for calibration because the high flexibility of this material results in erroneous measured loads.

Six holes were drilled in the plate for fastening the load cells to the plate. Three holes, 120 degrees apart, each located halfway between two screws, were used for connecting the aluminum plate to the FWD device. The other three holes were made along a diametral line. The first three holes are used for calibration and the other three to study the variation

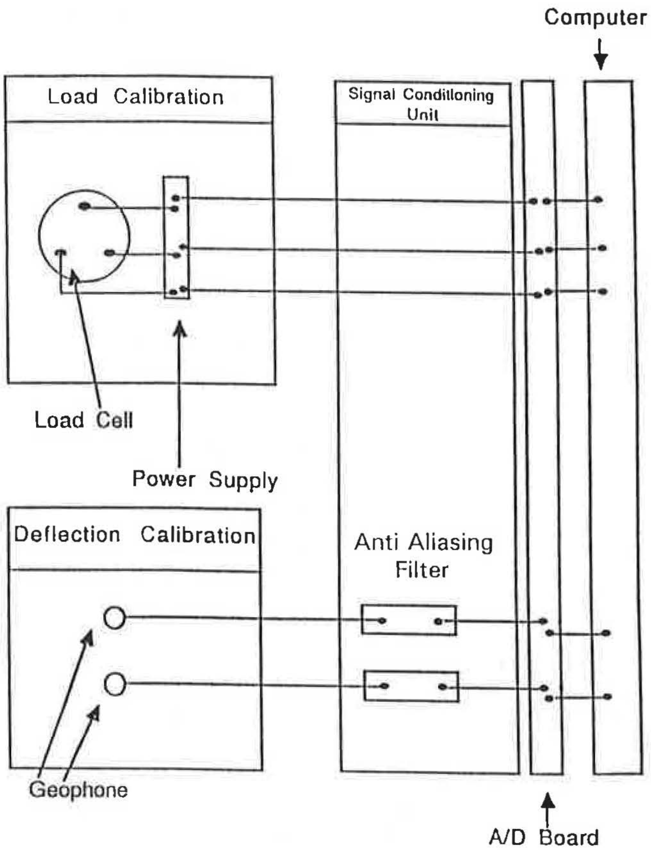


**FIGURE 4 Diagram of calibration system.**

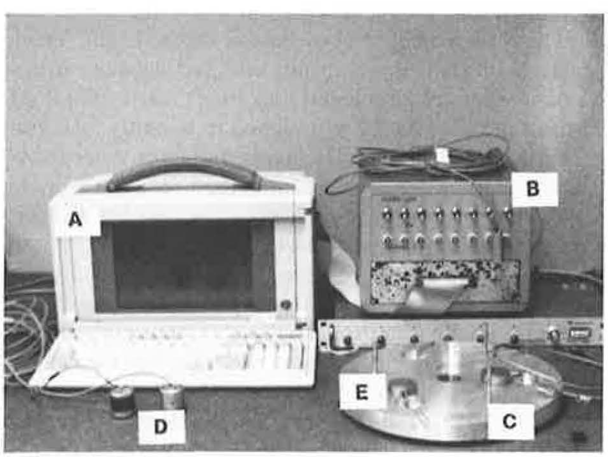


**FIGURE 5 Components of calibration system: A, computer; B, SCU; C, aluminum plate; D, geophones; E, load cell.**

of load along the diameter of the FWD plate. Grooves were cut in the plate to accommodate load cell cables. Three small holes were also provided for fastening the aluminum plate to the FWD device.

Three load cells with calibration curves traceable to the National Bureau of Standards were used. The nominal calibration factors for the load cells were 250 mV/kip with a capacity of 20 kips. The effect of mounting the load cells in the aluminum plate was found to be negligible (*3*).

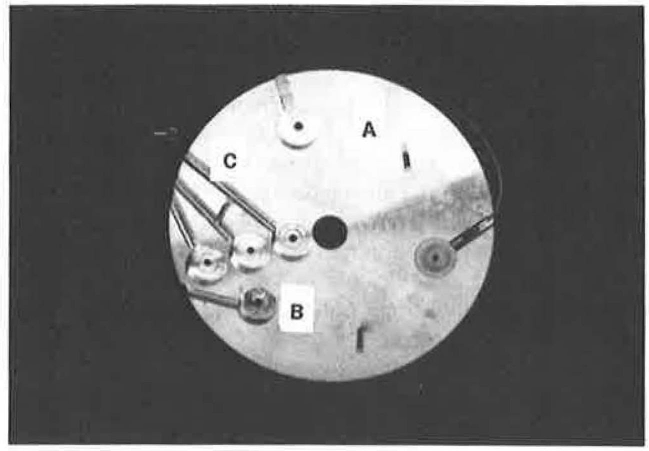


**FIGURE 6 Aluminum plate developed for calibration system: A, aluminum plate; B, hole for load cell; C, slot provided for load cell cables.**

The two geophones used in the calibration system have nominal natural frequencies of 4.5 Hz, nominal damping ratios of 70 percent, and nominal gain factors of 0.75 V/in./sec. For a typical pavement, the voltage output is on the order of 100 mV to 1 V.

The SCU, which was designed, built, and tested in house, consists of an eight-channel analog filter and a triggering mechanism, as shown in Figure 7. The filter is a fourth-order, low-pass filter with a cutoff frequency of 250 Hz. The unit is placed between the sensors and the analog-to-digital (A/D) board. Each load or displacement sensor is connected to one channel of the unit (see Figure 7). The signal can be filtered and output to the A/D board, or the filter can be bypassed and the output directed to the board. Each channel has a switch for directing or bypassing the signal through the filter. The SCU has 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. There are provisions in the unit for starting the A/D board through external triggering circuitry. The triggering sensor is a proxy sensor.

The A/D board used offers a dynamic range of 96 dB, which is well suited for calibration purposes. The throughput sampling rate of 50 kHz was used. The data at each channel are

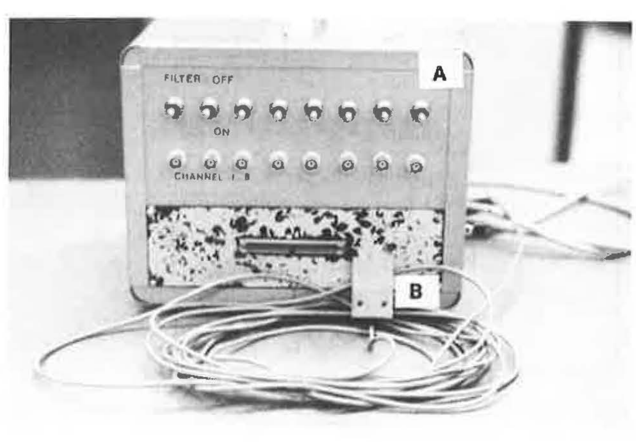


**FIGURE 7 A, SCU; B, proxy switch.**

measured at a rate of about 10 kHz. The A/D board is not equipped with a simultaneous sample-hold circuit. However, because most of the energy is concentrated below a frequency of 100 Hz, that deficiency is of little consequence.

Calibration system software was developed for an IBM PC–compatible computer. The program can control the acquisition and retrieval of the analog data captured by the sensors, reduce the collected data, and display and analyze the raw and reduced data. The program provides software-controlled initialization and identification of the A/D board and facilitates the collection of data using direct memory access. The acquired data are stored in a file for further processing. A flowchart of the program is shown in Figure 8. The program can be used in two modes: (*a*) to collect data through the board and process them or (*b*) to reduce previously collected data.

The software is programmed for calibration of either the Dynaflect or the FWD device. A third option is provided for flexibility. With this option, any other type of sensor reacting to either a steady-state sinusoidal load or an impulse load can be calibrated. If this option is selected, a table containing parameters for collection and reduction of data will appear on the screen. The parameters consist of the desired number of channels for collection of data, the type of sensor used with each channel, the calibration properties of each sensor, the time span for collection of data, and the number of data points per channel. The values of the parameters can be specified or default values chosen. The default values can also be read from a file previously saved.

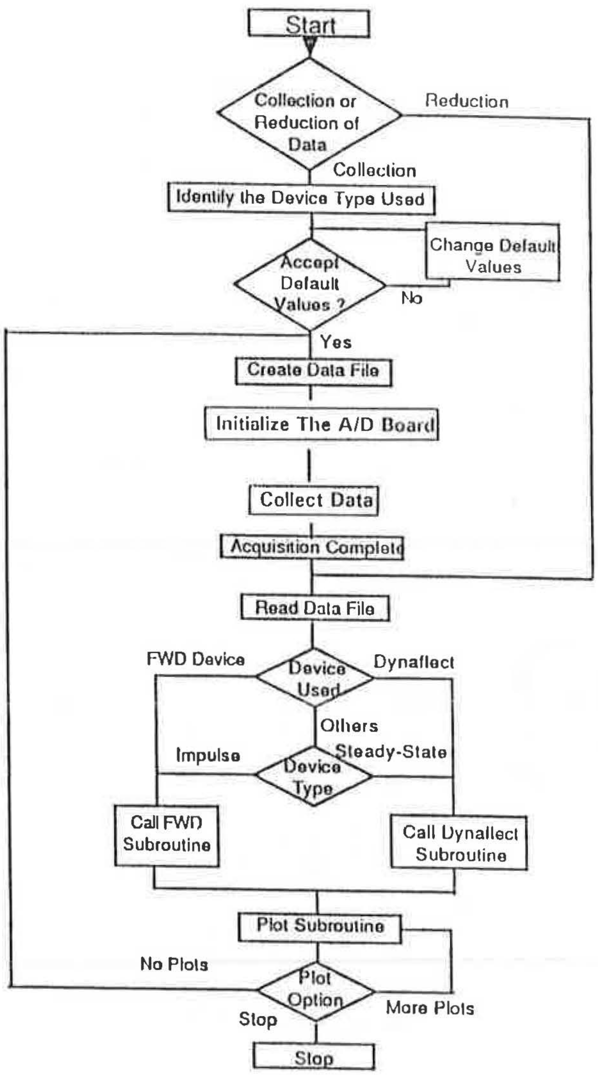


FIGURE 8 Flowchart of computer program.

The program saves the setup information and the collected data in one file. The program then reduces the collected data. The load obtained from each load cell and deflections measured with sensors are shown on the screen. The raw or reduced data can be plotted on the screen.

## DESCRIPTION OF CALIBRATION PROCESS

The process for calibrating the FWD load cell is as follows. An appropriate site, consisting of a thick rigid pavement section, should be identified. Concrete thickness of 18 in. or greater is recommended; otherwise, the loss of strain energy in the paving material may result in large errors. The site should be reasonably flat to minimize the nonuniform distribution of loads among the three load cells. An asphaltic pavement section is not appropriate for load calibration.

The FWD's PVC loading plate should be replaced by the aluminum plate encasing the calibration load cells. The use of rubber padding between the loading plate and the pavement is not recommended. The padding will absorb part of the energy imparted by the drop weight to the FWD system, which will cause erroneous results.

The calibration process should be performed in two phases. Both consist of 10 drops. In the first phase the FWD load plate remains seated between successive drops. In the second phase the load plate is lifted and reseated between drops. Both phases should be repeated four times, each from a different drop height. Phase 2 is designed to quantify load variability due to plate seating. The loads should be recorded by the FWD and calibration system simultaneously. The average, standard deviation, and the coefficient of variation of all drops should be calculated for each device, drop level, and phase. A Student's *t*-test should be done to test for differences in recorded load between the FWD and calibration system.

The data from the four drop heights should be plotted using the FWD loads as the independent variables and the calibration system loads as the dependent variables. The least-squares best-fit regression line should then be determined. The upper and lower bounds corresponding to a confidence level of 95 percent should be included on the same plot. If the 95 percent interval confidence level encloses the line of equality, no action should be taken. Otherwise, the calibration factor of the FWD load cell should be adjusted.

If the coefficient of variation is more than 4 percent, the calibration process should be terminated. Some other factor, such as the mounting mechanism or a bad electrical connection, may be interfering with the sensors. The value of 4 percent is based on the precision of the sensors.

The calibration process to be followed for the deflection sensors is similar to that for the loads. A flexible pavement site is appropriate for calibrating the FWD sensors. Deflections of more than 25 mils should be obtained for sensors

close to the loading plate. Tests on concrete sites are not recommended unless the FWD is used extensively on rigid pavements.

The reference geophones are placed close to the FWD sensors. The weight is dropped, and the deflections are measured with both the FWD and the calibration system. The load imparted to the pavement is also measured with the calibration system. The measured loads are used to normalize the deflection, as described later. This process is repeated at least 10 times. The average, standard deviation, and coefficient of variation of deflections measured with the two devices and the load measured with the calibration system are calculated. A Student's *t*-test on the two samples should be carried out to verify whether 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 using the deflections measured with the FWD as the independent variable and the deflections measured with the calibration system as the dependent variable. The least-squares best-fit line and the upper and lower bounds of a 95 percent confidence interval should be plotted. If the line of equality is enclosed within the 95 percent confidence interval, no change is necessary. Otherwise, the calibration values should be revised.

If the coefficient of variation measured with a sensor is more than 4 percent, the calibration process should be terminated. Some other factor, such as the mounting mechanism or a bad electrical connection, may be interfering with the sensors.

## CALIBRATION EXAMPLE

An example is included to clarify the steps involved in the calibration of an FWD. The data used in the example were collected with an FWD device (*3*).

A calibration curve for the load cell of an FWD device is shown in Figure 9. Forty data points, corresponding to the 10 drops per drop height, are included in the figure. The data are clustered in four groups corresponding to the four drop heights. The best-fit line and the line of equality are also shown. The two lines are close to one another, indicating the closeness of the calibration value to unity. The slope of the line (the calibration value) is actually 0.97.

The line of equality and upper and lower bounds corresponding to a confidence interval of 95 percent are shown in Figure 10. On the basis of this figure, a correction of the calibration value is necessary.

The calibration curve for Deflection Sensor 2 is shown in Figure 11. The data are clustered in three groups. Because of lack of time, only three load levels were used. The best-fit line and the line of equality are also shown in Figure 11. The best-fit line, line of equality, and upper and lower bounds of the 95 percent confidence interval are shown in Figure 12. Obviously, a significant difference exists between the FWD load cell and Deflection Sensor 2. There is no doubt that the calibration of Deflection Sensor 2 should be revised.

The calibration factors for all sensors are summarized in Table 2. The calibration factors for both the wraps and the repetitions are included. It can be seen that the effect on the calibration factors of lifting the loading pad after each drop is small.

## SUMMARY AND CONCLUSIONS

A system was developed for the absolute calibration of FWD devices. The calibration system consists of two well-calibrated geophones and three load cells with calibration constants traceable to the National Bureau of Standards. An SCU was also developed to precondition the signals. The SCU consists of antialiasing filters and a triggering mechanism. A computer algorithm was coded for collection and reduction of data. Data

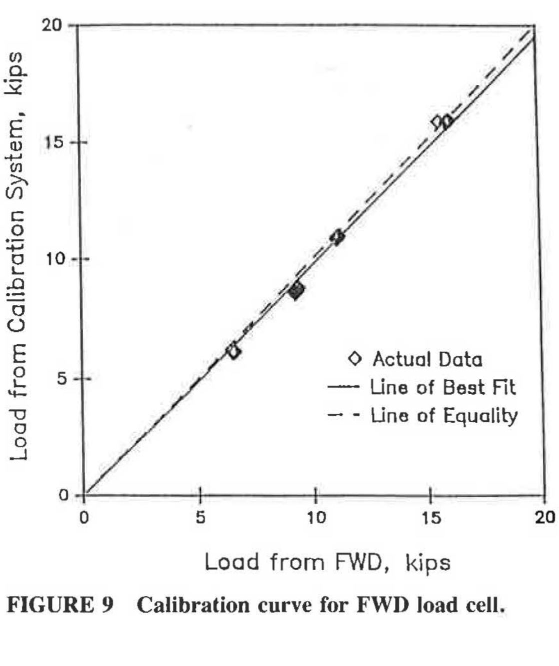


**FIGURE 9 Calibration curve for FWD load cell.**

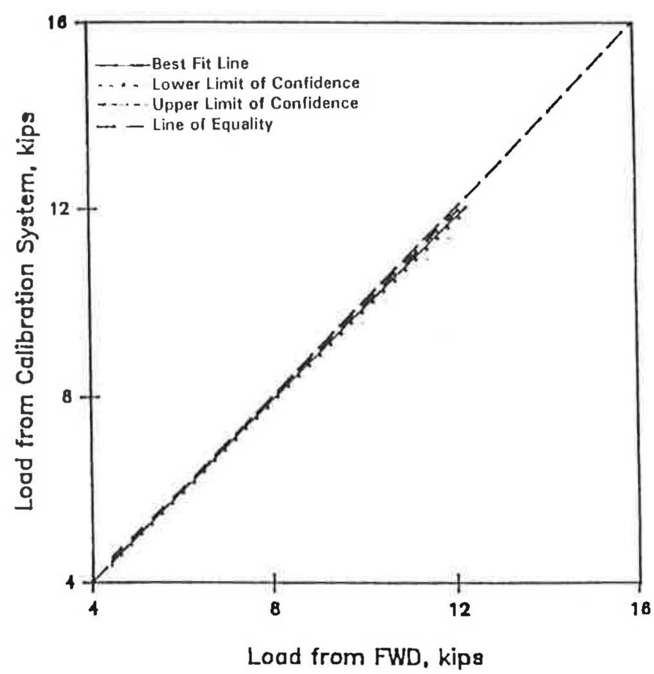


**FIGURE 10 Ninety-five percent confidence interval obtained from load measurements.**

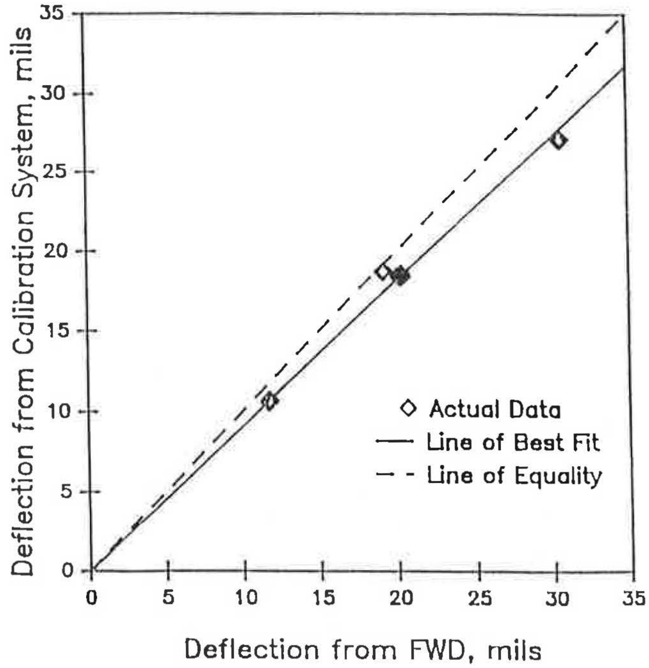


**FIGURE 11 Calibration curve of Sensor 2 of FWD.**

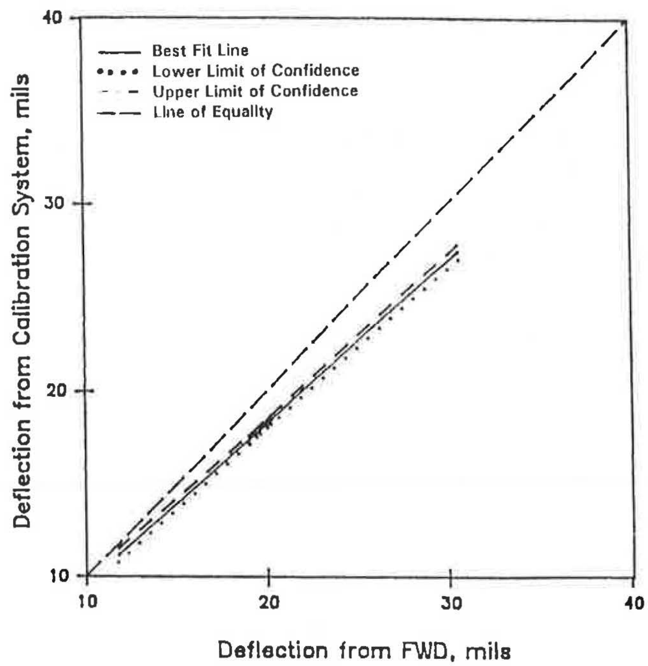


**FIGURE 12 Ninety-five percent confidence interval obtained from deflection measurement of Sensor 2.**

TABLE 2 CALIBRATION FACTORS FOR FWD SENSORS

| | Calibration Factor | |
|---|---|---|
| Sensor | 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 |

can be collected from the load cells and geophones, reduced, and compared with the loads and deflections obtained simultaneously from the FWD. A calibration factor for both the FWD load cell and geophones can be determined on the basis of linear regression between data collected by the calibration system and those reported by the FWD device.

On the basis of field and laboratory investigations, the following conclusions can be drawn: (*a*) the calibration of FWD devices used by highway agencies is necessary; (*b*) geophones are feasible for use in the calibration; and (*c*) for the calibration of load cells, a portland cement concrete pavement should be used, whereas deflection sensors should be calibrated on an asphalt section.

## ACKNOWLEDGMENTS

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