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16. Abstract

The degree of accuracy with which the Falling Weight Deflectometer (FWD) data are collected and analyzed has a direct impact on the conclusions drawn in many aspects of TxDOT operation. Since TxDOT owns 15 FWD units, one of the largest FWD fleets of any single transportation agency in the world, high levels of repeatability and reproducibility are considered to be of major importance for an adequate interchangeability of the FWD fleet. As summarized in Research Report 1784-1, the existing calibration protocol improves the repeatability of each FWD but it does not address the reproducibility of the fleet. In this report a new calibration process has been recommended that seems to improve the reproducibility of the fleet.

The calibration process consists of three steps: a routine and diagnostic maintenance, a simple calibration procedure followed by a comprehensive one if necessary

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Abstract

The degree of accuracy with which the Falling Weight Deflectometer (FWD) data are collected and analyzed has a direct impact on the conclusions drawn in many aspects of TxDOT operation. TxDOT owns 15 FWD units, one of the largest FWD fleets of any single transportation agency in the world. Both good repeatability and reproducibility are considered to be of major importance for an adequate interchangeability of the FWD fleet. As summarized in Research Report 1784-1, the existing calibration protocol improves the repeatability of each FWD but it does not address the reproducibility of the fleet. In this report a new calibration process has been recommended that seems to improve the reproducibility of the fleet. The calibration process consists of three steps: a routine and diagnostic maintenance, a simple calibration procedure followed by a comprehensive one if necessary.

Executive Summary

The Falling Weight Deflectometer (FWD) device has been extensively used by the Texas Department of Transportation (TxDOT) to support routine pavement design, to select rehabilitation strategies, to route super-heavy loads, to load zone, and to support other pavement management activities. A FWD primarily measures the pavement deflection at seven to nine points for a given load. The measured load and deflections, along with pavement parameters, are entered in a backcalculation program to obtain the stiffness profile of an existing pavement. These backcalculated moduli are then used to compute the strains at the interfaces of the pavement layers. The remaining life of the pavement is finally determined by using a semi-empirical relationship between the number of loads applied to the pavement and the critical strains at the interfaces of the different pavement layers. The degree of accuracy with which the FWD data are collected and analyzed has a direct impact on the conclusions drawn in many aspects of TxDOT operation.

The current fifteen-unit FWD fleet of TxDOT is of different vintages, and as such is manufactured of different components. Both good repeatability and reproducibility are considered to be of major importance for an adequate interchangeability of the FWD fleet. If the fleet is not reproducible, the predicted remaining life will depend on the FWD used. This will result in a systematic over- or under-estimation of the overlay thickness in a given region of the state. It will also positively or negatively impact the reported quality of a district's pavement condition.

The primary objective of this project is to develop realistic field protocols and specifications, which in a rational manner will allow TxDOT personnel to quantify the repeatability and reproducibility of existing and future FWD devices. As a result of this activity, a more comprehensive calibration methodology has been developed.

In this report, the new calibration procedure is described. The software is user-friendly so that it can be used by TxDOT personnel. The hardware is designed to minimize the time and effort needed by TxDOT personnel and at the same time allowing the FWD to be tested as an intact unit. Strategies for replacing components are also addressed.

It is believed that the new protocol will assist TxDOT to maintain a more reproducible and repeatable fleet that is well tuned and maintained for extended life of the FWD.

Implementation Statement

The major outcome of this project is a new test protocol, a replacement strategy for FWD components and recommendations for a more rigorous maintenance schedule for the FWD fleet.

The new procedure not only will improve the precision and accuracy of the FWD readings, it will also assist TxDOT in extending the life of the fleet by replacing defective parts long before they cause failure in the system.

The researchers recommend that the system be implemented as soon as it becomes feasible.

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Chapter 1

Introduction

Among a number of available nondestructive (NDT) methods, the Falling weight Deflectometer (FWD) is commonly considered to provide the estimates of material properties that are compatible with loads exerted by truck wheels. The FWD device has been extensively used by the Texas Department of Transportation (TxDOT) to support routine pavement design, to select rehabilitation strategies, to route super-heavy loads, to load zones, and to support other pavement management activities. A FWD primarily measures the pavement deflection at seven to nine points for a given load. The measured load and deflections along with pavement parameters are entered in a backcalculation program to obtain the stiffness profile of an existing pavement. These backcalculated moduli are then used to compute the strains at the interfaces of the pavement layers. The remaining life of the pavement is finally determined by using a semi-empirical relationship between the number of loads applied to the pavement and the critical strains at the interfaces of the different pavement layers.

The degree of accuracy of collected and analyzed FWD data has a direct impact on the conclusions drawn in many aspects of TxDOT operation. TxDOT owns 15 units, the largest FWD fleet of any single transportation agency in the world. TxDOT purchased its first unit in 1983 and has added additional FWDs on three- to four-year intervals over a span of 15 years. Although the same manufacturer has developed all FWDs, the performance of the fleet is not always comparable. Over time TxDOT has rebuilt a few of the FWDs in-house. Therefore, the current fleet consists of different vintage FWD units with different components. There is a concern that these differences may result in varying measured deflections among different FWDs.

A high degree of reproducibility is considered to be of major importance for an adequate interchangeability of the FWD fleet. If the fleet is not reproducible, the predicted remaining life will depend on the FWD used. This will result in a systematic over- or under-estimation of the overlay thickness in a given region of the state. It will also positively or negatively impact the reported quality of a district's pavement condition. To evaluate the reproducibility of a FWD fleet, it is essential that each individual FWD is precise and accurate.

Objective

The primary objective of this project is to develop realistic field protocols and specifications, which will allow TxDOT personnel to quantify the repeatability and reproducibility of existing and future FWD devices in an efficient manner. As a result of this activity, a more comprehensive calibration methodology will be developed. An additional outcome of the project will be new decision-making tools for maintaining a reproducible fleet. New tools will guide FWD maintenance crew in making more informed decision on when to replace components (such as buffers and sensor holders) in order to maintain a fully reproducible fleet.

In this report, the calibration protocol, and its corresponding hardware and software are described. The results from a trial implementation of the protocol are also included.

Organization

The report consists of nine chapters. A brief review of the motivation for developing this new calibration procedure is included in Chapter 2. The developed protocol is overviewed in Chapter 3. Chapters 4 and 5 describe in detail the hardware and process that has to be carried out to calibrate one FWD system. The software developed for this purpose is described in Chapter 6. Chapter 7 is a case study describing the results from calibrating three FWDs using the proposed procedure. The validation of the proposed process is reported in Chapter 8. Summary, conclusions and the future work plan are described in Chapter 9.

Chapter 2

Background

To maintain a reproducible FWD fleet, it is essential that all FWDs are accurate and precise. Thus, it is important that the reference or "absolute" calibration issues are addressed first, followed by the repeatability and then the reproducibility issues. It is critical to accurately determine the deflection basins and imparted loads in the field. Nazarian and Briggs (1989) have suggested that small errors in measured deflections may yield significantly erroneous modulus values. Hence, the use of a reliable method for evaluating the accuracy of the FWD sensors is essential.

Three different calibration systems for evaluating the accuracy and precision of the FWD sensors have been developed. A detailed description of these systems can be found in Report 1784-1 (Rocha et al., 2002). One of them, developed by the Strategic Highway Research Program (SHRP), performs a relative as well as a reference calibration of the geophones. In the SHRP reference calibration, deflections measured with a FWD are compared with those measured with an independent reference sensor. This sensor meets benchmarks traceable to the National Institute of Standards and Technology (NIST). On the other hand, the relative calibration ensures that the FWD sensors provide consistent results and function correctly. A brief description of these procedures is included in this report. A detailed description of them can be found in ASTM D4694.

The second method is the so-called Texas Calibration Method, which was developed at UTEP for TxDOT (Project 913). This protocol is equivalent to the SHRP protocol. One advantage of this calibration system is that the FWD geophones are not removed from the FWD holders, therefore, providing the calibration of the geophone system rather than the geophone alone. The main disadvantage of this and the SHRP methods is that one can only calibrate for peak deflections.

Under Project 2984, a third procedure was proposed that provides a more comprehensive way of conducting the calibration. That system is capable of calibrating geophones over a wide range of frequencies and deflections such that the whole time history of a deflection basin can be obtained accurately and precisely. The modified calibration method is also capable of identifying the problems associated with the FWD holding system or the geophones. This system is of critical importance should TxDOT decide to implement a dynamic, full-waveform analysis method. The new calibration protocol builds on the experience gained in Texas from the three aforementioned systems.

Before this system was developed, a study was carried out to establish the reproducibility and repeatability of TxDOT fleet. A detailed description of the study can be found in Rocha et al. (2002). Briefly, six representative FWDs were tested at three different site (weak flexible, strong flexible, and rigid) before and shortly after they were calibrated as per SHRP protocol.

The overall results from the repeatability study are summarized in Figure 2.1. To evaluate the impact of the calibration on the repeatability of the FWD fleet, the coefficients of variation (COVs) from before and after calibration are compared for all sensors, sites, attempts, and FWDs. Most of the COVs from different sensors of the FWD fleet fall within the 2% limit recommended by the manufacturer even before calibration. The data also suggests that in general the SHRP calibration procedure improves the repeatability of the fleet by decreasing the COVs for a number of parameters.

To establish the benchmark reproducibility of the fleet, differences from the baseline values (grand average of values from all repeats of all FWDs) before and after calibration (from all sensors, all sites and all drop heights) are compared in Figure 2.2. Most of the measurements reside within the 5% difference defined as acceptable. A number of sensors also measure deflections or loads that vary from the average by more than 5%. A systematic decrease in the

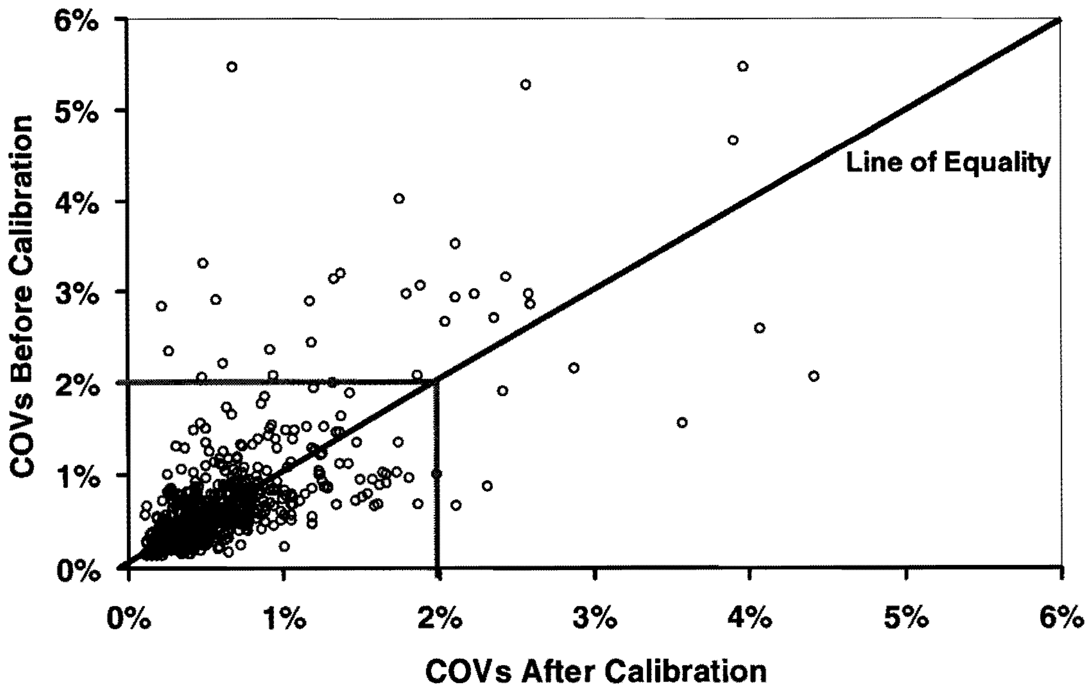


Figure 2.1 – Comparison of Repeatability of FWD Fleet Before and After SHRP Calibration (from Rocha et al., 2002)

difference from the baseline after the calibration is not evident in the data. This suggests that the SHRP calibration procedure may not necessarily improve the reproducibility of the FWD fleet. The data points are concentrated along the line of equality in Figure 2.2. This may indicate that the lack of reproducibility is not related to the behavior of the sensor itself but may depend on the FWD system as a whole (see Rocha et al., 2002 for more detail).

One of the major parameters that could contribute to a lack of reproducibility of the FWD is the movement of the FWD trailer during the impulse. If the sensors are not fully decoupled from the trailer, this motion can adversely impact the measured deflections. The movement of the trailer is related to the characteristics of the loading sub-assembly, the condition of the sensor holders, and the raise-lower system. Depending on the frequency and thoroughness of the trailer maintenance, the interaction between the trailer and sensor would change. To understand the nature of this interaction, three FWDs were instrumented in several manners. The movements of the strike plate (the plate that the buffers hit), the load plate (the plate that is in contact with pavement), the raise-lower bars, and the trailer itself were investigated. Several FWD components that can impact the response of FWD sensors (load cell and geophones) were also investigated. The items under study were the rubber buffers, geophone holder elements and the load plates. It was found that transient motions that occurred in the FWD during loading seemed to impact the peak loads and deflections measured by the FWD. These transient motions appear to be a function of the structural design of the trailer, the condition of the buffers, and the load plates. It was also observed that the stiffness and age of the buffers, as well as the condition of the components of the geophone holding assembly, would also impact the measured loads and deflections.

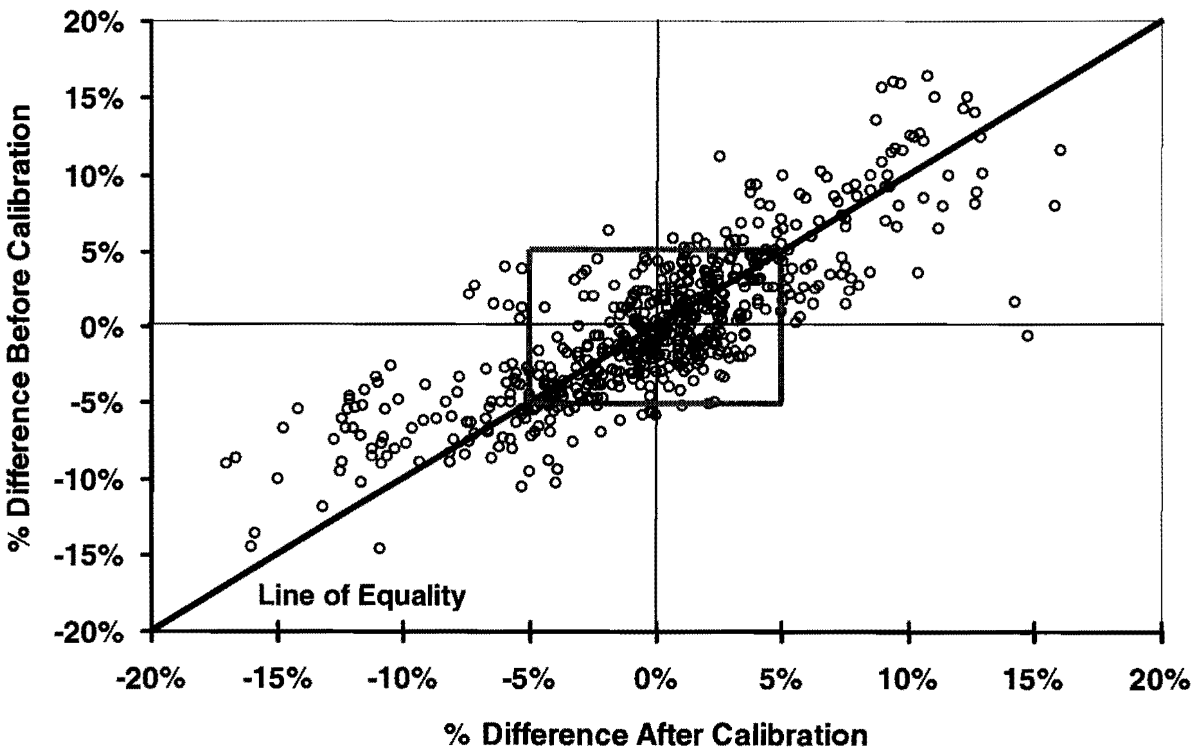


Figure 2.2 – Comparison of Deviation from Grand Average from Before and After SHRP Calibration (from Rocha et al., 2002)

Chapter 3

Calibration Process

The calibration process as it stands now is comprised of several steps that will enable personnel carrying it out to maintain uniformity throughout the FWD fleet. Following are the steps required for the calibration of each FWD:

- Physical inspection and component replacement
- Preliminary calibration
- Comprehensive calibration

Physical Inspection and Component Replacement

The trailer should be thoroughly cleaned from excess grease or dirt. The mechanical integrity of the FWD is checked in this step. The major components that should be considered are indicated in Figures 3.1 and 3.2. Particular attention should be placed on the geophone raise/lower bar assembly, ensuring there are no loose or missing bolts and that its operation is smooth. The geophone holder assembly rods should be checked and replaced, if they are excessively damaged. The springs of the geophone holder and the neoprene guide should be automatically replaced. Rocha et al. (2002) have shown that it is more cost effective to replace these components as opposed to checking them for integrity.

The electrical and hydraulic systems should also be maintained during this step. Check the electrical system for frayed wires and/or loose connections, particularly those going to the grounding points in the FWD trailer. Test the battery to ensure that it can maintain sufficient charge while the FWD is in operation. The hydraulic fluid should be checked and filled to proper level or replaced. Special attention should be paid to rust in areas close to electric connections.

Visually inspect the system to verify that it does not crawl or sway during the release of the drop weight. The load cell assembly should be checked to ensure that the swivel is well lubricated and verify that it moves freely.

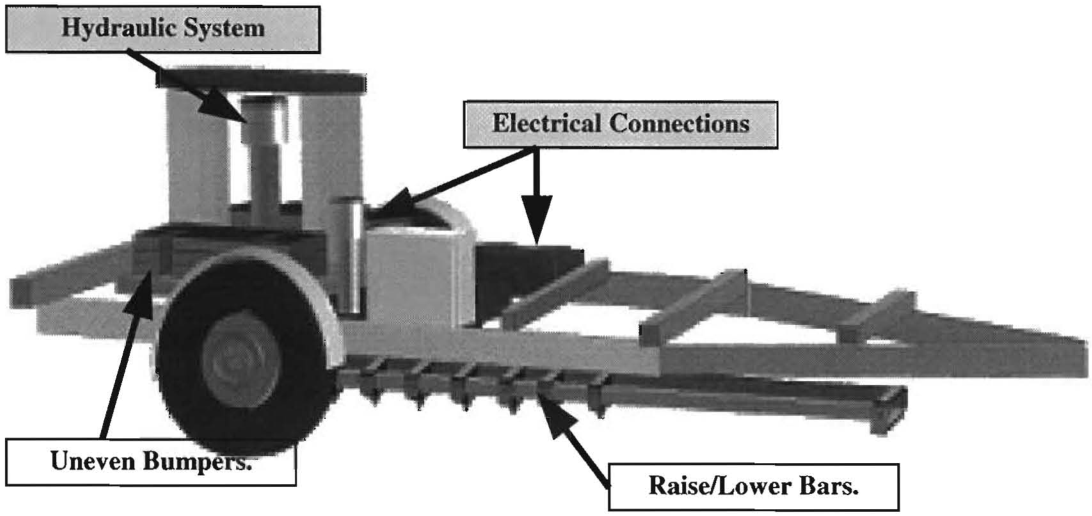


Figure 3.1 – Components to Inspect on a FWD Trailer

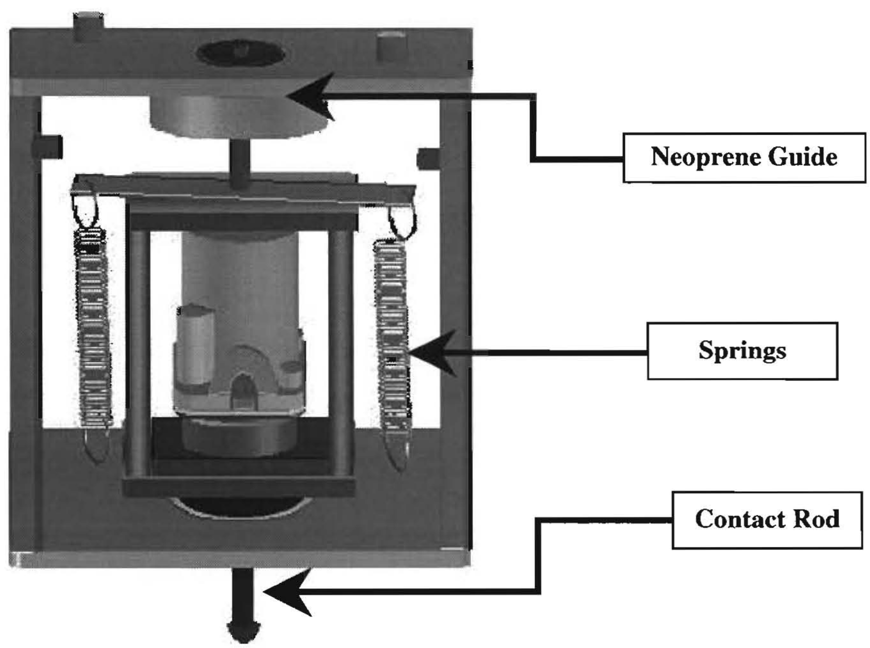


Figure 3.2 – FWD Geophone Holder Parts to be Inspected and/or Replaced

The buffers should be inspected for aging and visible damage. If one or more of the buffers are defective, all four buffers should be replaced at the same time. The buffers should be tightened in place with a torque wrench to ensure uniformity. A torque of 30 lb-in. is currently recommended.

Preliminary Calibration

To optimize the calibration process, an initial calibration is carried out first. This process is similar to the current SHRP calibration process. Figure 3.3 contains a flow chart of this process while Appendix A contains a test protocol for this process. At the completion of this step, the sensors that are potentially faulty are identified for a comprehensive diagnosis.

The hardware and test protocol for the preliminary calibration will be thoroughly described in Chapter 4. Similar to the SHRP process, the response of each sensor is compared with the response of a well-calibrated sensor for about 24 drops of the FWD load. Unlike the SHRP protocol, all deflection sensors are simultaneously calibrated within their sensor holders. For each sensor that has deflections or load values within 1% of those measured with the calibration system, no further action is necessary. On the other hand, if the deflections or loads from any FWD sensor differ by more than 2% from those measured with the calibration system, the sensor will be subjected to a comprehensive calibration. If all deflection sensors and load cell yield readings that are within 2% of the well-calibrated values, the calibration process is complete.

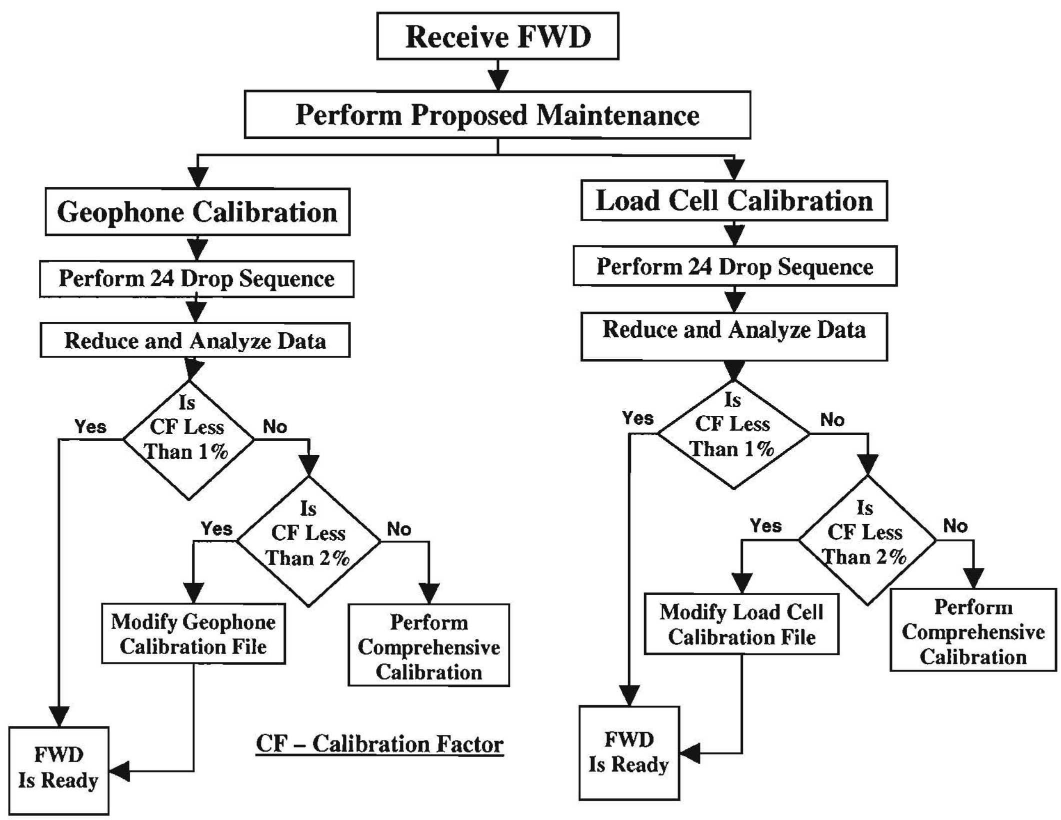


Figure 3.3 – Flowchart of Preliminary Calibration

Comprehensive Calibration

The sensors that are identified as "out of calibration" will be subjected to a comprehensive calibration process. The flow chart in Figure 3.4 summarizes the comprehensive calibration process. The hardware, software, and the protocol for this process is fully described in Chapter 5. Briefly, the appropriateness of the calibration curve from each sensor is investigated, and the impact of the sensor holder on the calibration is determined. In that manner, the component(s) contributing to the lack of calibration are identified and replaced.

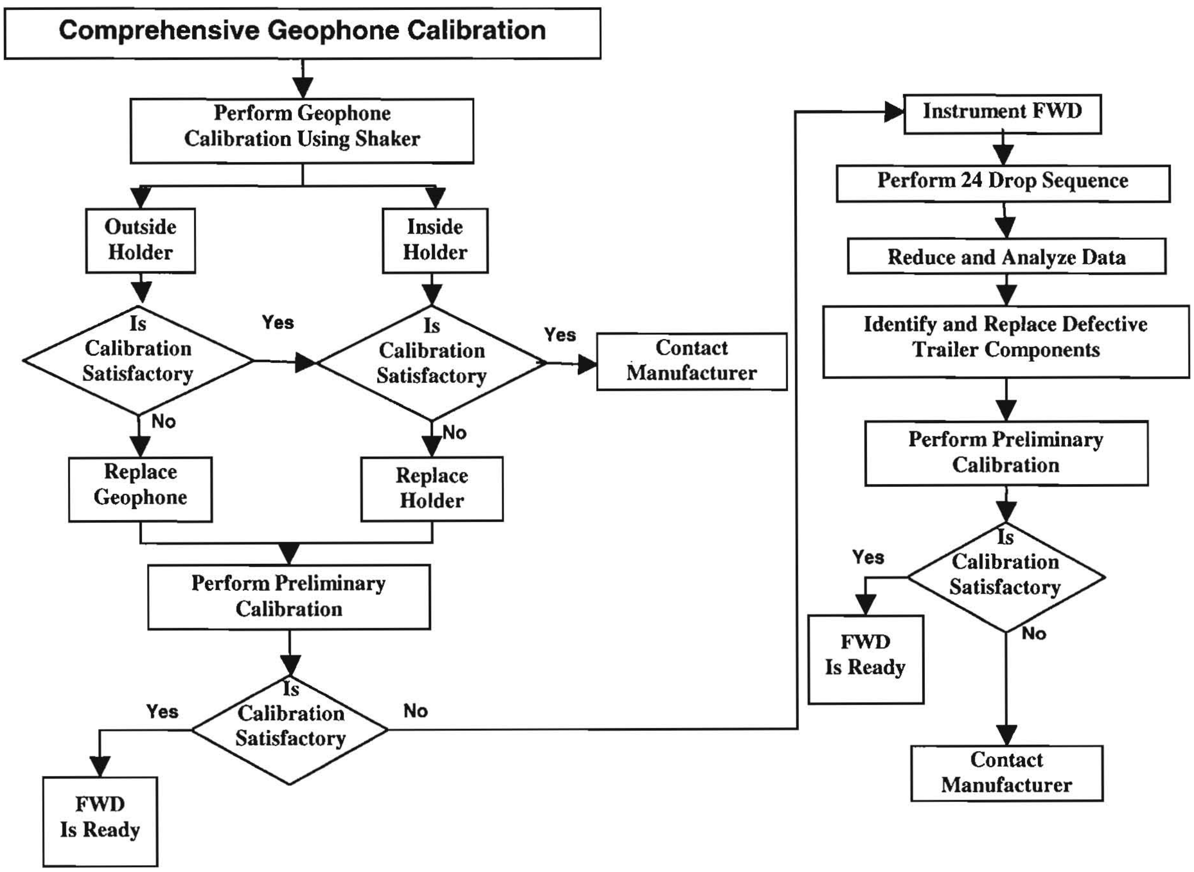


Figure 3.4 – Flowchart of Comprehensive Calibration

Chapter 4

Preliminary Calibration Process

The preliminary calibration process is performed on the load cell and the deflection sensors. The set up, hardware, and process for each of these sensors are summarized below.

Load Cell Calibration

The load cell calibration is carried out on a concrete slab about 6 in. to 8 in. thick specifically prepared for this purpose (see Figure 4.1). The slab has a circular opening of precise depth and diameter which allows the placement of the load cell calibration assembly. To ease this portion of the calibration procedure, the depth of the opening is chosen so that the assembly is flush with the top of the concrete slab.

The load cell assembly consists of three dynamic load cells securely fastened to a steel plate (see Figure 4.2). A rubber sheet similar to those placed under the FWD load cell is glued to the bottom of this plate. Another steel plate is placed on top of the three load cells so that the FWD load plate can be placed on top of it. The three load cells are connected to a data acquisition board through a specially developed calibration sensor box as shown in Figure 4.3. The data acquisition board is placed inside a laptop computer to interface with the developed software.

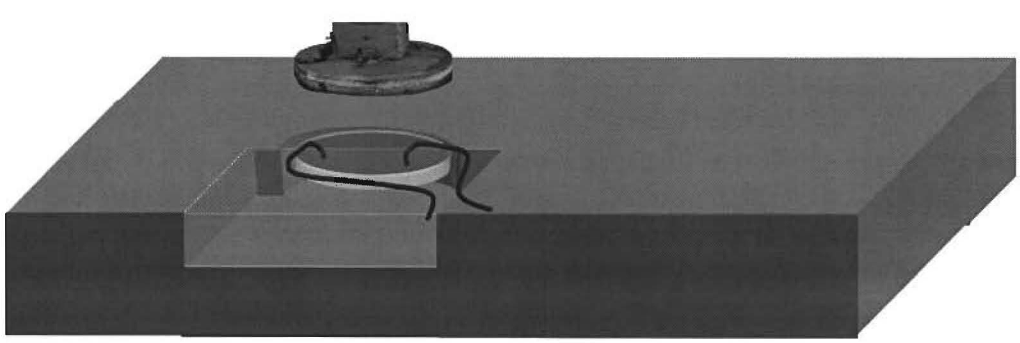
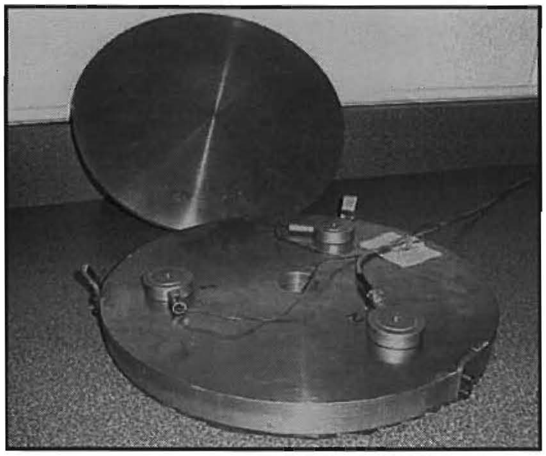


Figure 4.1 - Concrete Slab Used during Load Cell Calibration



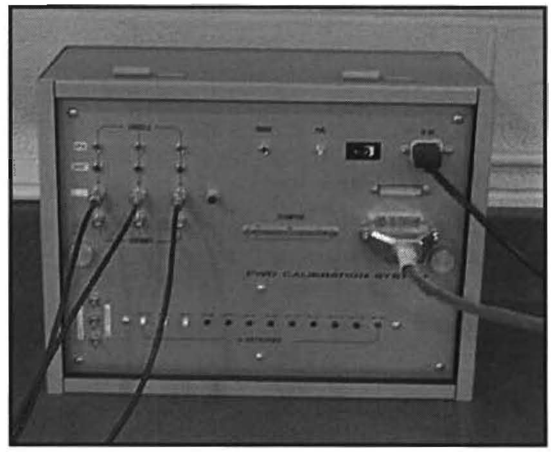


Figure 4.2 - Load Cell Calibration Assembly.

Figure 4.3 - Signal Conditioning Box used During Data Acquisition

With the assembly in position, the FWD load plate is directly lowered on top of it. A series of 24 drops (six drops from four drop heights) are applied. The drop heights are adjusted to nominal loads of 6000 lbs, 9000 lbs, 12,000 lbs and 15,000 lbs. For each drop, the load readings from the three calibration load cells are summed to allow comparison with the load measured by the FWD.

To determine the calibration factor for the load cell, the corresponding loads from the calibration system and the FWD are plotted against one another as shown in Figure 4.4. The inverse of the slope of the best fit line through the data is the calibration factor. The calibration factor is then incorporated in the FWD software provided it is greater than 0.98 or less than 1.02. If the calibration factor is greater than 1.02 or less than 0.98, the load cell should be subjected to the comprehensive calibration as discussed in Chapter 5.

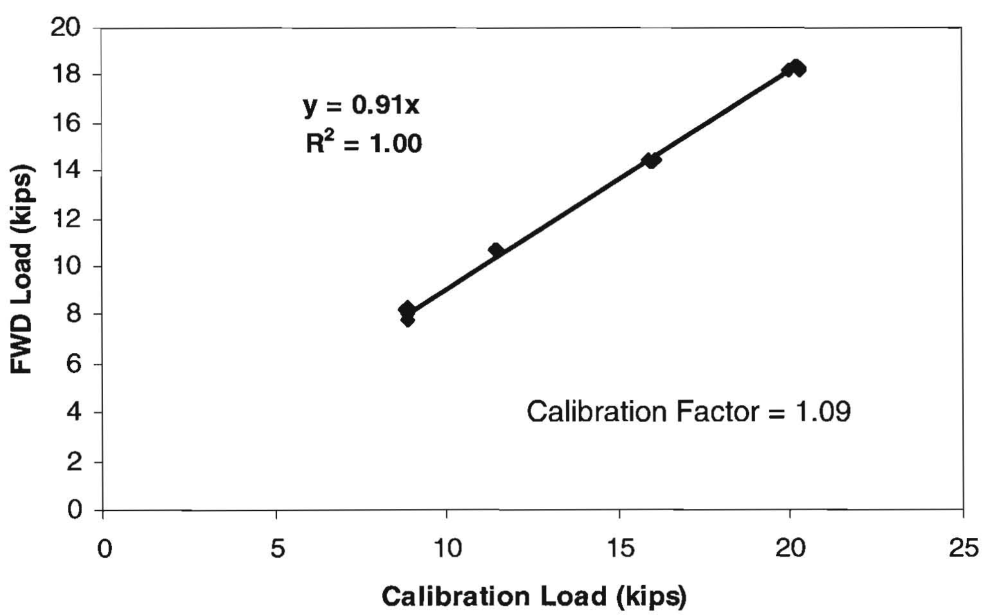


Figure 4.4 - Determining Load Cell Calibration Factor

Deflection Sensor Calibration

One of the positive aspects of the new calibration system is that it allows all deflection sensors to be calibrated simultaneously. An especially instrumented concrete slab is constructed for this purpose. As with the load cell, this concrete slab should also be about 6 in. to 8 in. thick (see Figure 4.5). One important specification is that the sensor farthest from the load cell should deflect a minimum of 1 mil for the smallest load (6000 lbs). Seven calibration geophone holders are embedded in the slab so that the seven FWD sensor contact rods can become in constant contact with these holders.

The holders of the calibration geophones are machined from stainless steel for magnetic isolation (see Figure 4.6). They are designed in a way that the calibration geophones can be conveniently removed for detailed calibration or replacement. The calibration deflection sensors used in this system were wired, tested and subjected to a comprehensive calibration process before being placed into their holders.

To calibrate the seven geophones simultaneously, the FWD trailer should be maneuvered until all seven FWD geophones are directly on top of their corresponding reference sensor. Once the geophones are lowered, their position should be verified to ensure they are still centered. A further aspect to check is that only the contact rod, and not the FWD geophone holder, is in contact with the stainless steel holder throughout data collection. A series of 24 drops (six drops from four drop heights) is applied. As with the load cell calibration, the drop heights are adjusted to nominal loads of 6000 lbs, 9000 lbs, 12,000 lbs and 15,000 lbs. For each drop, the signals from our calibration sensors are collected and analyzed to calculate the deflection peaks so that they can be compared with those registered by the FWD.

To determine the calibration factors for the geophones, the corresponding deflection peaks from the calibration system and the FWD are plotted against one another. Typical results are shown in Figure 4.7. The inverse of the slope of the best fit line through the data is the calibration factor. The calibration factor is then incorporated in the FWD software provided it is greater than 0.98 and less than 1.02. If the calibration factor is greater than 1.02 or less than 0.98, the deflection sensor should be subjected to the comprehensive calibration as discussed in Chapter 5.

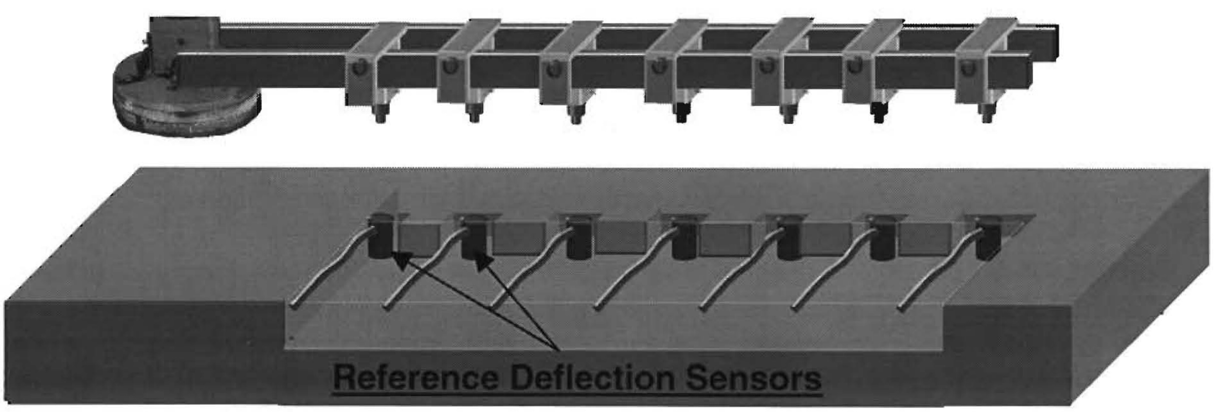


Figure 4.5 - Instrumented Slab Used During Deflection Sensor Calibration

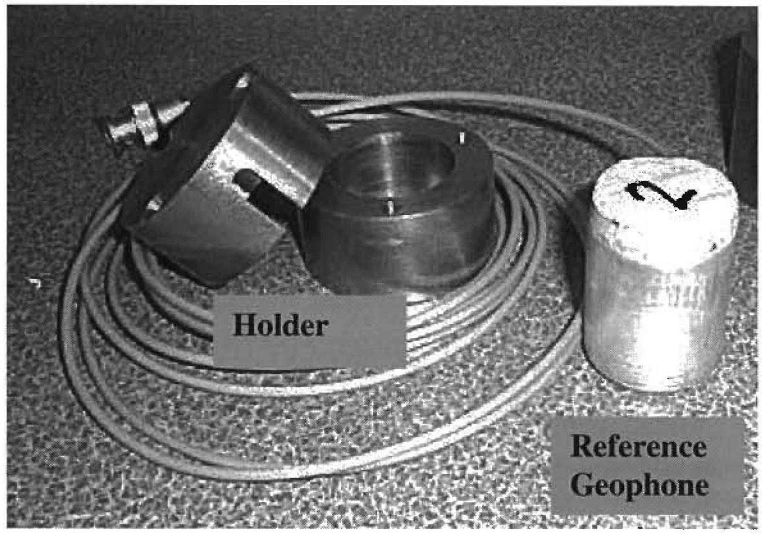


Figure 4.6 - Reference Deflection Sensor Assembly

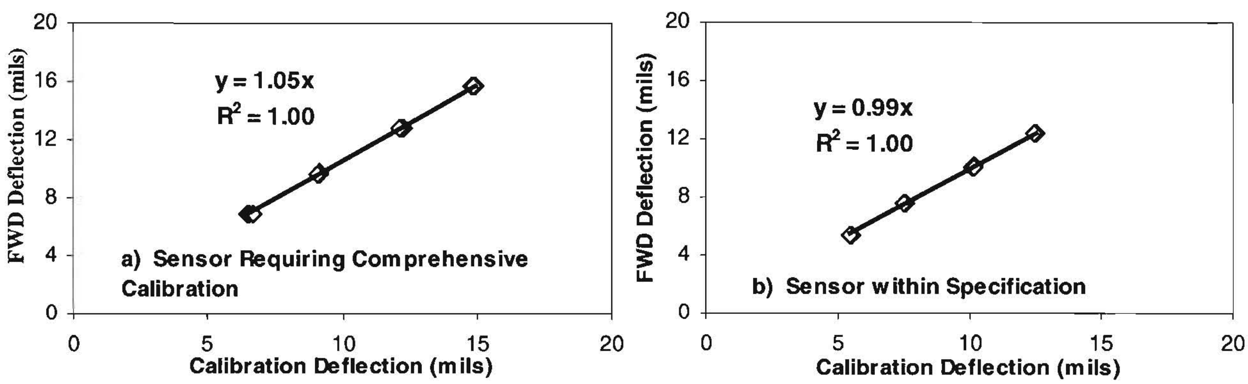


Figure 4.7 - Typical Results from Preliminary Calibration

Chapter 5

Comprehensive Calibration

The comprehensive calibration process is a multiple-step process that only applies to sensors that do not pass the preliminary calibration. The goal of this process is to determine whether the sensor, the sensor holder, or other components contribute to the deflections that are inaccurate. By examining the response of the FWD geophone holder, the lift/lower assembly, the strike plate and the FWD trailer motion, the defective element can be identified and replaced. In contrast to the preliminary calibration procedure, the comprehensive calibration process is more time consuming and labor intensive. As described in Figure 3.4, the geophone assembly (i.e., the FWD geophone and its holder) are the first targets.

Geophone Assembly Calibration

To conduct the comprehensive calibration of the geophone assembly, a specially-designed concrete slab and a shaker retrofitted with a calibration sensor are used. No deflection limits are placed on the make up or construction of this slab. Therefore, it is practical to utilize the same slab that was used for the preliminary calibration. As shown in Figure 5.1, a cavity located in the center of the slab allows for the positioning of a shaker. The concrete slab and the bottom of the cavity should be leveled. After the shaker is placed within the cavity, a metal plate retrofitted with a hole that

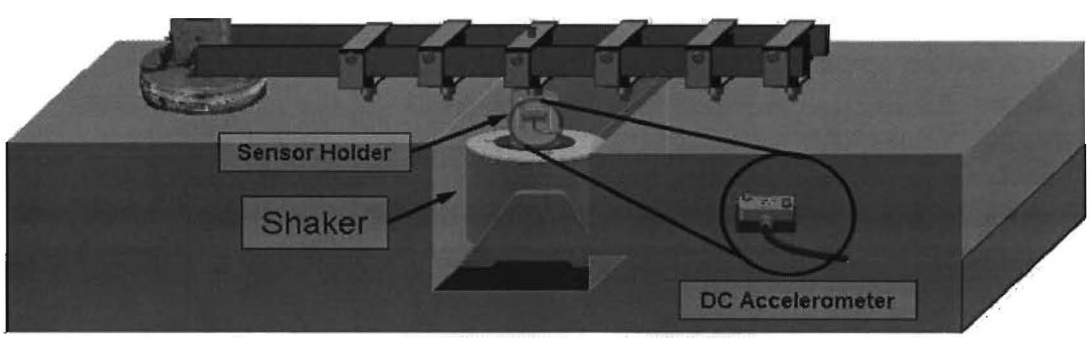


Figure 5.1 - Concrete Slab with Cavity for Shaker Calibration

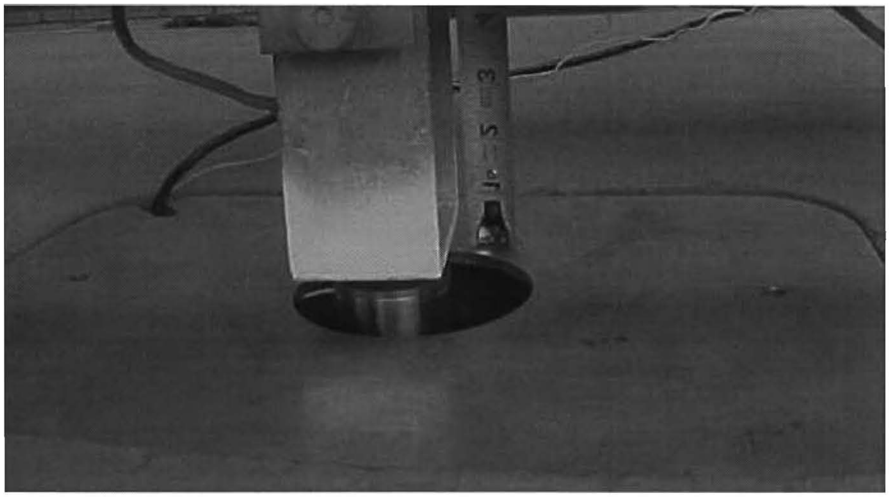


Figure 5.2 - Sensor Holder on Shaker Protected by Metal Cover

matches the head of the shaker is placed flush with the slab (see Figure 5.2). The purpose of this set up is to allow the placement of each faulty deflection sensor, while still in its original holder, right on top of the shaker.

A special holder, as shown in Figure 5.3, is needed to attach a reference sensor to the shaker. The reference sensor used for this portion of the calibration process is a DC Accelerometer. The holder can be machined out of steel since the accelerometer is impervious to magnetism. The sensor holder should permit for a vertical adjustment of about 0.25 in. A dynamic signal analyzer (DSA) is also needed to deliver a sinusoidal sweep signal and to collect the response signals from the sensors under test and the reference sensor.

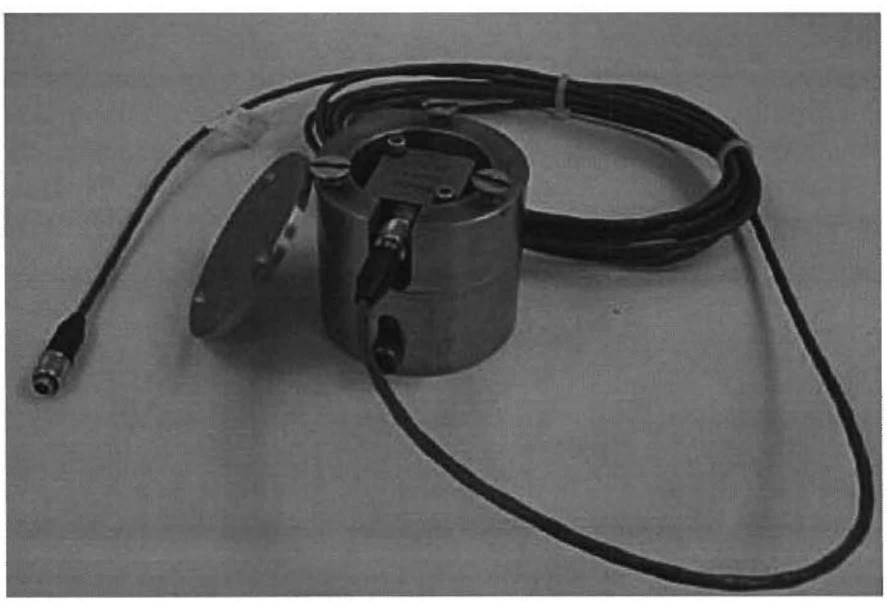


Figure 5.3 - Calibration Accelerometer in its Holder

The calibration is carried out in two phases: the FWD sensor outside the holder and keep the FWD sensor inside the holder. Each step is described below.

Geophone Outside of Holder

If after preliminary calibration, a geophone is found to exceed the 2% calibration limit, the first step is to determine its status isolated from any other elements of the FWD system. To do so, the following steps should be carried out:

- Place the shaker alongside the FWD trailer, near the geophone under test.
- Remove the FWD geophone from its holder and place it directly on the accelerometer holder. The magnet should be strong enough to hold on securely, verify this by tugging on it as shown in Figure 5.4.
- Set the DSA to produce a sinusoidal sweep from 0.5 Hz to 50 Hz.
- Set the DSA to collect voltage signals from the FWD geophone and the DC Accelerometer.
- Display the frequency response and coherence between the two signals on the DSA.

The DSA takes from 3 to 5 minutes to complete the data collection. The voltage outputs from the FWD geophone and the reference accelerometer are transmitted to the DSA so that the frequency response and the coherence function from the outputs of the two signals are determined. Typical frequency response and coherence functions are shown in Figure 5.5. As expected, the response begins to increase rapidly to a frequency of about 5 Hz (close to the natural frequency) and just as rapidly decreases down to a frequency of 10 Hz. Above 10 Hz it continues to decrease but at a slower rate. The coherence function is practically equal to unity. This corresponds to an extremely high signal-to-noise ratio. Below a frequency of about 1 Hz, the coherence values are lower than 1. This indicates lower quality data which can be attributed to shaker performance in that range.

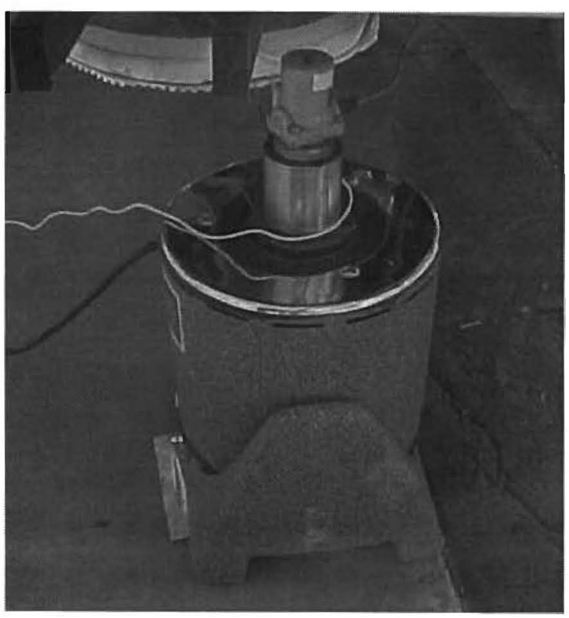


Figure 5.4 – Set up for Calibration of FWD Sensor Outside Holder

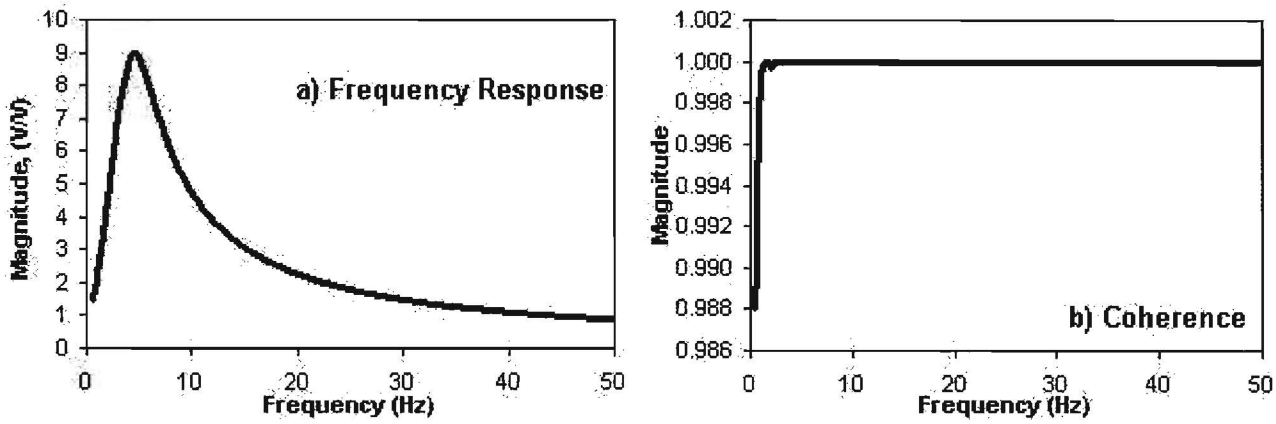


Figure 5.5 - Typical Spectral Functions from Geophone Calibration outside Holder

The output of a geophone is velocity and that of an accelerometer is acceleration. To determine the calibration parameters of the geophone, the frequency response is first multiplied by the calibration factor of the reference accelerometer. The derivative of the resulting curve is then used to obtain the parameters to the calibration curve of the FWD geophone.

Typical calibration curves after data reduction are shown in Figure 5.6. In Figure 5.6a, the variation in amplitude with frequency is shown. The amplitude above a frequency of 15 Hz is constant. However, the amplitude gradually decreases below that frequency. The variation in phase with frequency is shown in Figure 5.6b. A phase shift of 180 degrees is observed. The graph exhibits the classical behaviors of a single-degree-of-freedom (SDOF) dynamic system. As described in Tandon and Nazarian (2000), geophones are designed to behave as perfect SDOF systems. An SDOF system is defined by a natural frequency, a damping ratio, and a gain factor. The manufacturers of FWD or the companies that fabricate geophones usually provide these three parameters.

Tandon and Nazarian (2000) describe in detail the process of extracting the SDOF system parameters for graphs such as those shown in Figure 5.6. For simplicity, a built-in feature of the DSA can be used to extract these three parameters. The extracted parameters are compared with those specified by the manufacturer. If the difference in any parameter is more than 10%, the

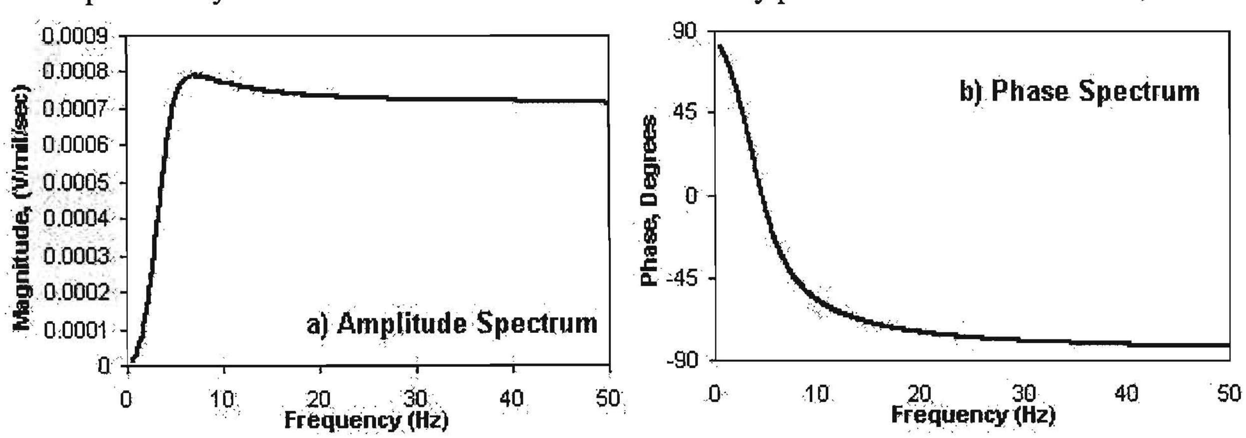


Figure 5.6 – Calibration Curves of Typical FWD Geophone

sensor should be replaced. In the absence of the manufacturer's information, assume the nominal natural frequency to be 4.5 Hz and the damping ratio to be about 70%. The gain is somewhat variable, but for most FWD sensors, it is approximately 800 µv/mil/sec (0.8 V/inch/sec). The shape of the frequency response should also be examined for any abnormalities, such as lack of smoothness or discontinuities in the curve. These abnormalities point towards damage to the geophone.

Geophone Inside of Holder

If the three calibration parameters of the geophone are within the specification and no anomalies are detected on the amplitude or phase spectra, the geophone is placed in the holder and the calibration process described above should be repeated. The shaker is placed in the slab cavity shown in Figure 5.1. The levelness of the head of the shaker should be ensured using a bubble level. The metal plate is then placed on top of the cavity.

The free movement of the shaker is a significant aspect of this type of testing. Therefore, it is important to eliminate any contact between the FWD geophone holder with the reference sensor holder while the calibration is in progress. The height of the holder is adjusted to ensure that the shaker head is almost flush with the plate (see Figure 5.2). For this purpose the accelerometer holder was machined with a vertical adjustment to let us correct for the ideal height.

The FWD trailer will have to be maneuvered to ensure the sensor being tested is positioned directly above the shaker. As in the previous step, the DSA is setup to deliver a sinusoidal sweep, to collect the resulting signals from the sensors and to display frequency response and coherence. After appropriate signal analyses, the amplitude and phase spectra are determined.

The resulting phase and amplitude spectra obtained in this step are compared with those measured when the geophone is placed directly on top of the shaker. The two spectra should only differ slightly. Any discrepancies in the frequency response curve will indicate that the problem is with the holder. It is assumed that the holder springs and neoprene guide were replaced and that there were no obvious signs of physical damage, so replacement of the entire holder assembly is the recommended corrective action.

The phase and amplitude spectra measured for a geophone in its holder are compared with those measured outside the holder. Figure 5.7a shows a holder that is functioning well while figure 5.7b shows one that exhibits problems. The amplitude and phase spectra measured within and outside the holder for the well-performing geophone assembly are for all practical purposes the same. On the other hand, the amplitude and phase spectra of the out of calibration geophone differ, especially in the amplitude. Those differences even increase in magnitude differences around 15 Hz and maintain about the same difference afterwards.

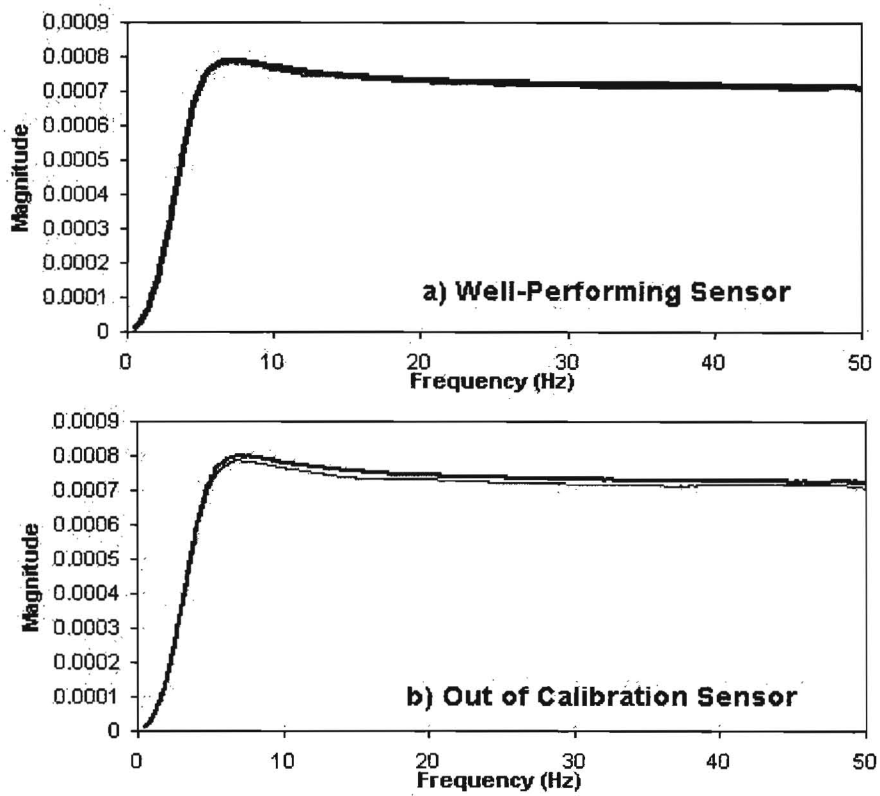


Figure 5.7 – Impact of Holder on Responses of Well-Performing and Out-of-Calibration FWD Geophones

FWD Instrumentation

If there are no signs of defective hardware up to this point, a third and final step is to observe components other than the FWD geophone/holder assembly. The same concrete slab that was used during the preliminary deflection sensor calibration procedure can be used. Since the focus at this stage is not on the response of the FWD geophones, the position of the FWD on the slab is not important.

The elements that will be evaluated (in order of importance) are the movement of the raise/lower bar, the behavior of the hit bracket, the response of the load plate and the movement of the trailer. To minimize the calibration time, all these parameters can be checked with a 12 drop sequence (three drops at four drop heights) provided the appropriate sensors are placed beforehand. The software as discussed in Chapter 6 will be able to simultaneously collect and analyze the data. The deflections from the FWD should also be recorded.

The movement of the raise lower bar is monitored by securely attaching three external geophones to the bar using a dab of vacuum grease. As shown in Figure 5.8, the geophones are placed as close as possible to FWD sensors 2, 4 and 6. Typical response of the bar is shown in Figure 5.9. The maximum deflection of the bar should be compared with the maximum deflection measured for the corresponding sensor at that location. More experience is needed to exactly define excessive movement. At this time, we are considering a maximum bar movement of 20% of the peak deflection as excessive.

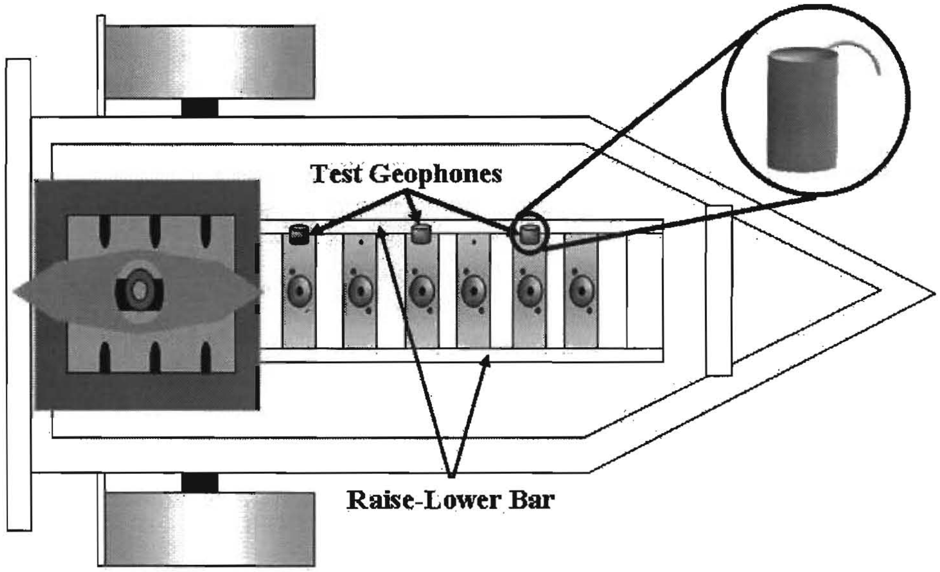


Figure 5.8 - Instrumentation of Raise-Lower Bar

Excessive movement of the bar would indicate that the assembly has loose or missing bolts, or that the assembly is not setting properly during testing. To remedy this problem, the operator should verify that all bolts are in fact in place and that the bolts are properly tightened. If all the bolts are in place, the operator should manually check the operation of the assembly to ensure that the movement of the associated cable is neither restricted nor too loose. If the problem is with the cable, it should be adjusted to the appropriate length while the assembly is in the down position.

The hit bracket has to be instrumented with four dynamic strain gauges as shown in Figure 5.10. The strain gauges are bonded to the plate with superglue, about 0.5 in. from the edge of each bumper. It is extremely important that the surface where the sensor is to be placed be clean of any dirt, oil, or paint. It is also very important to position the sensor correctly before the glue dries. The time history of the four strain gauge signals are superimposed to ensure that all four bumpers hit the bracket simultaneously (see Figure 5.11). The rise times, pulse widths, and peak strains of the signals are also compared to ensure that the bumpers are in proper working order. A lack of

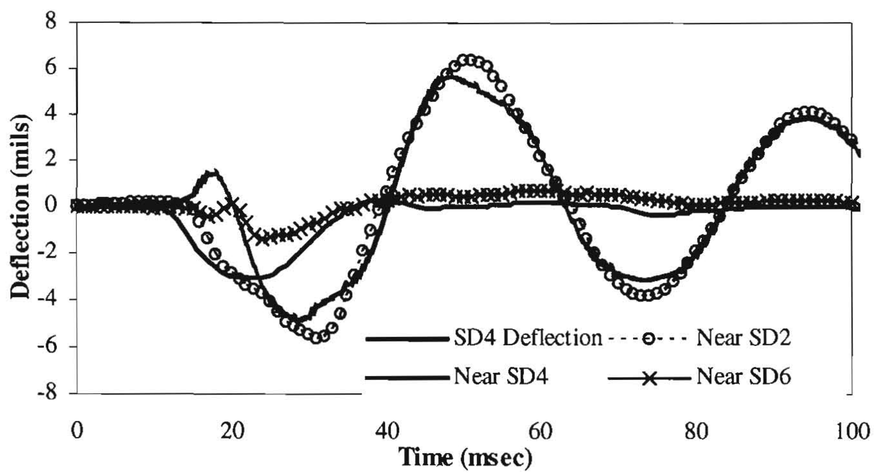


Figure 5.9 – Movement of Raise-Lower Bar

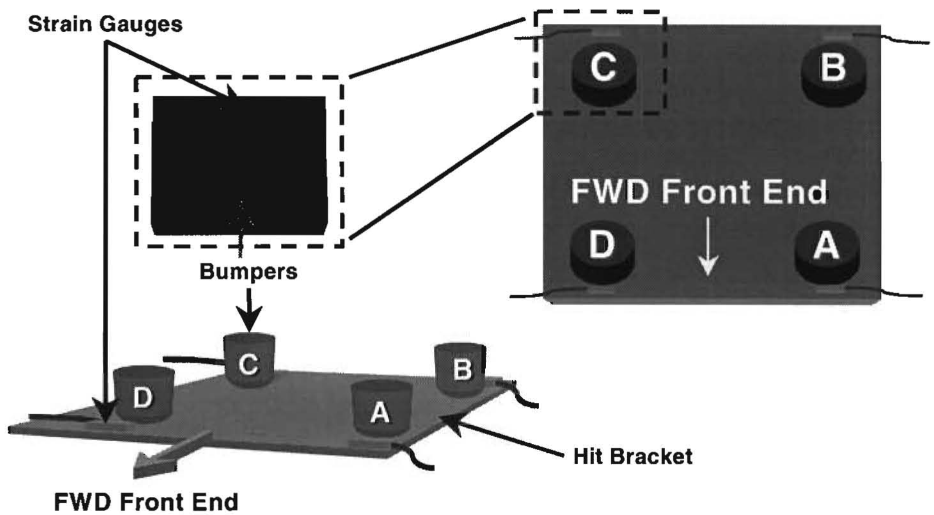


Figure 5.10 – Strain Gauge Set up Used to Measure Strike Plate Behavior

synchronization in the strain signals or significant difference in the amplitude of strains among the four signals is an indication of either uneven wear on one or more bumpers or that the bumper set is made up of different style bumpers or that the lack of symmetry in the loading bracket. The corrective action for the first two items is to replace all four bumpers with a brand new set of very similar bumpers. The lack of symmetry of the loading bracket, which is rare, cannot be readily resolved without a major reconstruction of the FWD.

The accelerometers on the load cell plate, as shown in Figure 5.12 along with the load cell time history an be used to determine the evidence of malfunction in the load delivery system. Excessive double peak of the load cell signal is an indication of a stuck swivel. While replacing the whole load assembly would only happen in extreme situations, it is often the case that by simply removing and reinstalling the same load cell assembly after proper lubrication of the swivel, will correct a stuck swivel problem. This will not only improve the reproducibility of the FWD, it will also minimize the risk of damage to the load cell. As a matter of fact, greasing the swivel should be carried out monthly as part of preventive maintenance to improve the performance of the FWD.

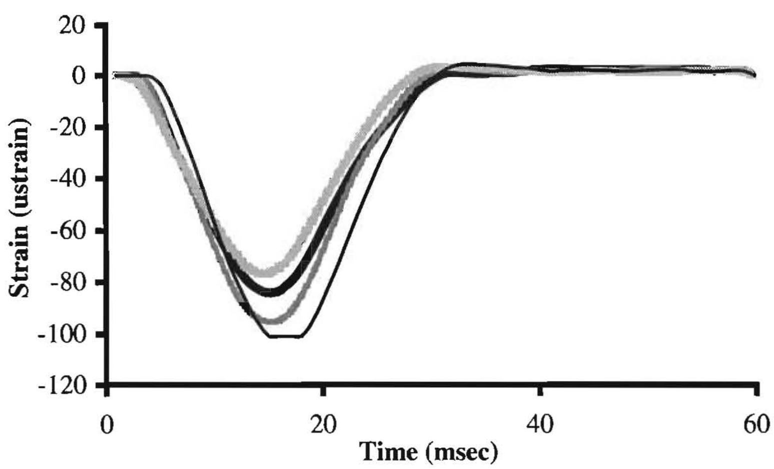


Figure 5.11 – Variations in Typical Strain Time Histories of Strike Plates

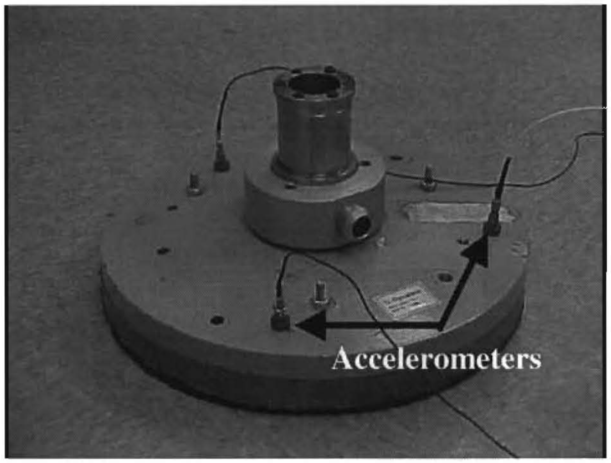


Figure 5.12 – Typical placement of Accelerometers on Load Plate

Typical accelerometer signals are shown in Figure 5.13. If the responses from the four accelerometers on a flat concrete slab are not synchronized, one can conclude that the components under the plate are either worn out or damaged. The ribbed rubber pad and/or the PVC plate should be carefully inspected and replaced if necessary.

With the geophones on the trailer frame, as shown in Figure 5.14 we monitor for out of phase motion of the FWD system. These geophones should be secured to the frame on both sides of the FWD frame, aligned with FWD Sensors 2 and 6. An example is shown in Figure 5.15. Rocha et al. (2002) demonstrated that this trailer movement, which may slightly affect the measured deflections, is related to the structural construction of the trailer. Figure 5.15 shows how the motion on the driver side of the FWD is more pronounced than on the passenger side; this points to an uneven weight distribution of the trailer components. Given the fact that the impact is small, the only necessary corrective action is to ensure that the trailer is loaded symmetrically during the reconstruction of the FWD. For example, the battery should be placed in a symmetrical manner perhaps near the tongue of the trailer.

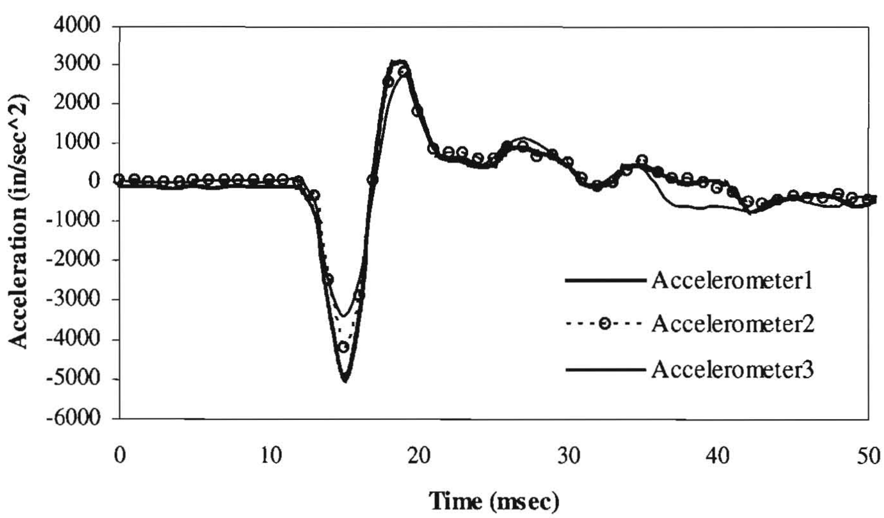


Figure 5.13 – Typical Accelerometer Signals on Load Plate

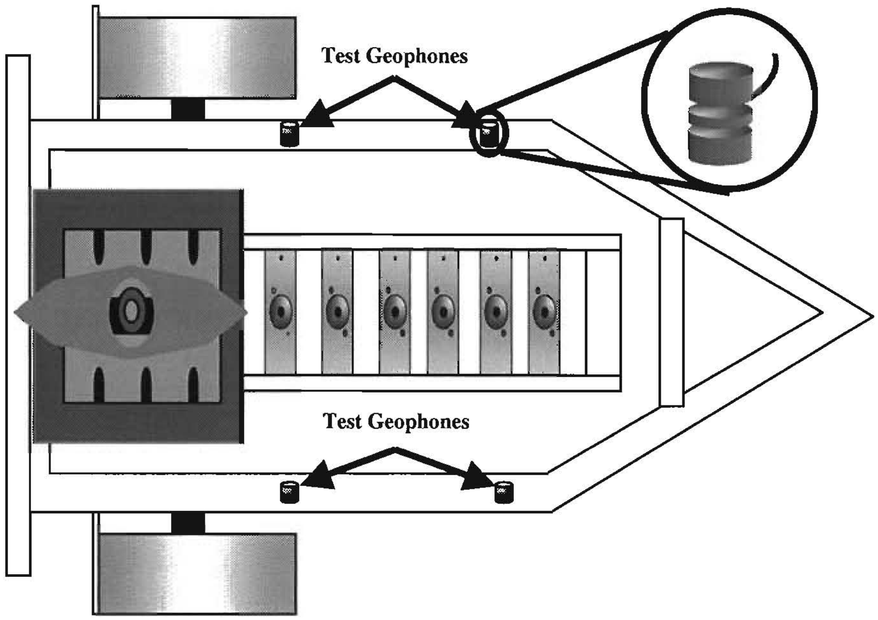


Figure 5.14 – Placement of Geophones on FWD Frame

After each of the previous steps and the replacement of any defective parts, a preliminary calibration should be performed to ensure the corrective action was effective in reducing the calibration factor. We firmly believe that these steps will also improve the reproducibility of the system.

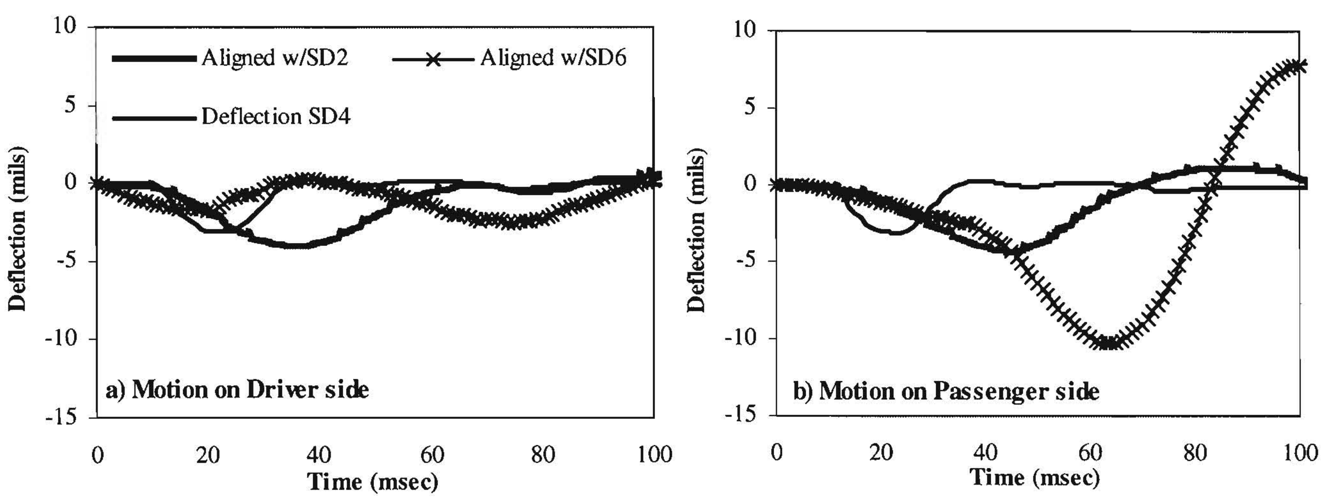


Figure 5.15 – Typical FWD Frame Motion

Chapter 6

Brief Description of Developed Software

The program developed for the new calibration system is easy to use, has the flexibility to manipulate different sensors in every channel and also has the ability to save, and recall collected information. The program also allows us to acquire the data, analyze it and observe results, for every step of the calibration system, with the exception of the comprehensive calibration.

LabVIEW software works seamlessly with the National Instruments hardware that has been used in the new system. The software package is powerful enough to control the data acquisition (DAQ) hardware, generate graphical interfaces and analyze collected data.

Before any data can be collected, the active data channels and the types of sensor connected to them have to be defined. The interactive interface for this portion of the program is shown in Figure 6.1. The channel definition includes a sensor name, sensor type and sensor calibration factor. Since this portion is the most time consuming, the program has the option to save these

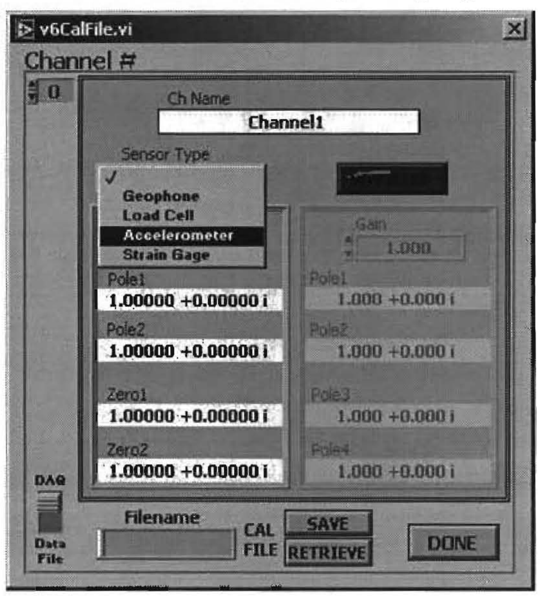


Figure 6.1 – Generating Sensor Calibration File

settings to a calibration file for later use. This would be needed in cases where a particular step is to be repeated or the same sensors are to be used.

Other settings that may be adjusted are: number of data points to acquire, sampling frequency and triggering levels. The default settings for those variables are almost always the desired values, so while it is possible to change them, it is usually not necessary to adjust them.

Once the sensors are placed in position, the channels and other program settings are defined, the program is ready to begin acquiring data. This process is initiated by clicking on the acquire data button. Initially the program will ask whether the data is to come from a file or from sensors, after this selection is made the program will continue to display information from the selected source until a reset or a program restart.

As shown in Figure 6.2, the program extensively uses a graphical user interface, that is, most selections and options are of the point and click variety. The program is designed to be able to observe the data flow of more than one channel at a time. The operator will be able to monitor the raw and reduced data from any channel as it is collected. Since the data analysis is a

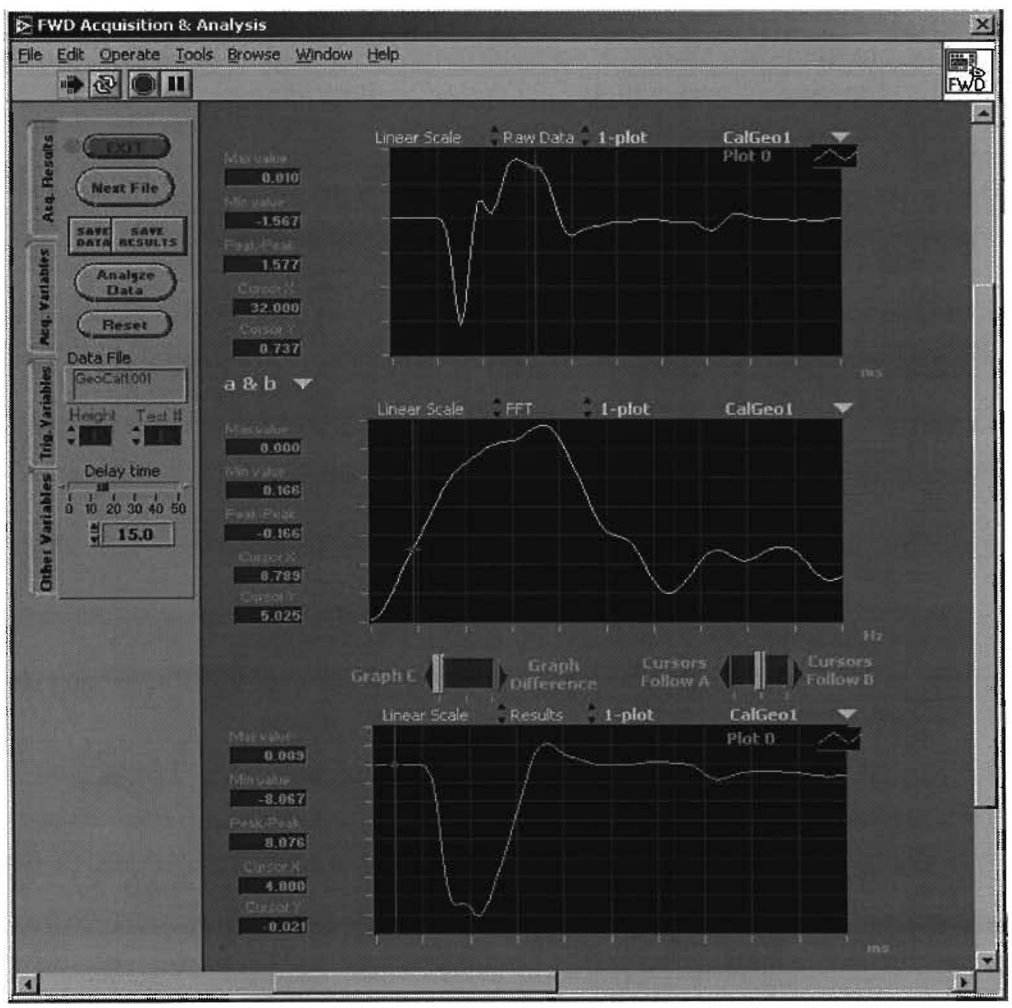


Figure 6.2 – Data Progression Display (Top: Raw Data, Middle: Frequency Domain Data, Bottom: Processed Data)

complex procedure, the experienced user can monitor the intermediate steps during the data reduction. For example, a number of analyses are conducted in the frequency domain. The operator is able to review the response of different sensors in the frequency domain if he/she chooses to do so. This sort of display is shown in Figure 6.2.

One other feature of the software is its ability to display reduced or raw data from several channels in a single screen. This is particularly helpful when the behavior of multiple FWD sensors need to be monitored simultaneously to determine the overall system behavior. For example, Figure 6.3 contains the records obtained simultaneously from the accelerometers placed on the load plate, the geophones attached to the FWD frame, and the strain gauges super glued to the hit bracket.

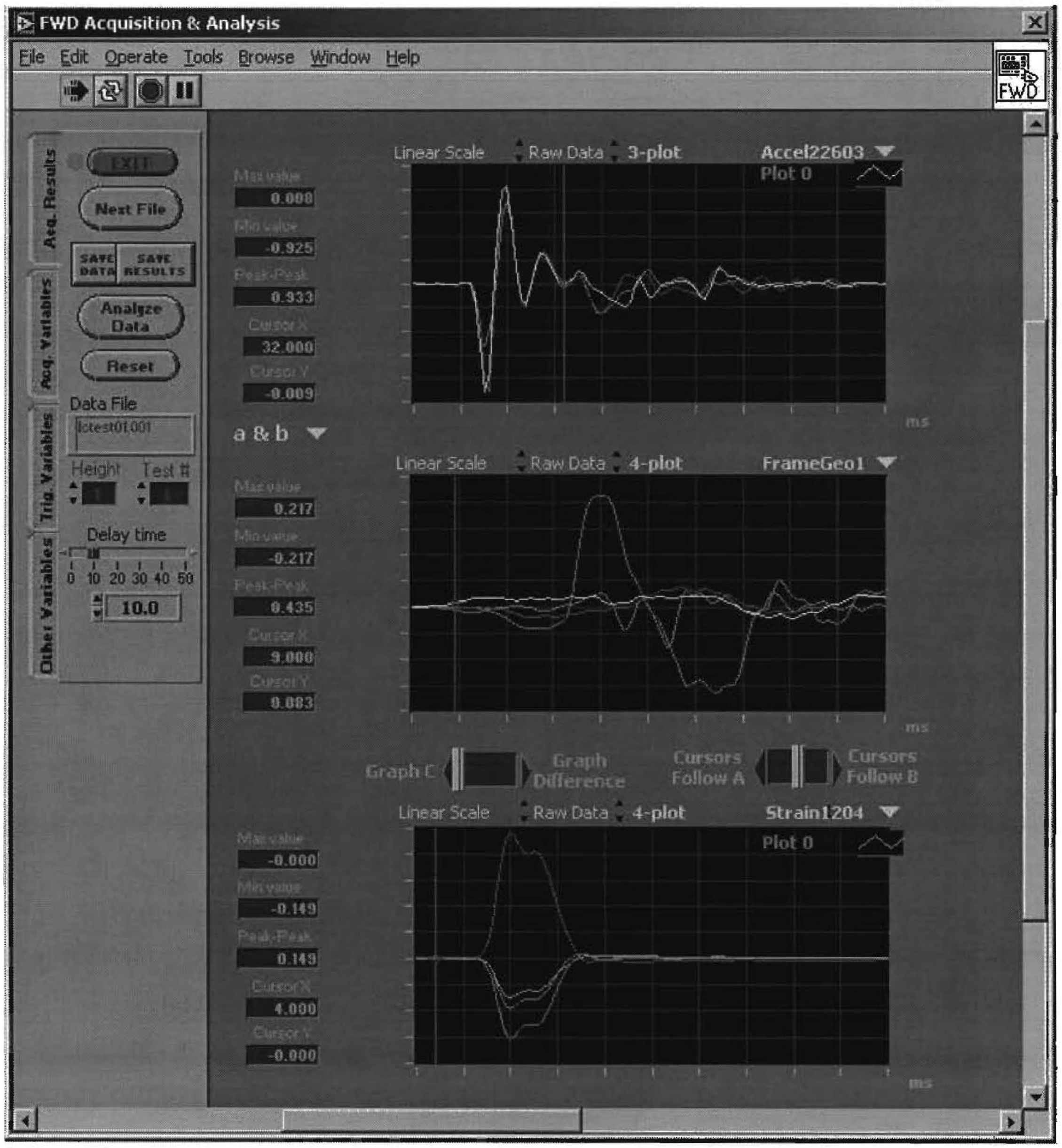


Figure 6.3 – Multiple Sensor Display

The primary purpose of this program is to acquire signals from different sensors, to reduce the data and to report the results. Figure 6.4 shows a deflection basin from our calibration concrete slab. While the figure shows all seven geophones in a single screen, it only displays the signal information from the first geophone. The program provides the freedom to display individual signals along with their information for each sensor. The load cell from the FWD is also displayed to show the time history relationship between load and deflection.

After each acquisition, the user has the option to save the entire information of all sensors for later analysis. This is done to speed up the acquisition aspect of calibration when more than one FWD has to be calibrated.

Once a drop sequence has been carried out, the analysis results can also be saved to a spreadsheet or tab-delimited text file. From that point, the FWD data can be transferred into the same spreadsheet file for calibration purposes.

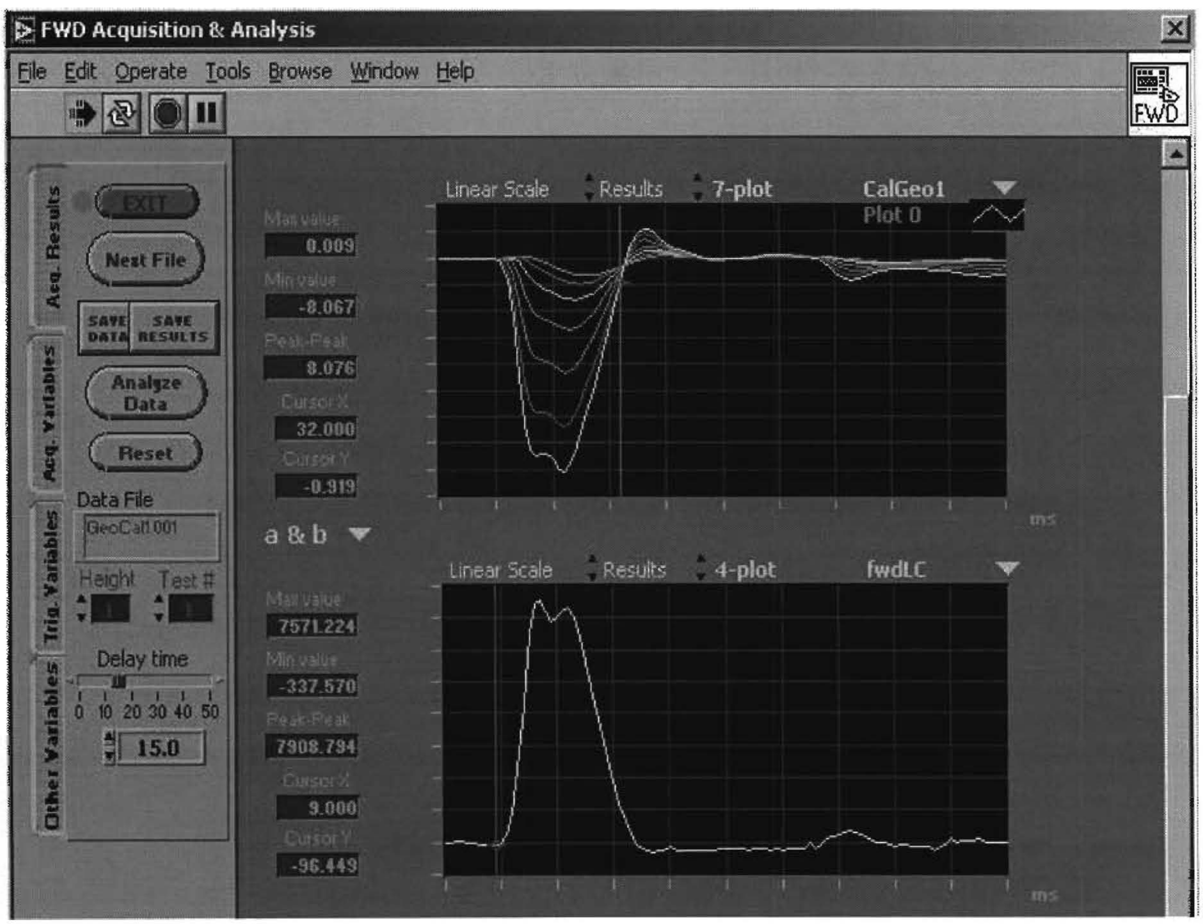


Figure 6.4 – Deflection Basin of Calibration Concrete Slab

The load cell calibration is executed in similar fashion as the geophone calibration. The one obvious difference is the number of sensors being collected and compared. Figure 6.5 displays the typical load cell calibration scenario; three calibration load cells (top) and the FWD load cell (bottom). The FWD load cell information is mostly used to compare signal shapes and to ensure that there are no glaring errors in the acquired data.

After the data from a set of drops is collected and analyzed, the results are saved into a spread sheet program for data manipulation and comparison against load cell data obtained from the FWD system.

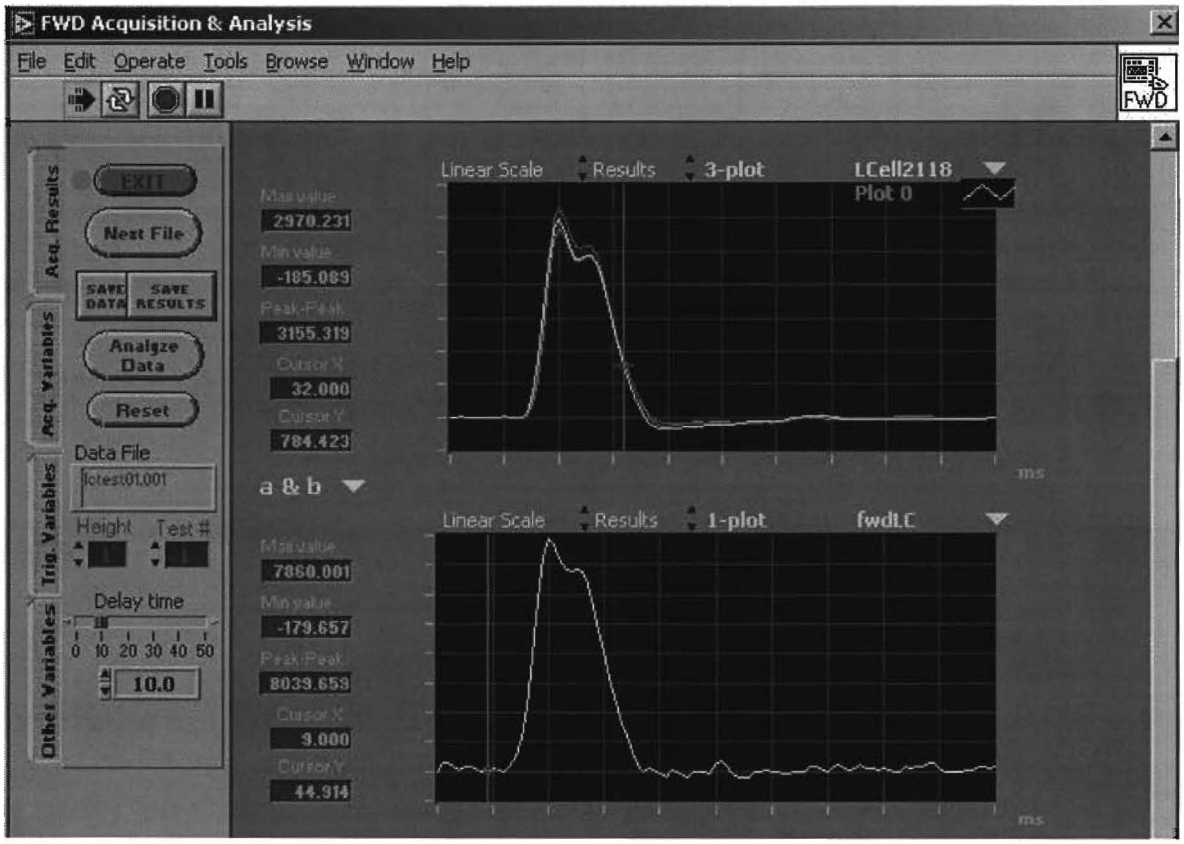


Figure 6.5 – Load Cell Comparison (Calibration Load Cells vs. FWD Load Cell)

Figures 6.6 and 6.7 show the results obtained from FWD069. A spreadsheet was prepared to bring the results from both, the Calibration System and the FWD system to determine the calibration factors for all the FWD sensors.

Comparison of FWD069 Deflections and Calibration Slab Geophones															
LabVIEW CalGeo1	FWD SD1	LabVIEW CalGeo2	FWD SD2	LabVIEW CalGeo3	FWD SD3	LabVIEW CalGeo4	FWD SD4	LabVIEW CalGeo5	FWD SD5	LabVIEW CalGeo6	FWD SD6	LabVIEW CalGeo7	FWD SD7	LabVIEW FWD LC	FWD Load
9.07	8.84	7.09	7.00	4.81	4.67	3.01	2.94	1.78	1.73	1.15	1.02	0.80	0.69	8792	8247
9.03	8.90	7.01	7.01	4.76	4.71	2.96	2.92	1.74	1.72	1.13	0.99	0.79	0.64	8889	8259
9.02	8.94	7.03	7.04	4.77	4.72	2.98	2.94	1.76	1.74	1.13	1.00	0.79	0.65	8889	8279
8.99	8.68	7.02	6.85	4.72	4.57	2.96	2.88	1.75	1.69	1.14	0.99	0.80	0.65	8889	7997
8.98	8.57	7.02	6.74	4.72	4.50	2.97	2.83	1.75	1.67	1.14	0.98	0.79	0.61	8889	7810
8.93	8.81	7.00	7.01	4.72	4.70	2.95	2.93	1.74	1.73	1.12	1.03	0.79	0.66	8792	8207
11.28	11.17	8.82	8.86	5.97	5.94	3.76	3.76	2.25	2.24	1.46	1.33	1.00	0.89	11401	10666
11.38	11.15	8.87	8.88	5.99	5.90	3.79	3.78	2.26	2.24	1.47	1.32	1.02	0.88	11449	10611
11.24	11.23	8.76	8.98	5.96	5.91	3.75	3.84	2.24	2.26	1.46	1.35	1.00	0.90	11401	10678
11.30	11.17	8.84	8.93	6.00	5.89	3.77	3.83	2.26	2.25	1.45	1.34	1.02	0.90	11449	10642
11.30	11.26	8.82	8.96	5.97	5.92	3.75	3.86	2.25	2.26	1.48	1.36	1.02	0.91	11449	10726
15.21	14.95	11.89	12.04	8.07	7.86	5.15	5.22	3.13	3.11	2.09	1.91	1.45	1.26	16038	14416
15.24	14.99	11.94	12.11	8.10	7.88	5.16	5.24	3.15	3.11	2.10	1.91	1.46	1.26	16087	14452
15.20	14.94	11.88	11.99	8.09	7.88	5.14	5.20	3.13	3.11	2.09	1.87	1.46	1.26	15990	14353
15.18	14.88	11.89	12.05	8.05	7.87	5.11	5.19	3.14	3.08	2.09	1.89	1.44	1.21	15942	14321
15.18	14.98	11.87	12.00	8.08	7.94	5.13	5.22	3.14	3.11	2.07	1.92	1.45	1.25	15894	14468
18.34	18.00	14.37	14.38	9.75	9.52	6.23	6.30	3.83	3.77	2.56	2.34	1.80	1.55	20290	18305
18.49	17.89	14.42	14.38	9.82	9.65	6.27	6.22	3.83	3.77	2.57	2.29	1.78	1.49	20290	18182
18.45	18.11	14.42	14.59	9.82	9.72	6.26	6.32	3.83	3.81	2.56	2.32	1.78	1.52	20241	18361
18.31	18.01	14.35	14.47	9.72	9.64	6.19	6.30	3.82	3.80	2.56	2.30	1.77	1.56	20000	18202
18.49	18.15	14.39	14.61	9.82	9.72	6.27	6.35	3.83	3.82	2.58	2.31	1.78	1.55	20145	18353

Figure 6.6 –Typical Spreadsheet Chart Containing Calibration Information

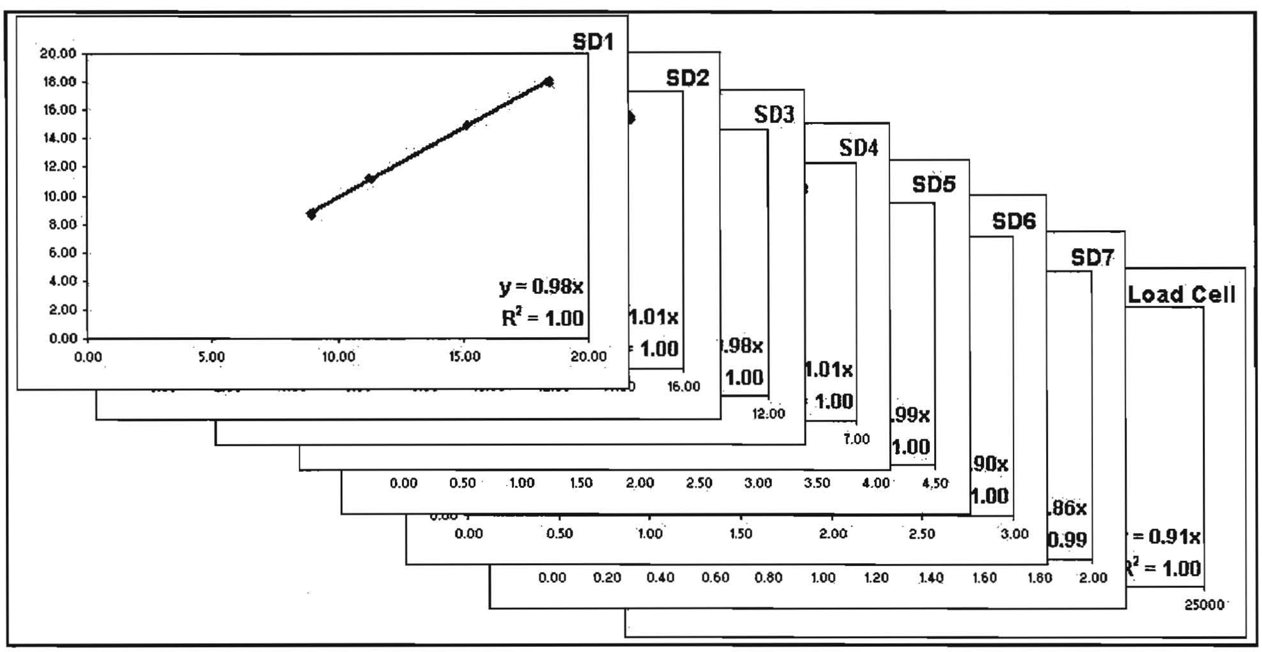


Figure 6.7 – Spreadsheet Graphs Depicting Calibration Information

Chapter 7

Example of Data Collection and Analysis

On December 2001 three FWDs were subjected to the calibration process described in the previous chapters. The results from this activity are summarized here in.

Preliminary Steps

Before being able to calibrate any FWD sensors, concrete slabs, reference sensors, data acquisition and computer program must be prepared. While the concrete slabs only need to be kept clean after their construction, the reference sensors need to be calibrated regularly. Tandon and Nazarian (1999) described in detail the process of calibrating each reference sensor. The reference load cells can be sent to the manufacturer for recalibration or can be calibrated in-house using a modern digital MTS system.

Table 7.1 – Calibration Factor of Reference Load Cells Provided by Manufacturer

Load Cell	Serial Number	Calibration Factor, mv/lb
1	2118	0.2770
2	1806	0.2426
3	2100	0.2480

Every reference deflection sensor should also be periodically calibrated in the laboratory as per Tandon and Nazarian (1999). The frequency response is then curve fitted to obtain the natural frequency, damping ratio and gain. Since a SDOF is similar to a high-pass filter, these three parameters can be numerically converted to poles, zeroes, and gain (see Tandon and Nazarian, 2000 for a detailed formulation). Table 7.2 contains the parameters of the reference deflection sensors used. Once calibrated, the deflection sensors are placed inside their respective holders. Although the holders are machined to very close specifications, a small amount of vacuum grease is placed in the bottom part of the holder to ensure that holder and sensor move as a single unit.

Table 7.2 - Calibration Values for Reference Deflection Sensors

Sensor	Poles	Natural Frequency (Hz)	Damping Ratio (%)	Gain (mV/in./sec)
1	-3.0268 ± i3.5473	4.663161	64.9%	-873.2
2	-2.9213 ± i3.2213	4.348688	67.2%	-862.4
3	-3.0766 ± i3.69100	4.805059	64.0%	-873.9
4	-3.2366 ± i3.7651	4.964998	65.2%	-896.2
5	-3.0399 ± i3.7812	4.851591	62.7%	-880.0
6	-3.1984 ± i3.1609	4.496726	71.1%	-885.9
7	-3.0886 ± i3.7662	4.870648	63.4%	-876.3

All zeros are equal to 0 ± 0i

Establishing Pre-calibration Repeatability and Reproducibility

Two sites, one flexible and one rigid located on UTEP property, were selected. The layer thickness at each site is summarized in Table7.3. The flexible site was a Parking lot. The rigid site was a breeze way near the Engineering building.

Table 7.3 – Layer Information of Selected Sites

Site	Condition	Layer Information
1	Flexible	1.5 in. ACP
		8 in. Granular Base
2	Rigid	6 in. PCC

The overall average deflections (based on five drops and three attempts) from the two sites at a load level of 9 kip are presented in Table 7.4. The deflections from the rigid and flexible sites were quite different. One should especially be aware of the very small deflections measured by Sensors 6 and 7 at the rigid site.

At each site, two thermocouples were installed to monitor the changes in pavement and air temperature during testing. The monitoring of temperature was essential to ensure that the change in temperature would not impact our study. In addition, tests were carried out at or after sunset to minimize the change in temperature during testing. In general, the average change in pavement temperature from beginning to end of testing was less than 3^{o}F at each site.

Table 7.4 – Average Deflections from Two Sites Normalized to 9 kips

Serial No.	Site	Average Deflections Normalized to 9 kip Load, mils						
		D1	D2	D3	D4	D5	D6	D7
FWD040	Flexible	27.1	14.5	6.5	3.7	2.5	1.9	1.5
	Rigid	10.2	7.1	4.2	2.3	1.2	0.4	0.3
FWD069	Flexible	26.2	13.9	6.4	3.7	2.4	1.8	1.4
	Rigid	9.7	6.6	4.0	2.2	1.0	0.3	0.3
FWD089	Flexible	26.5	14.5	6.5	3.6	2.4	1.8	1.5
	Rigid	10.7	7.2	4.3	2.3	1.1	0.4	0.3

The repeatability of each FWD was evaluated by repeating the test three times and reproducibility was evaluated by testing same location with the three FWDs. The following test protocol was followed at each site:

1) Measure Air and Pavement Temperature.

2) Perform FWD tests
   a) Perform 2 seating drops at a nominal load level of 12 kip.
   b) Drop load six times at four nominal load levels of 6 kip, 9 kip, 12 kip and 15 kip. At each load level, record peak loads and peak deflections.
   c) Lift load plate and drive away.

3) Perform Step 2 for each FWD

4) Repeat Steps 1 through 3 two additional times by driving away and repositioning FWD.

To identify the repeatability of each FWD, the coefficients of variation (COV) of the measured deflections or loads for the last five drops of each attempt were calculated. To determine the COVs from deflections, the deflections were first normalized to their appropriate nominal load levels i.e., 6 kip, 9 kip, 12 kip and 15 kip. For each load level, the average and maximum COVs from the three attempts were then determined. These values were used to assess the repeatability of each sensor. The average COV corresponds to the overall repeatability anticipated for a given device. On the other hand, the maximum of the three COVs corresponds to the worst-case scenario associated with a given device. To further summarize the results, the maximum COVs from all drops heights and all attempts were calculated to represent the repeatability of a given sensor.

Detailed results can be inspected in Appendix B. The average and maximum COVs for all sites are summarized in Table 7.5. Considering a COV of 2% as acceptable, most sensors are quite repeatable. For the flexible site, almost all sensors yielded a Coefficient of Variation of less than 2%. For the rigid site, all sensors except Sensors 6 and 7 are considered repeatable. A review of

Table 7.5 – Average and Maximum Coefficients of Variation from Sites at a Nominal Load of 9 kips

a) Flexible Site

Serial No.	Test Period	Average Coefficient of Variation							
		Load	D1	D2	D3	D4	D5	D6	D7
FWD040	Average	0.19%	0.16%	0.37%	0.47%	0.45%	1.24%	1.66%	1.78%
	Maximum	0.23%	0.21%	0.61%	0.69%	0.61%	1.81%	2.31%	2.62%
FWD069	Average	0.51%	0.24%	0.23%	0.35%	0.58%	0.81%	0.54%	0.85%
	Maximum	0.75%	0.31%	0.32%	0.54%	0.78%	1.14%	0.68%	1.79%
FWD089	Average	0.24%	0.18%	0.20%	0.19%	0.49%	0.50%	0.65%	0.64%
	Maximum	0.28%	0.21%	0.24%	0.23%	0.79%	0.73%	0.89%	0.75%

b) Rigid Site

Serial No.	Test Period	Average Coefficient of Variation							
		Load	D1	D2	D3	D4	D5	D6	D7
FWD040	Average	0.30%	0.30%	0.37%	0.38%	0.40%	1.65%	5.80%	6.17%
	Maximum	0.36%	0.36%	0.46%	0.55%	0.42%	2.03%	7.67%	13.38%
FWD069	Average	0.60%	0.28%	0.32%	0.35%	0.50%	1.04%	3.04%	3.97%
	Maximum	1.09%	0.52%	0.67%	0.72%	1.07%	2.15%	6.01%	6.27%
FWD089	Average	0.42%	0.25%	0.32%	0.23%	0.57%	1.08%	2.12%	5.88%
	Maximum	0.65%	0.36%	0.38%	0.36%	0.94%	1.48%	3.26%	10.51%

the average deflections for this site in Table 7.4 reveals that the large coefficients of variations observed for these sensors are due to very small deflections at the site, and should not be considered as problems with the FWD system.

To evaluate the reproducibility of the FWD fleet at each site, for each drop height and for each sensor (either geophone or load cell), the average value from the last five drops for each attempt and each device was determined separately. In addition, an overall average that included all sites and all FWDs was determined. Considering this grand average as the "baseline" value, the percent difference between each average and the baseline value was calculated from:

$$Difference = \frac{AvgValue - BaselineAvg}{BaselineAvg} * 100\% \qquad (7.1)$$

To summarize the results further, the differences measured from the three attempts for each FWD were averaged. In addition, the largest of the three values was also noted. For a reproducible fleet, all FWDs should measure deflections and loads that are close to the baseline. In that case, the average and maximum deviation from the baseline will be rather small.

The average deviations from the baseline for Drop Height 2 are summarized in Table 7.6. As a whole, a number of sensors are quite reproducible. However, a few yielded values that were outside the 5% selected band that is considered as reproducible.

Table 7.6 – Average Difference from Baseline Values from Sites at a Nominal Load of 9 kips

a) Flexible Site

Serial No.	Average Difference from Baseline Value							
	Load	D1	D2	D3	D4	D5	D6	D7
FWD040	-5.97%	3.48%	3.47%	2.34%	2.43%	2.53%	1.68%	0.94%
FWD069	-0.95%	-1.54%	3.49%	1.75%	0.65%	0.53%	-1.30%	-0.85%
FWD089	6.92%	-1.94%	-6.96%	-4.09%	-3.07%	-3.06%	-0.38%	-0.09%

b) Rigid Site

Serial No.	Average Difference from Baseline Value							
	Load	D1	D2	D3	D4	D5	D6	D7
FWD040	-4.22%	3.82%	4.52%	1.60%	-0.60%	-1.45%	5.42%	-26.04%
FWD069	-3.97%	1.60%	3.24%	5.04%	5.44%	6.80%	3.36%	13.27%
FWD089	8.18%	-5.42%	-7.76%	-6.64%	-4.83%	-5.36%	-8.77%	12.77%

Preliminary Calibration

Table 7.7 shows the load cell calibration data collected from the three reference load cells for FWD Serial No. 069. Figure 7.1 shows how the reference load cell totals are then compared against the load values measured with the FWD system. The calibration factor is the inverse of the slope of the linear curve fit of the graphed data points, in this case, about 1.09.

Table 7.8 shows the deflections collected with the FWD system and those of the reference sensors collected with the calibration system. Each pair of columns is then compared against each other and curve fitted, in the same way as the load cell data. This is done to obtain calibration factors for each deflection sensor. Table 7.9 contains a summary of all calibration factors from the three FWD systems. The table has been prepared to easily determine which sensors need to go through a comprehensive calibration procedure.

The load cells of all three FWDs demonstrate calibration factors that are greater than 2% recommended by the manufacturer. This is occurring possibly because the calibration load cell previously used is out of calibration.

For all three FWDs, the calibration factors for Sensors 6 and 7 are large. But since these sensors experienced deflections less than 1 mil, the differences are not considered significant. The slab used for this study is extremely stiff. We prefer to use such a slab during the development of the calibration system because if the results are reproducible on such a stiff system, it should be even more reproducible on a slab that provides larger deflections.

Table 7.7 – Load Cell Calibration Data for FWD 069

Drop Height	Loads from Reference Load Cell (lbs)				Load from FWD (lb)
	Load Cell 1	Load Cell 2	Load Cell 3	Total	
1	2758	3341	2913	9013	7885
	2741	3341	2913	8996	7870
	2741	3371	2923	9036	7882
	2705	3310	2913	8930	7882
	2679	3300	2894	8874	7790
2	3419	4297	3770	11487	10257
	3384	4297	3790	11471	10289
	3366	4266	3770	11404	10154
	3375.	4307	3790	11472	10253
	3366	4307	3790	11464	10217
3	4671	5927	5256	15855	14607
	4680	5897	5217	15794	14516
	4653	5917	5188	15759	14492
	4688	5927	5188	15804	14536
	4662	5937	5197	15797	14484
4	5870	7436	6487	19794	18492
	5870	7457	6389	19716	18413
	5861	7447	6418	19726	18441
	5834	7406	6398	19640	18305
	5808	7396	6379	19584	18282

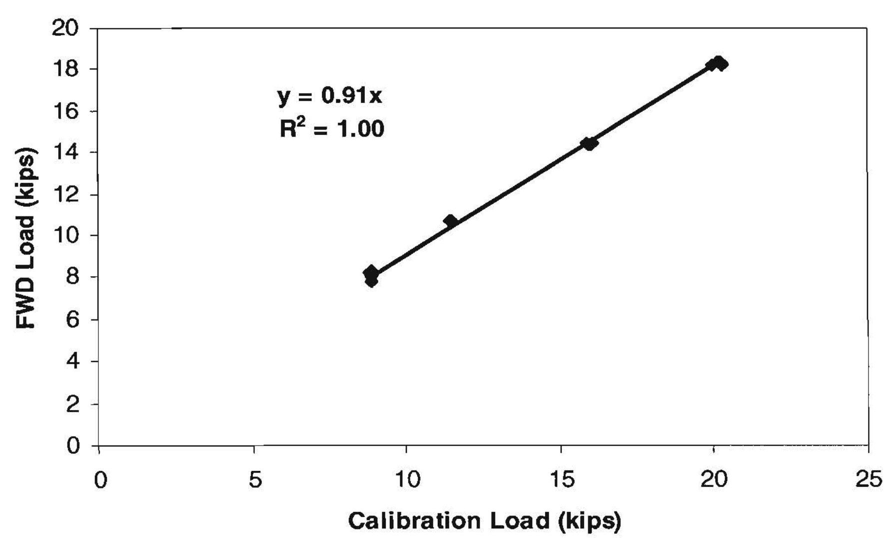


Figure 7.1 – Graphical Determination of Load Cell Calibration Factor

Table 7.8 – Deflection Sensor Calibration Data from FWD069

Drop Height	Sensor 1		Sensor 2		Sensor 3		Sensor 4		Sensor 5		Sensor 6		Sensor 7	
	FWD	CAL	FWD	CAL	FWD	CAL	FWD	CAL	FWD	CAL	FWD	CAL	FWD	CAL
1	8.90	9.03	7.01	7.01	4.71	4.76	2.92	2.96	1.72	1.74	0.99	1.13	0.64	0.79
	8.94	9.02	7.04	7.03	4.72	4.77	2.94	2.98	1.74	1.76	1.00	1.13	0.65	0.79
	8.68	8.99	6.85	7.02	4.57	4.72	2.88	2.96	1.69	1.75	0.99	1.14	0.65	0.80
	8.57	8.98	6.74	7.02	4.50	4.72	2.83	2.97	1.67	1.75	0.98	1.14	0.61	0.79
	8.81	8.93	7.01	7.00	4.70	4.72	2.93	2.95	1.73	1.74	1.03	1.12	0.66	0.79
2	11.17	11.28	8.86	8.82	5.94	5.97	3.76	3.76	2.24	2.25	1.33	1.46	0.89	1.00
	11.15	11.38	8.88	8.87	5.90	5.99	3.78	3.79	2.24	2.26	1.32	1.47	0.88	1.02
	11.23	11.24	8.98	8.76	5.91	5.96	3.84	3.75	2.26	2.24	1.35	1.46	0.90	1.00
	11.17	11.30	8.93	8.84	5.89	6.00	3.83	3.77	2.25	2.26	1.34	1.45	0.90	1.02
	11.26	11.30	8.96	8.82	5.92	5.97	3.86	3.75	2.26	2.25	1.36	1.48	0.91	1.02
3	14.95	15.21	12.04	11.89	7.86	8.07	5.22	5.15	3.11	3.13	1.91	2.09	1.26	1.45
	14.99	15.24	12.11	11.94	7.88	8.10	5.24	5.16	3.11	3.15	1.91	2.10	1.26	1.46
	14.94	15.20	11.99	11.88	7.88	8.09	5.20	5.14	3.11	3.13	1.87	2.09	1.26	1.46
	14.88	15.18	12.05	11.89	7.87	8.05	5.19	5.11	3.08	3.14	1.89	2.09	1.21	1.44
	14.98	15.18	12.00	11.87	7.94	8.08	5.22	5.13	3.11	3.14	1.92	2.07	1.25	1.45
4	18.00	18.34	14.38	14.37	9.52	9.75	6.30	6.23	3.77	3.83	2.34	2.56	1.55	1.80
	17.89	18.49	14.38	14.42	9.65	9.82	6.22	6.27	3.77	3.83	2.29	2.57	1.49	1.78
	18.11	18.45	14.59	14.42	9.72	9.82	6.32	6.26	3.81	3.83	2.32	2.56	1.52	1.78
	18.01	18.31	14.47	14.35	9.64	9.72	6.30	6.19	3.80	3.82	2.30	2.56	1.56	1.77
	18.15	18.49	14.61	14.39	9.72	9.82	6.35	6.27	3.82	3.83	2.31	2.58	1.55	1.78

Table 7.9 – Calibration Factors Determined for Three FWDs

Sensor	FWD 040		FWD 069		FWD 089	
	Calibration Factor	R^2	Calibration Factor	R^2	Calibration Factor	R^2
Load Cell	0.96	1.00	1.10	1.00	0.94	1.00
SD1	1.01	1.00	1.02	1.00	0.95	1.00
SD2	1.01	1.00	0.99	1.00	1.01	1.00
SD3	1.01	1.00	1.02	1.00	1.02	1.00
SD4	1.02	1.00	0.99	1.00	1.04	1.00
SD5	1.01	1.00	1.01	1.00	1.02	1.00
SD6	1.09	0.99	1.11	1.00	1.07	1.00
SD7	1.13	0.99	1.16	0.99	1.13	1.00

Comprehensive Calibration

Aside from Sensors 6 ad 7, all other sensors from FWD 040 and 069 are within the manufacturer's tolerance. For FWD 080, two sensors (Sensors 1 and 4) exhibit larger than anticipated calibration factors. As such, these two sensors should be subjected to comprehensive calibration.

As an example, the results from the calibration of Sensor 4 on a shaker inside and outside the holder are shown in Figure 7.2. The two curves look reasonably similar at the scale shown. However, when one compares the ratio of the two calibration curves (see Figure 7.3), it becomes clear how these differences can contribute to the larger than usual calibration. In this case, the holder should be replaced.

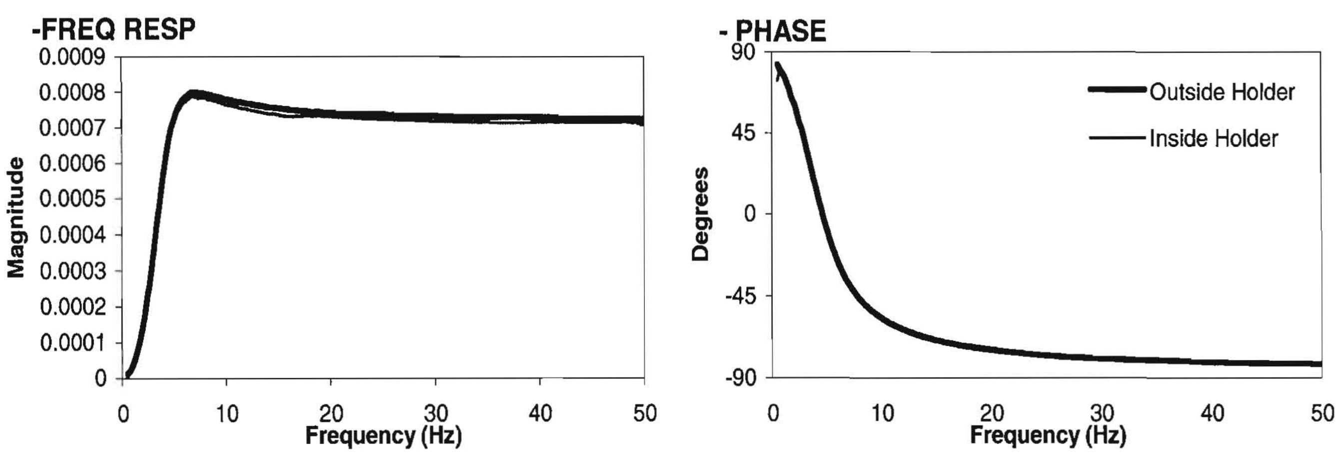


Figure 7.2 - Comparison of Calibration of Sensor 4 of FWD 089 Inside and Outside Sensor Holder

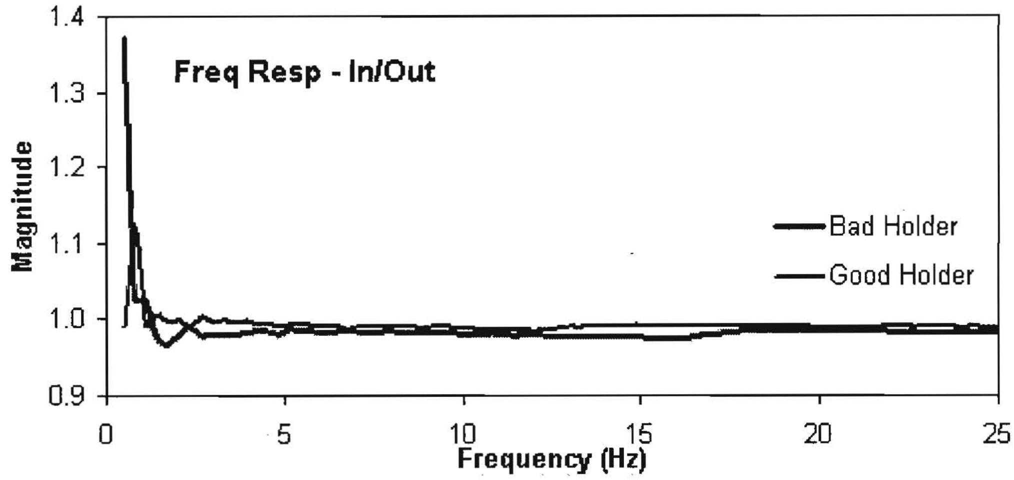


Figure 7.3 - Variation in Ratio of Calibration Curves for a Bad and a Good Holder

Due to time limitations, the characteristics of the FWD systems were not measured. As such, they are not included herein.

Establishing Post-calibration Repeatability and Reproducibility

After the three FWDs were calibrated, they were subjected to the same process described above to reevaluate their repeatability and reproducibility. The complete set of data compiled in this step is included in Appendix B. For the sake of brevity, Tables 7.5 (providing information about repeatability) and Table 7.6 (providing information about reproducibility) are represented again but with the post-calibration results. A comparison of Tables 7.5 and 7.10 indicates that the repeatability of the system is quite similar before and after calibration. To better demonstrate this matter, the coefficient of variation of each sensor from each site and each repeat from before calibration is compared with the same after the calibration. In the graph, the results from Sensors 6 and 7 on the rigid site are not shown. We believe that the deflections measured with these two sensors are too small to be a representative of the behavior of these sensors. Almost all COVs from before calibration and all COVs after calibration are within 2% limit set for a repeatable sensor.

To appreciate the changes in the reproducibility of the fleet, a comparison of Tables 7.6 and 7.11 is appropriate. From these two tables, the reproducibility of the system has significantly improved. To better illustrate the improvements in reproducibility, the deviations from baseline before and after calibration are compared. Once again, the results from Sensors 6 and 7 on rigid sections are removed. About two dozens of data points from before calibration lie outside the 5% bound. Only about half a dozen data points from after calibration are outside the 5% range with almost all of them within a 6% range. This demonstrates that the new calibration methodology seems to be successful in improving the reproducibility of the system.

Table 7.10 - Average and Maximum Coefficients of Variation from Sites at a Nominal Load of 9 kips (Post-calibration)

a) Flexible Site

Serial No.	Test * Period	Average Coefficient of Variation							
		Load	**D1**	**D2**	**D3**	**D4**	**D5**	**D6**	**D7**
FWD040	Average	0.35%	0.44%	0.34%	0.45%	0.56%	0.63%	1.60%	1.85%
	Maximum	0.72%	0.72%	0.52%	0.62%	0.69%	0.74%	2.38%	3.02%
FWD069	Average	0.50%	0.25%	0.22%	0.25%	0.59%	0.61%	0.52%	1.50%
	Maximum	1.08%	0.35%	0.35%	0.43%	1.25%	0.90%	0.78%	2.67%
FWD089	Average	0.22%	0.17%	0.17%	0.38%	0.35%	0.54%	0.98%	0.84%
	Maximum	0.31%	0.22%	0.20%	0.55%	0.47%	0.77%	1.38%	1.22%

b) Rigid Site

Serial No.	Test * Period	Average Coefficient of Variation							
		Load	**D1**	**D2**	**D3**	**D4**	**D5**	**D6**	**D7**
FWD040	Average	0.29%	0.28%	0.45%	0.49%	0.96%	1.24%	3.09%	6.44%
	Maximum	0.42%	0.39%	0.58%	0.82%	1.86%	1.72%	4.65%	7.99%
FWD069	Average	1.12%	0.44%	0.27%	0.69%	0.51%	0.96%	4.45%	4.95%
	Maximum	1.35%	0.62%	0.39%	0.77%	0.71%	1.38%	6.95%	7.41%
FWD089	Average	0.23%	0.30%	0.36%	0.24%	0.31%	0.94%	1.01%	2.99%
	Maximum	0.29%	0.35%	0.52%	0.28%	0.41%	1.50%	1.22%	3.37%

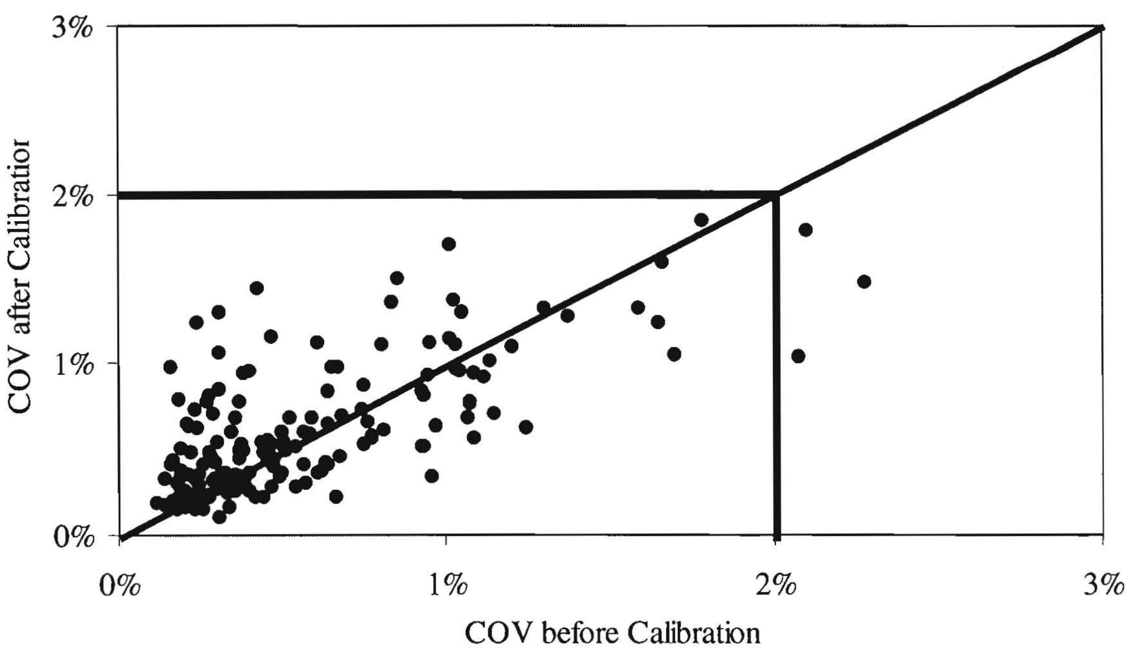


Figure 7.4 – Overall Repeatability before and after calibration.

Table 7.11 - Average Difference from Baseline Values from Sites at a Nominal Load of 9 kips (Post-calibration)

a) Flexible Site

Serial No.	Average Difference from Baseline Value							
	Load	D1	D2	D3	D4	D5	D6	D7
FWD040	-1.96%	-3.54%	-2.06%	0.14%	-1.35%	-1.40%	-2.02%	-1.19%
FWD069	1.19%	-1.34%	3.58%	0.81%	2.26%	0.42%	-0.40%	1.60%
FWD089	0.76%	4.88%	-1.52%	-0.94%	-0.90%	0.98%	2.42%	-0.41%

b) Rigid Site

Serial No.	Average Difference from Baseline Value							
	Load	D1	D2	D3	D4	D5	D6	D7
FWD040	-1.20%	-1.96%	-2.07%	-0.02%	-1.30%	-5.55%	-3.32%	-12.87%
FWD069	-1.58%	2.22%	5.67%	4.58%	6.14%	5.76%	12.15%	10.48%
FWD089	2.78%	-0.27%	-3.60%	-4.56%	-4.85%	-0.21%	-8.83%	2.39%

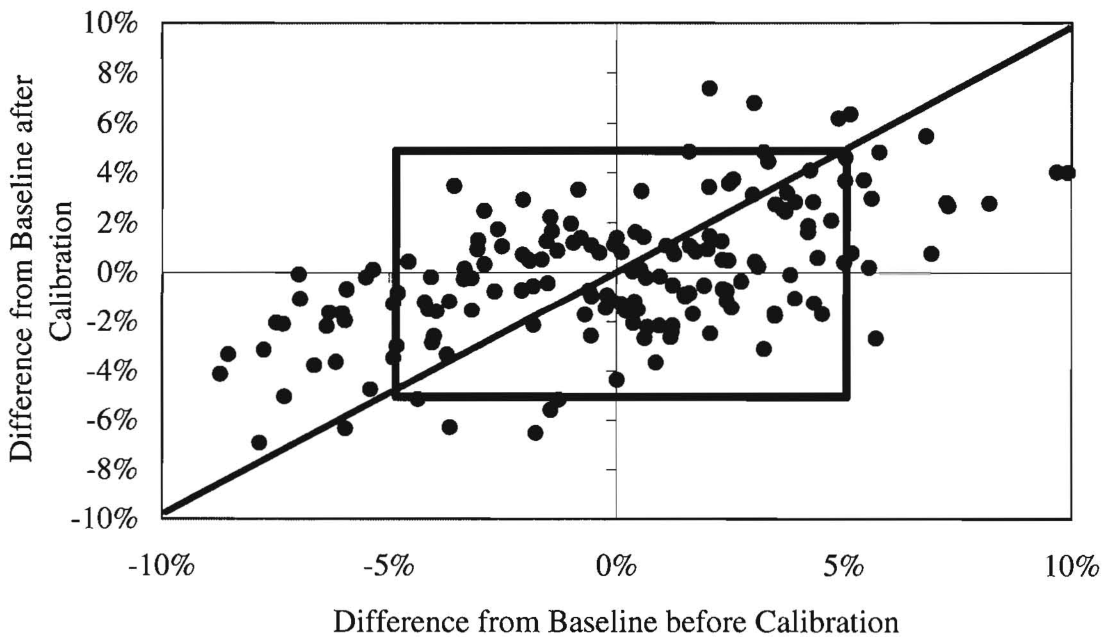


Figure 7.5 - Overall Reproducibility before and after Calibration

Chapter 8

Validation of Calibration Process

To validate the new calibration process, a facility was developed and tested at the Texas A&M Riverside Campus. Upon completion of the facility, four FWDs were calibrated using the protocol included in Appendix A. A set of repeatability and reproducibility tests was then carried out at the original sites used to establish the repeatability of the TxDOT fleet in December 1999. The results of this activity are reported here.

Development of Facility

The new calibration facility was constructed in a concrete slab on the existing runway at the Texas A&M Riverside Campus between July 13 and July 18, 2002. As shown in Figure 8.1, seven calibration sensors and a load calibration plate were retrofitted into the existing slab. A water proof box was retrofitted on the side of the runway to house all the wires. A shake table was also placed in a concrete box for comprehensive calibration of sensors.

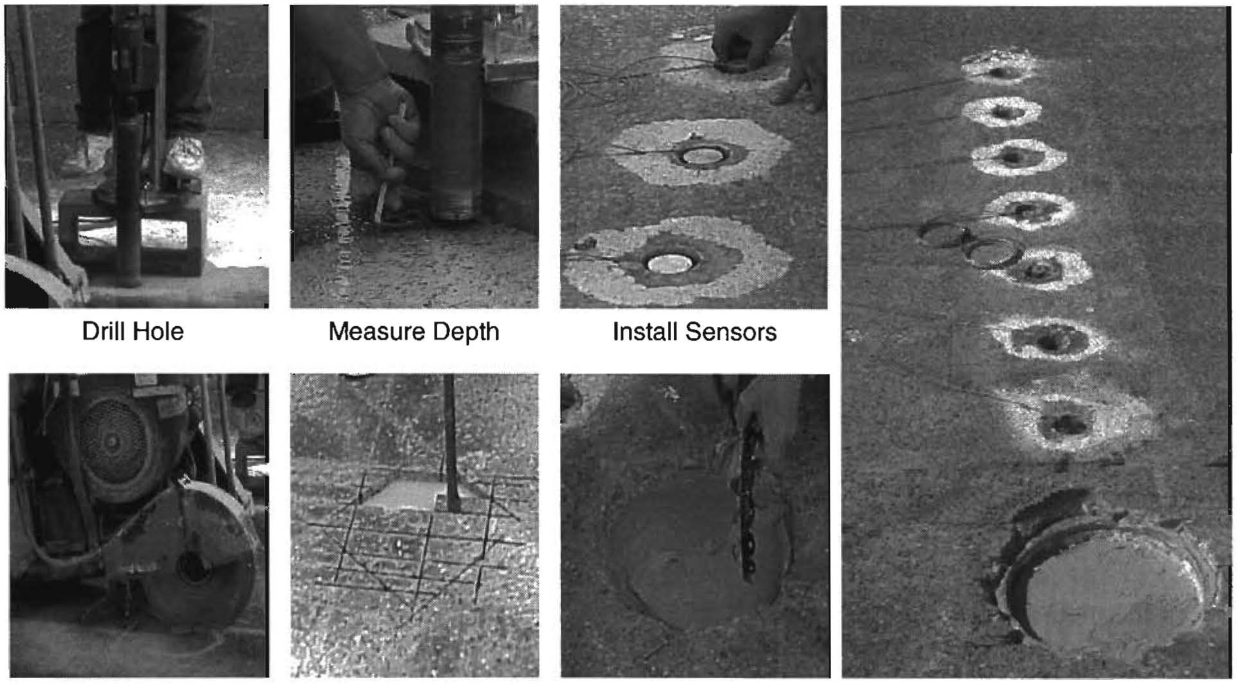
The construction of the facility in such a short period of time was only possible because of close collaboration among the staff of TxDOT, Texas Transportation Institute and UTEP.

Selection of FWDs

Four FWDs were selected by TxDOT staff for the validation process. The four FWDs, as summarized in Table 8.1, were more than ten years old. Since they were acquired at different times, they demonstrated different characteristics. TxDOT calibrates the entire FWD fleet annually using the SHRP procedure. The last time that each FWD had been calibrated using the SHRP protocol is also reflected in the table.

Site Selection

The three pavement sections used in the benchmark study were also used in this study. Two flexible and one rigid site were tested. The layering at each site is summarized in Table 8.2. The sites are extensively described in Rocha et al. (2002).



Drill Hole Measure Depth Install Sensors

Cutting slab Chipping slab Smooth/Level Cavity

Figure 8.1 Construction of Calibration Facility.

Table 8.1 – FWD Units Selected for Validation of New Calibration Process

Serial No	District	Year of Acquisition	Last SHRP Calibration
038	Houston	1986	October 2001
046	Bryan	1987	March 2001
071	Beaumont	1989	February 2002
090	San Antonio	1990	March 2002

Table 8.2 – Layer Information of Selected Sites

Site	Condition	Layer Information
1	Strong Flexible	5 in. (125 mm) ACP
		12 in. (300 mm) Stabilized Base
2	Weak Flexible	1.5 in. (37 mm) ACP
		10 in. (250 mm) Granular Base
3	Rigid	8 in. (200 mm) PCC

The overall average deflections (based on five drops and three attempts) from the three sites at a load level of 9 kips (40 kN) from the validation activity are presented in Table 8.3. Significant differences exist between the deflections from the two flexible sites. Therefore, the impact that the flexibility of the site had on the resulting reproducibility and repeatability could be observed. The deflections from the rigid and strong flexible sites are fairly close. This information can be used to study the impact of the top pavement layer on the reproducibility of the fleet.

Table 8.3 – Average Deflections from Three Sites Normalized to 9 kips

a) Site 1

Serial	Average Deflections Normalized to 9 kip Load, mils						
No.	D1	D2	D3	D4	D5	D6	D7
038	9.04	5.64	3.01	1.91	1.47	1.23	1.08
046	9.22	5.73	2.96	1.98	1.51	1.26	1.12
071	8.85	5.57	3.03	1.98	1.52	1.27	1.15
090	9.22	5.76	3.17	1.99	1.55	1.30	1.14

b) Site 2

Serial	Average Deflections Normalized to 9 kip Load, mils						
No.	D1	D2	D3	D4	D5	D6	D7
038	38.23	21.33	10.31	6.00	4.17	3.26	2.72
046	38.61	21.85	10.34	6.13	4.22	3.27	2.80
071	36.89	20.99	10.29	6.10	4.26	3.29	2.85
090	37.93	21.37	10.71	6.06	4.25	3.28	2.77

c) Site 3

Serial	Average Deflections Normalized to 9 kip Load, mils						
No.	D1	D2	D3	D4	D5	D6	D7
038	6.55	5.91	4.57	3.36	2.54	1.87	1.29
046	6.71	6.02	4.61	3.49	2.56	1.87	1.32
071	6.74	5.87	4.64	3.48	2.57	1.91	1.39
090	6.88	6.05	4.83	3.59	2.68	1.95	1.38

Site Preparation

A detailed description of site preparation is included in Rocha et al. (2002). The location of the load plate and the orientation of the sensors were clearly marked to ensure that the same point was tested each time. To facilitate the precise positioning of the FWD at each test location, the site was striped with masking tape from about 30 ft (10 m) before the test location. This strategy was effective in minimizing the set up time and as such the overall test period.

Tests were carried out after sunset to minimize the change in temperature during testing. At each site, two thermocouples were installed to monitor the changes in pavement and air temperature during testing. The average change in pavement temperature from beginning to end of testing was less than 2°F (1°C) at each site.

Test Protocol

The repeatability of each FWD was evaluated by repeating the test three times and reproducibility was evaluated by testing the same location with four FWDs. The following test protocol was followed at each site:

1) Measure Air and Pavement Temperature
2) Perform FWD tests
   a) Perform 2 seating drops at a nominal load level of 12 kip (53 kN).
   b) Drop load six times at four nominal load levels of 6 kip (27 kN), 9 kip (40 kN), 12 kip (53 kN) and 15 kip (67 kN). At each load level, record peak loads and peak deflections for all the drops and record deflection time history for drops 2, 4 and 6.
   c) Lift load plate and drive away
3) Perform Step 2 for each FWD
4) Repeat Steps 1 through 3 two additional times by driving away and repositioning the FWD

Data Analysis

In total, 384 deflection basin data sets were collected so that the effectiveness of the new calibration protocol in terms of improving the reproducibility of the FWD fleet can be evaluated. A single FWD is deemed repeatable if under identical testing conditions at a given test site, it provides loads and deflections from multiple drops that vary less than the tolerance suggested by the manufacturer (2% in this case). A fleet is said to be reproducible when all FWDs operated by various crews, produce similar deflection basins for a specific test site under identical testing conditions. As discussed by Rocha et al. (2002), a level of reproducibility of 5% was set as the goal to be achieved by the end of this project. The raw data are included in Appendix C for completeness.

Repeatability

To identify the repeatability of each FWD, the coefficients of variation (COV) of the measured deflections or loads for the last five drops of each attempt were calculated. To determine the COVs from deflections, the deflections were first normalized to their appropriate nominal load levels i.e., 6 kip, 9 kip, 12 kip and 15 kip (27 kN, 40 kN, 53 kN, and 67 kN). For each load level, the average and maximum COVs from the three attempts were then determined. These values were used to assess the repeatability of each sensor. The average COV corresponds to the overall repeatability anticipated for a given device. On the other hand, the maximum of the three COVs corresponds to the worst-case scenario associated with a given device. To further summarize the results, the maximum COVs from all drops heights and all attempts were calculated to represent the repeatability of a given sensor.

Typical average COVs of the measured parameters for Drop Height 2 (nominal load of 9 kip, 40 kN) at Site 3 are shown in Figure 8.2. The average COVs for this particular height are less than 2% for all sensors which is an improvement over the year 2000 thump-off.

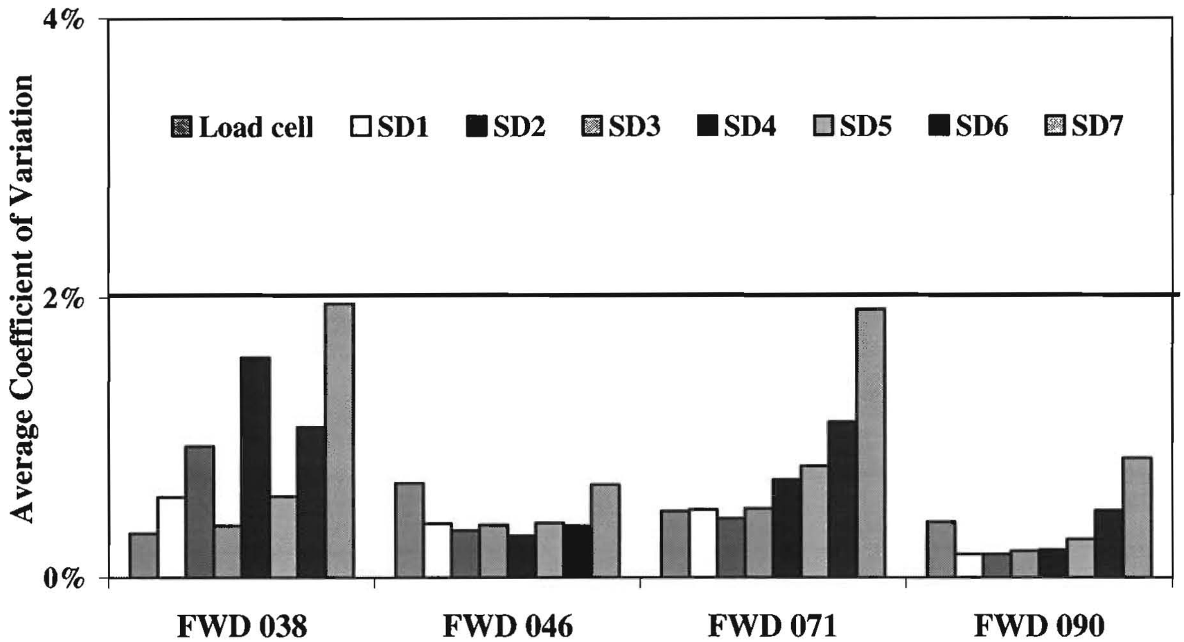


Figure 8.2 – Typical Coefficients of Variation Measured at Site 3 for Drop Height 2

The average COVs for all sites are summarized in Table 8.4. In all cases the 2% repeatability is achieved. For two FWDs, the average values for sensors 7 are barely below 2%.

The maximum COVs from the three attempts and from the four different drop heights for each FWD are summarized in Figure 8.3. The maximum COVs for units 046, 071 and 090 are almost never greater than 3%. These values are observed at Site 3 (rigid pavement) at Drop Height 1 (a nominal load of 6 kips, 27 kN). Considering that the average deflections are less than 2 mils (50 microns), the differences can be attributed to the absolute error anticipated for the calculation of defections. The manufacturer specifies this error to be on the order of 0.1 mil (2.5 microns)

The worst performance is observed with FWD 038 in which in one occasion for one series of five drops at Drop Height 1 (a nominal load of 6 kips, 27 kN) at the rigid pavement site the maximum COVs for three sensors are higher than 4%. The reason for such an anomalous measurement at that particular test sequence is not known. But it certainly contributes to the larger than normal average COVs reported in Figure 8.2 for Sensors 2 and 4 of the FWD 038. The average deflection for sensor 7 at site 3 is about 0.7 mils (18 microns); therefore, a COV as high as 8% can provide deflections well within the accuracy of calculation by the FWD algorithm.

Table 8.4 – Average Coefficients of Variation from Three Sites at Drop Height 2, with a Nominal Load of 9 kips (40 kN)

a) Site 1

Serial No.	Average Coefficient of Variation							
	Load	D1	D2	D3	D4	D5	D6	D7
038	0.40%	0.54%	0.29%	0.29%	0.64%	0.70%	0.95%	0.71%
046	0.85%	0.55%	0.44%	0.59%	0.49%	0.82%	0.63%	0.58%
071	0.40%	0.41%	0.52%	0.56%	0.96%	0.99%	1.04%	1.27%
090	0.58%	0.38%	0.31%	0.26%	0.29%	0.33%	0.30%	0.53%

b) Site 2

Serial No.	Average Coefficient of Variation							
	Load	D1	D2	D3	D4	D5	D6	D7
038	0.23%	0.27%	0.36%	0.38%	0.58%	0.61%	0.73%	0.81%
046	0.52%	0.68%	0.70%	0.69%	0.64%	0.67%	0.87%	0.83%
071	0.41%	0.51%	0.62%	0.57%	0.59%	0.68%	0.60%	0.71%
090	0.33%	0.46%	0.47%	0.44%	0.48%	0.58%	0.75%	0.86%

c) Site 3

Serial No.	Average Coefficient of Variation							
	Load	D1	D2	D3	D4	D5	D6	D7
038	0.31%	0.57%	0.94%	0.37%	1.57%	0.58%	1.08%	1.96%
046	0.67%	0.38%	0.33%	0.37%	0.30%	0.39%	0.37%	0.66%
071	0.47%	0.48%	0.42%	0.49%	0.70%	0.80%	1.11%	1.92%
090	0.39%	0.17%	0.17%	0.19%	0.20%	0.27%	0.48%	0.85%

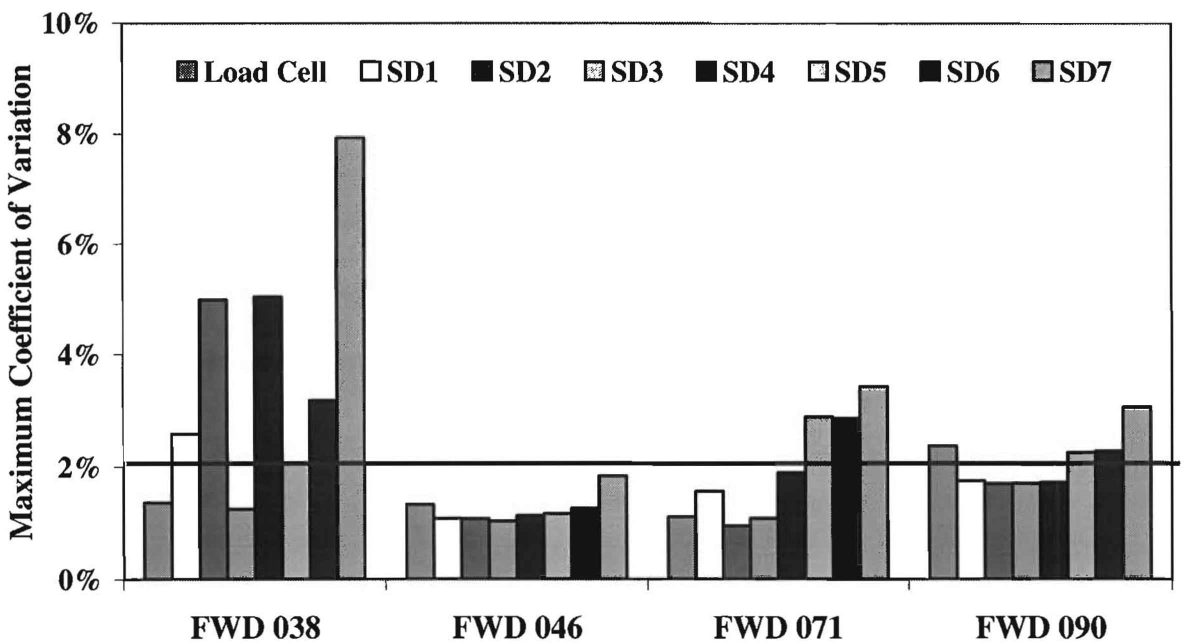


Figure 8.3 – Maximum Coefficients of Variation Observed for All Sites and All Drop Heights

Reproducibility

To evaluate the reproducibility of the FWD fleet, the data reduction process described below was followed. At each site, for each drop height and for each sensor (either geophone or load cell), the average value from the last five drops for each attempt and each device was determined separately. This corresponds to 24 average values per sensor, per drop height per site. In addition, an overall average that included all three attempts from all FWDs at each site was determined. Considering this grand average as the "baseline" value, the percent difference between each average and the baseline value was calculated from:

$$Difference = \frac{AvgValue - BaselineAvg}{BaselineAvg} * 100\% \qquad (8.1)$$

To summarize the results further, the differences measured from the three attempts for each FWD were averaged. In addition, the largest of the three values was also noted. The process was repeated for three sites, eight sensors, and four drop heights. The average deviations from the baseline for Drop Height 2 (a nominal load of 9 kips, 40 kN) are summarized in Table 8.5. While there are variations between the different devices, these are not as large as those observed from the data collected in the Year 2000. In no case the deviation from the baseline is greater than 5%.

Table 8.5 – Average Difference from Baseline Values from Three Sites at Drop Height 2, with a Nominal Load of 9 kips (40 kN)

a) Site 1

Serial No.	Average Difference from Baseline Value							
	Load	D1	D2	D3	D4	D5	D6	D7
038	-0.24%	0.50%	0.67%	1.19%	3.02%	2.97%	2.67%	3.88%
046	1.40%	-1.51%	-0.94%	2.79%	-0.86%	0.06%	0.37%	0.50%
071	-2.04%	2.59%	1.87%	0.31%	-0.92%	-0.77%	-0.28%	-2.38%
090	0.88%	-1.57%	-1.60%	-4.29%	-1.24%	-2.26%	-2.76%	-2.00%

b) Site 2

Serial No.	Average Difference from Baseline Value							
	Load	D1	D2	D3	D4	D5	D6	D7
038	0.49%	-0.83%	0.25%	1.01%	1.23%	1.27%	0.42%	2.20%
046	1.29%	-1.83%	-2.15%	0.72%	-0.99%	0.24%	0.21%	-0.48%
071	-2.62%	2.70%	1.83%	1.13%	-0.44%	-0.84%	-0.53%	-2.32%
090	0.84%	-0.04%	0.07%	-2.86%	0.21%	-0.67%	-0.10%	0.60%

c) Site 3

Serial No.	Average Difference from Baseline Value							
	Load	D1	D2	D3	D4	D5	D6	D7
038	0.59%	2.49%	0.91%	1.95%	3.54%	1.76%	1.56%	4.28%
046	0.23%	0.17%	-1.00%	1.13%	-0.18%	1.13%	1.65%	1.93%
071	-2.68%	-0.26%	1.58%	0.43%	-0.13%	0.67%	-0.50%	-3.48%
090	1.85%	-2.41%	-1.48%	-3.51%	-3.22%	-3.56%	-2.72%	-2.73%

The differences from the baseline values for all sensors at the three sites are shown in Figure 8.4. Based on average deviations from the baseline value, the reproducibility of the fleet is site dependent. For site 1, strong flexible site, the maximum deviation was above 5% once, both occurring at Drop Height 1 for FWD 071. The same phenomenon occurs one more time for the same FWD at Site 2 (weak flexible). No plausible reason for this behavior can be offered at this time. Such a transient behavior can only be traced to the electronic components or an electrical surge from the charging system during the operation of the device.

The largest discrepancy was for FWD038 at site 3 (rigid) where deflections from sensors 4 through 7 are less than 2 mils (50 microns) at a load level of 9 kips (40 kN). In this case, the drop height 1 for FWD 038 is not as reproducible as the other three; however given the small deflection values, these levels are acceptable.

The histogram in Figure 8.5 demonstrates the reproducibility of the fleet from all measurements made with the four FWDs. More than 98% of the measurements fall within a ±5% band. Seven measurements out 384 do not fall within the 5% range. Most of these points correspond to isolated measurements at Drop Height 1 as indicated before.

To sum up the effectiveness of the procedure, the cumulative absolute deviations from the baseline (errors in reproducibility) from benchmark study conducted in January 2000 are compared with those from this study in Figure 8.6. The initial thump off provided a reproducibility of better than 5% in about 70% of the measurements. Under the new procedure more than 98% of the measurements are reproducible within 5% and 70% of the measurements are reproducible within 2%. Even though more experience is needed with the new system, it seems that developed calibration protocol does improve the reproducibility of the FWD fleet.

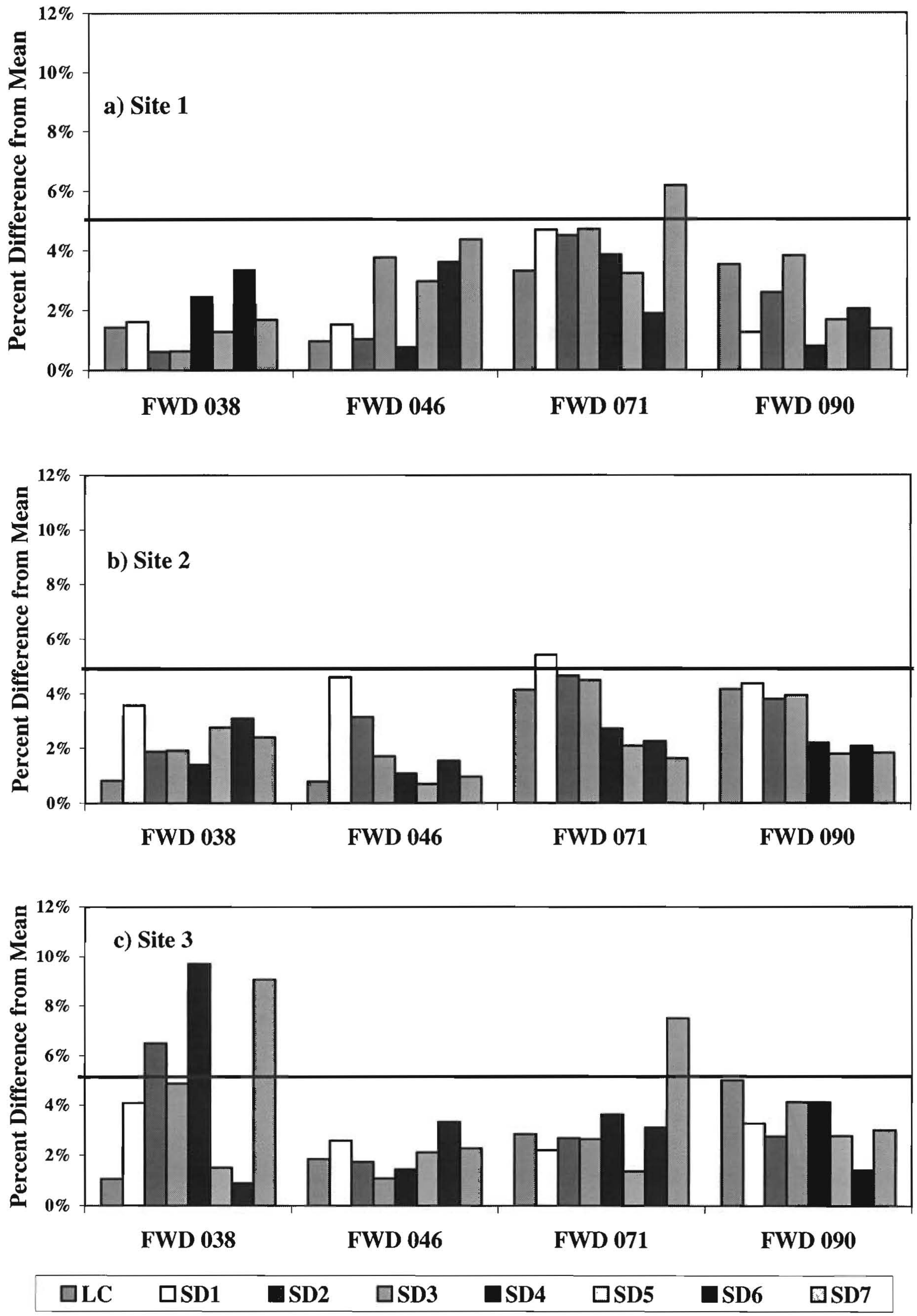


Figure 8.4 – Variations in Average Difference from Mean (Grand Average of all FWDs) at Drop Height 1, with a Nominal Load of 6 kips (27 kN)

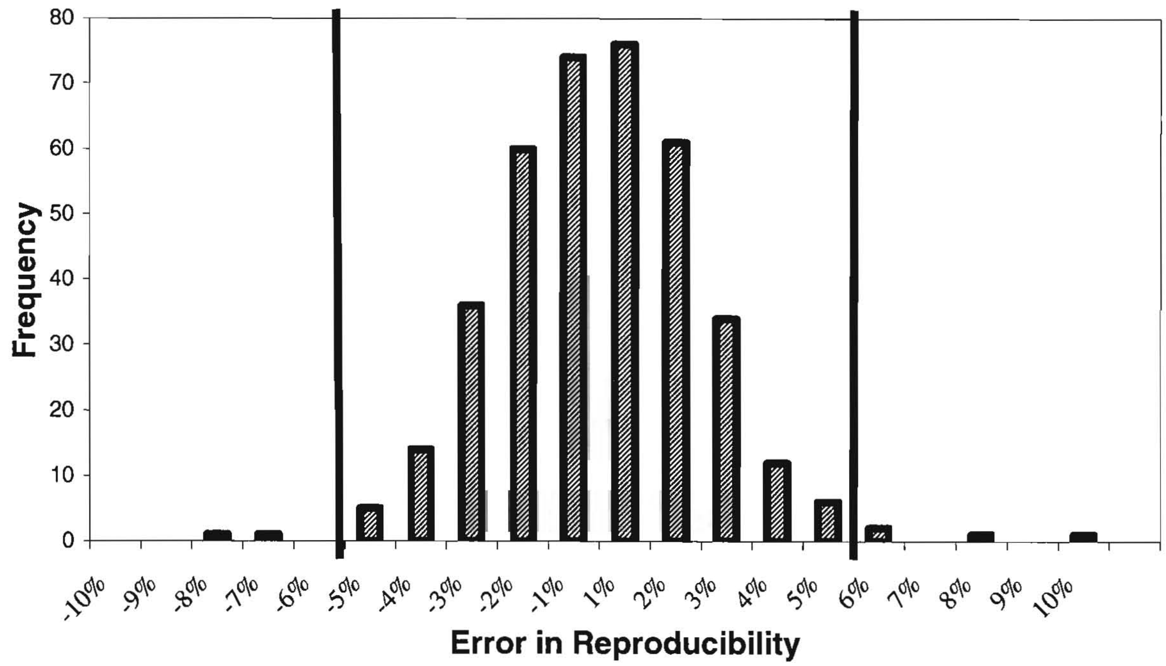


Figure 8.5 – Histogram of Reproducibility of Measured Loads and Deflections for July 2002 Calibration

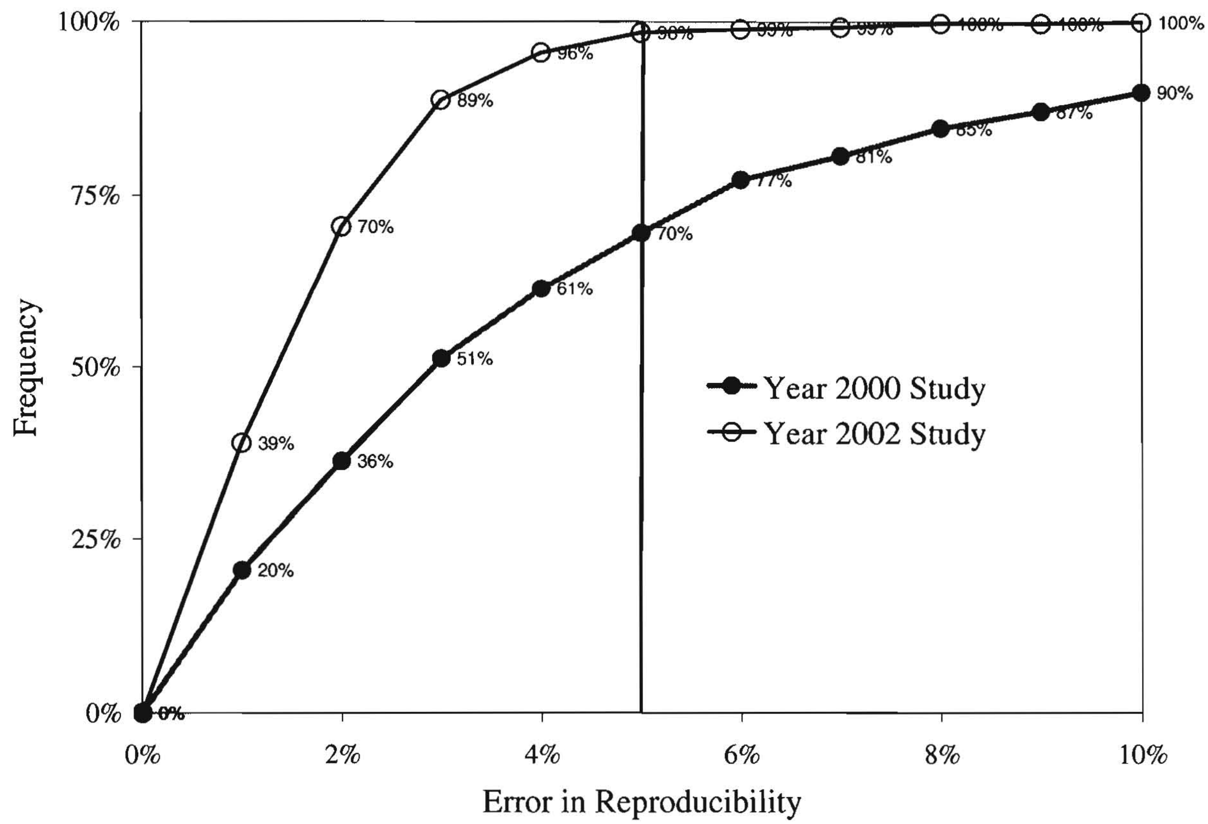


Figure 8.6 – Comparison of Reproducibility Errors of FWD Fleet from January 2000 Thump-off and from July 2002 Thump-off

Chapter 9

Closure

The primary objective of this project is to develop realistic field protocols and specifications, which in a rational manner will allow TxDOT personnel to quantify the repeatability and reproducibility of existing and future FWD devices. As a result of this activity, a more comprehensive calibration methodology has been developed. An additional outcome of the project has been new decision-making tools for maintaining a reproducible fleet. These new tools will give those who are involved in repairing and upgrading FWDs to decide more quantitatively when to replace components to maintain a reproducible fleet.

This report contains recommendations and procedures for a comprehensive calibration of FWD devices. The existing calibration strategies for the FWD were reviewed and modified so that the device can be calibrated more conveniently and more comprehensively. The calibration is carried out along a concrete slab. The unique features of the proposed methodology are as follows:

1. The FWD does not have to be disassembled for the preliminary calibration.
2. The impact of the sensor holder on the response of the sensor can be quantified.
3. The variation in calibration parameters as a function of frequency can be developed so that the full-waveform analyses can be performed accurately.

The new protocol contains up to three steps. These steps include:

1. Physical Inspection and Component Replacement: This step includes a thorough check of the electrical and electronic components, replacement of mechanical components (e.g., geophone hold down springs, neoprene guides etc.), tune-up of the FWD to minimize excessive trailer movement and sensor bar movement; ensure smooth and centered load application. These steps not only contribute to better reproducibility of the fleet, it will also extend the life of the fleet.
2. Conduct Preliminary Calibration: Compare deflections and load measured with the FWD with those of well-calibrated sensors embedded in a calibration slab. This step will provide a

calibration procedure very similar to the SHRP calibration. The only difference is that all deflection sensors are calibrated simultaneously and in place within their sensor holders. If the FWD system passes the calibration process. It would be ready for operation. For the sensors that fail, a second stage calibration and diagnostic process is needed.

3. Comprehensive Calibration: In this stage the sensors that failed will go through a thorough calibration to identify whether the sensor, the sensor holder or the electronic system is the cause of the lack of calibration.

In addition, a monthly inspection of the FWD by the operator to replace the worn out components, ensuring appropriate tension in bolts and screws and the lubrication and cleaning of the load cell assembly and sensor holding assembly is recommended.

A preliminary implementation of the protocol in December 2001 using three FWDs demonstrates that the new protocol is quite suitable in improving the reproducibility of the fleet. To validate the process, a facility was constructed and four FWDs were calibrated as per proposed protocol. The results from that study demonstrated the versatility of the proposed process. In the researchers' opinion, the project has led to practical products and protocols that can be used by TxDOT. More experience is needed to improve the hardware and software associated with each calibration setup. A database should be initiated and maintained for this purpose.

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1. Nazarian, S. and Briggs, R.C. (1990), "Determination of Structural Integrity of Secondary Roads Using Falling Weight Deflectometer. Proc., 2nd International Conference on Bearing Capacity of Roads and Airfields, Trondheim, Norway.

2. Tandon, V. and Nazarian, S. (1999), "Calibration Procedures for Seismic and Deflection-Based Devices: Supplementary Information" Research Report No. 2984-2F, Texas Department of Transportation, Austin, Texas

3. Tandon, V. and Nazarian, S. (2000), "Calibration Procedures for Seismic and Deflection-Based Devices," Report No. 2984-2F, Texas Department of Transportation, Austin, Texas.

4. Rocha S., Tandon V. and Nazarian S. (2002), "Reproducibility of Texas Department of Transportation Falling Weight Deflectometer Fleet," Research Report No. 1784-1, Texas Department of Transportation, Austin, Texas

Appendix A

Calibration Protocol

Physical Inspection and Component Replacement

	Step	Action
Trailer	1	Wash trailer.
	2	Remove and clean all sensors.
	3	Remove foam rings and remove old adhesive.
	4	Clean and check all holder assembly clamping discs.
	5	Remove and replace springs.
	6	Check sensors for proper distance and perpendicular orientation of the holder assembly.
	7	Clean and lubricate catch assembly.
	8	Check all relay and switch connections.
	9	Check all cables for damage – replace as needed.
	10	Check all power and ground connections.
	11	Remove and replace foam rings in Load cell assembly.
	12	Remove and replace springs above Load cell assembly.
	13	Grease swivel.
	14	Replace metering rods.
	15	Inspect and replace buffers if needed
	16	On control panels check the ground lugs and power fuses.
	17	Check load capability of trailer battery.
	18	Clean connectors with contact cleaner

	Step	Action
Vehicle	1	Check frame ground connections.
	2	Inspect and replace defective data cable.
	3	Check fast idle setting.
	4	Check all electrical connections.
	5	Check processor for proper voltage limits.

Procedure for Preliminary FWD Calibration

Step	Action
1	Set the four drop heights so that the FWD imparts nominal loads of 6 kip. 9 kips, 12 kips and 15 kips or any other nominal load that is desirable for the agency
2	Check the Load calibration assembly. Make sure the calibration load cells are tightly fastened to the bottom plate and that the top plate does sit evenly on top of them.
3	Place the load calibration assembly in the slab cavity being careful not to damage the wiring. Note: The load calibration assembly is about 30 lbs of cold rolled steel, exercise care when setting it up.
4	Position the FWD trailer until the FWD Load plate is centered on the load calibration assembly. Once in place, execute a 24-drop sequence (6 drops, 4 heights). Note: While performing this step, the FWD system should be setup in the same way as when testing is carried out in the field. The warning lights should be on, the air conditioning should also be running, and the auto idle should be enabled.
5	Compare FWD system peak loads against those obtained with the calibration System. Chart the sum of the three calibration load cells against the peak loads from the FWD load cell for 20 data point to obtain its calibration factor. Note: Always ignore the results from the first drop at each height
6	Thoroughly clean the slab where the calibration geophones are embedded. Make sure there is no loose debris around the sensor holders and verify that the cables leading to the connection box are in good condition.
7	Carefully maneuver the FWD until its deflection sensors (SD1-SD7) are directly on top of the calibration sensors.
8	Lower the raise-lower assembly and verify that all the FWD geophones are centered on the calibration sensors. Adjust the FWD trailer as needed until all seven sensors are aligned with the calibration system sensors. Execute a 24-drop sequence (6 drops, 4 heights). Note: While performing this step, the FWD system should be setup in the same way as when testing is carried out in the field. The warning lights should be on, the air conditioning should also be running, and the auto idle should be enabled.
9	Compare the deflections measured with each FWD sensor against those obtained with the corresponding embedded geophone to obtain the calibration factor for that FWD deflection sensor. Note: Always ignore the results from the first drop at each height
10	Perform comprehensive calibration on each sensor that its calibration factor is greater than 1.02 or less than 0.98.

Procedure for Comprehensive FWD Calibration

Step	Action
1	Attach the calibration accelerometer to the shaker using the special holder shown in Figure 5.3.
2	Place the shaker alongside the geophone that exceeded the 2% error limit.
3	Remove the deflection sensor from its holder and place it directly on top of the shaker as shown in Figure 5.4.
4	Deliver a sinusoidal sweep signal to the shaker with a dynamic signal analyzer, and capture the voltage output of the FWD geophone and the calibration accelerometer. Measure the frequency response and coherence function between the two sensors and save them for future analysis. Note1: The FWD and the towing vehicle should be setup in the same way as when testing is carried out in the field. The warning lights should be on, the air conditioning should also be running, and the auto idle should be enabled. Note 2: This process takes from 3 to 5 minutes per sensor to complete. Note 3: Step-by-step procedure for conducting this task in an automated fashion is provided to TxDOT employees
5	Ensure that the transfer function obtained in Step 4 is representative of the response of a single degree of freedom system. Also ensure that the response is similar to those provided by the manufacturer. Replace the sensor, if either one of these two conditions is not met.
6	Place the shaker in the cavity built into the calibration slab. Level both the shaker and the cavity cover. Adjust the calibration accelerometer holder so that it is slightly below the cover level.
7	Place the geophone back in its corresponding holder. Carefully maneuver the FWD until the deflection sensor of interest is directly centered above the shaker and the accelerometer holder
8	Lower down the geophone assembly so that the sensor holder is sitting on the cover and the contact rod is the only thing that touches the calibration sensor holder
9	Repeat Step 4 under the new set up. Compare the obtained frequency response curve with the one measured in Steps 4. If the transfer functions obtained when the FWD geophone is within and without the holder are not essentially the same, replace the geophone holder and repeat the preliminary calibration procedure.
10	If there are no apparent differences in the signals, instrument the FWD trailer as described below. The following sensors are used: four strain gauges on the hit bracket, three accelerometers on the load plate, three geophone on the raise/lower bar, and four geophones on the trailer frame. Note: Data from all sensors can be collected simultaneously and analyzed using the calibration data acquisition system by performing a 24 drop sequence (6 drops, 4 heights).

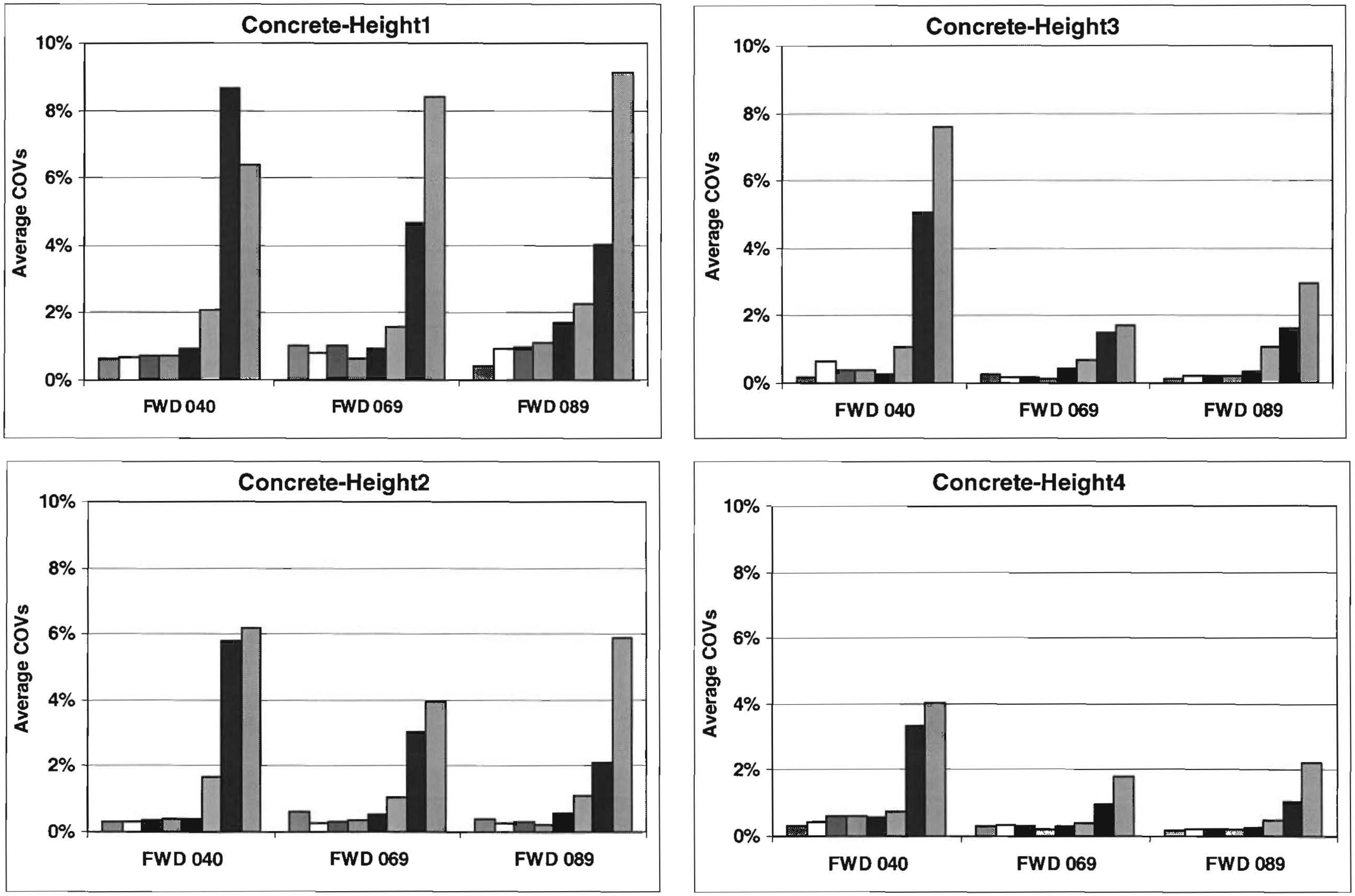
Procedure for Instrumentation of FWD

Step	Action
1	Place four dynamic strain gauges on the hit bracket near each bumper. Attach each strain gauge about 0.5 in. from the area where the bumper hits. Use Figure 5.10 for reference. The strain gauge time histories should follow one another very closely. Replace all four bumpers as a set, if this criterion is not met. Note: Super glue works well as long as the surfaces are cleaned of any oil, dirt or paint.
2	Place three accelerometers in a circular pattern on the load plate 120 degrees apart. The accelerometers have a magnetic base that is used to attach them to any metallic surface. The signals from the accelerometers on the load plate should be synchronized and have similar magnitudes. Excessive differences among these signals, indicates a stuck swivel. Remove, lubricate and reinstall the load cell assembly to correct this problem Note: Ensure these sensors are equidistant from the load plate center
3	Place three well-calibrated geophones on the raise/lower bar near SD2, SD4 and SD6. . See Figure 5.8 for reference. If the motion of the bar relative to the deflections measured is deemed excessive, make sure that all the bolts holding the raise/lower assembly are tight and the associated cable does not have any slack. Note: Vacuum grease seems to work well to attach the geophones to the raise lower bar
4	Place four geophones on the trailer frame, two on each side aligned with SD2 and SD6. Also use vacuum grease to attach the geophones to both sides of the fwd trailer. See Figure 5.14 for reference. If any significant swaying or rocking motion is detected, the reconstruction of the trailer may be necessary. Note 1: Vacuum grease seems to work well to attach the geophones to the FWD frame Note 2: The impact of the motion of the trailer o the deflection has been found to be rather small and should be remedied unless a reconstruction of the trailer is warranted for other purposes.

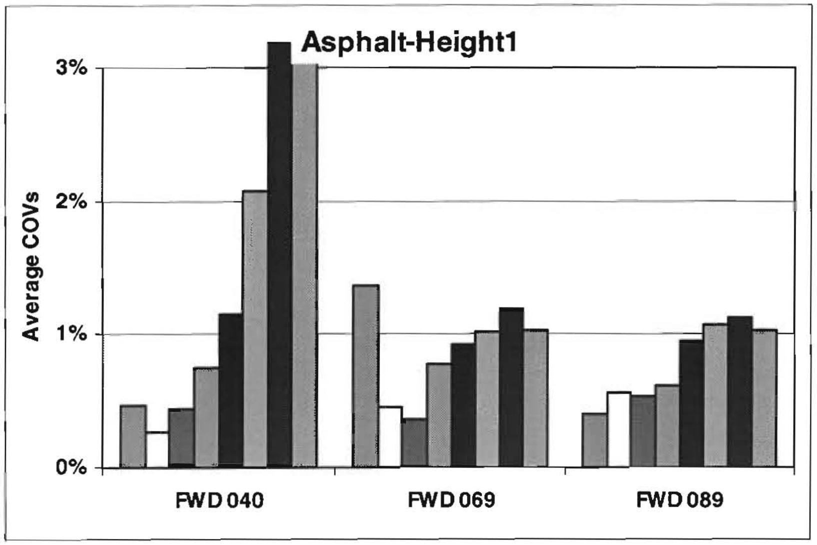
Appendix B

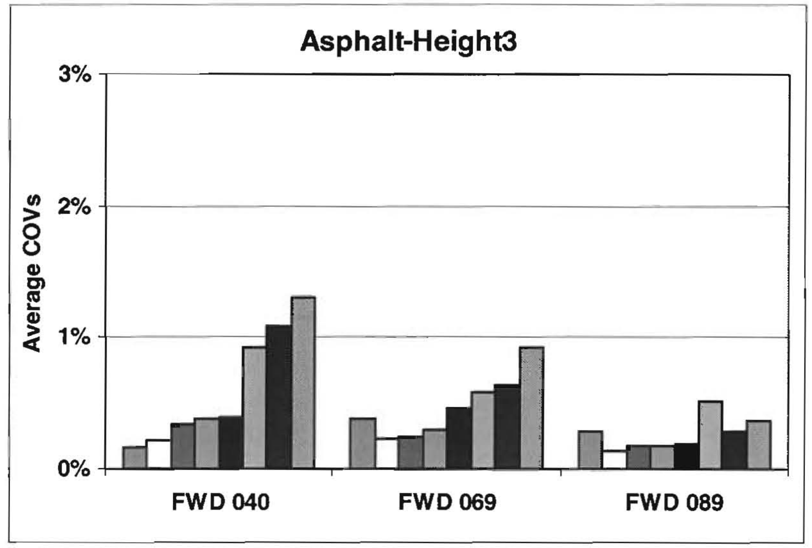
Complete Repeatability and Reproducibility Data

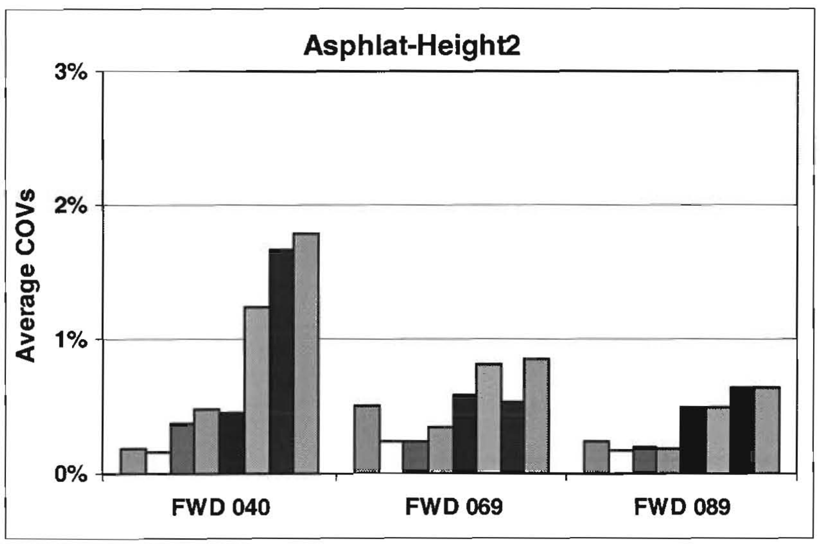
Overall Repeatability - Before Calibration

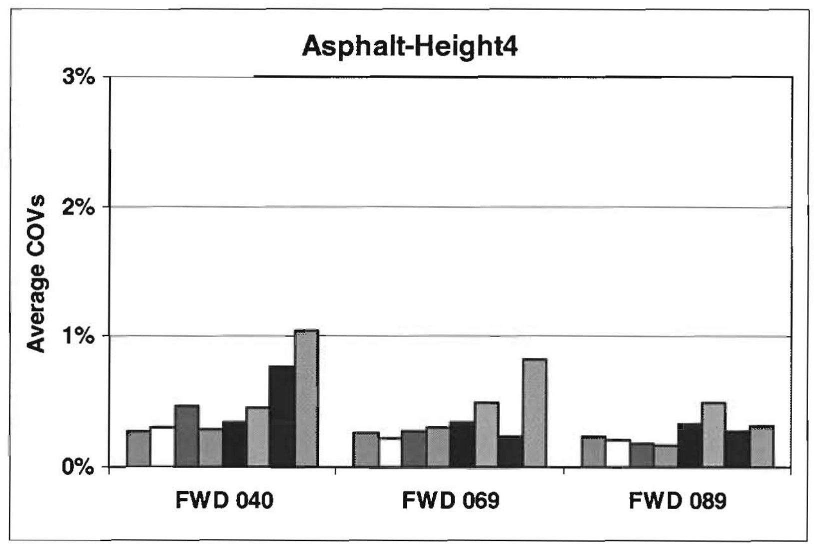


Overall Repeatability - Before Calibration





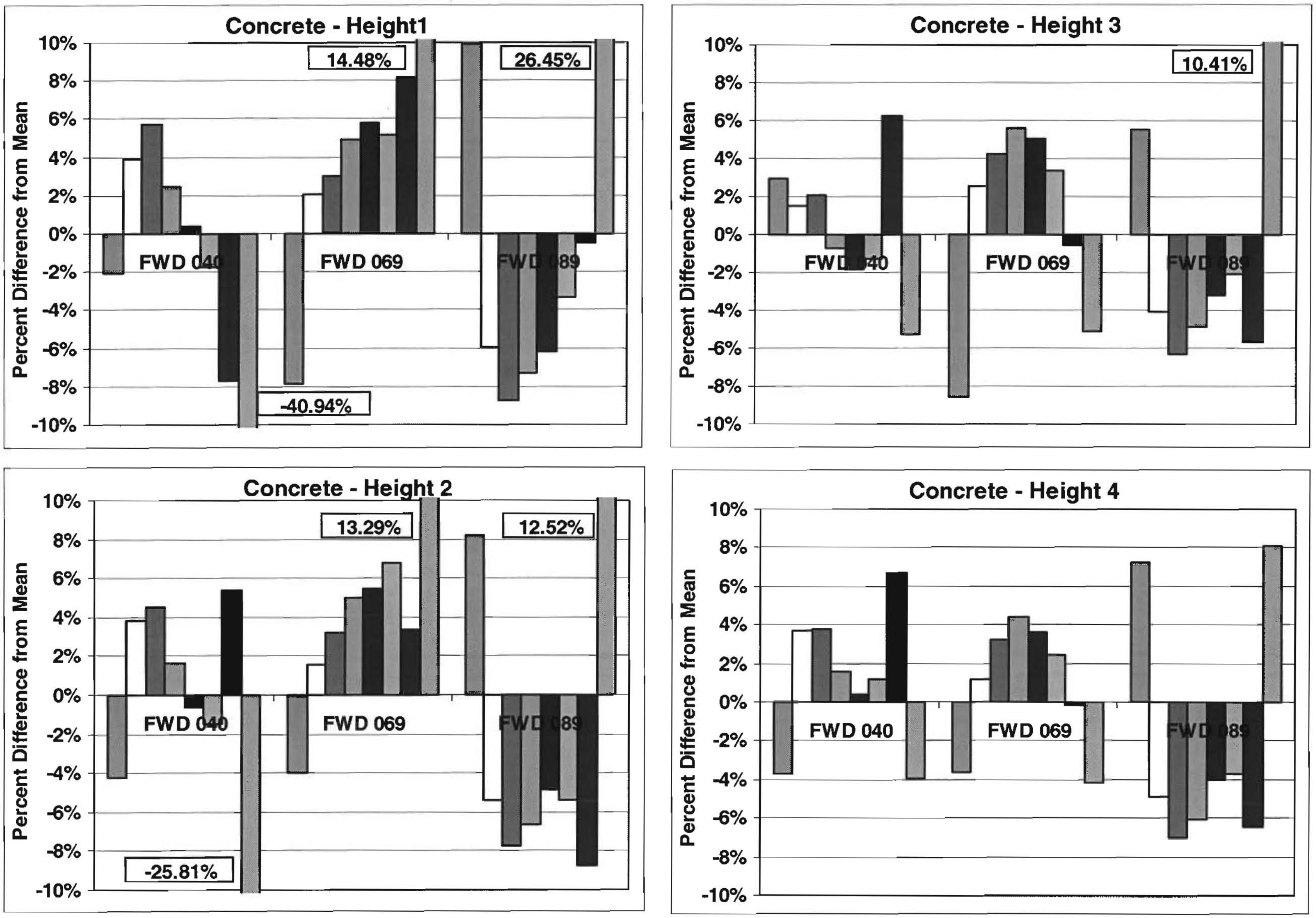




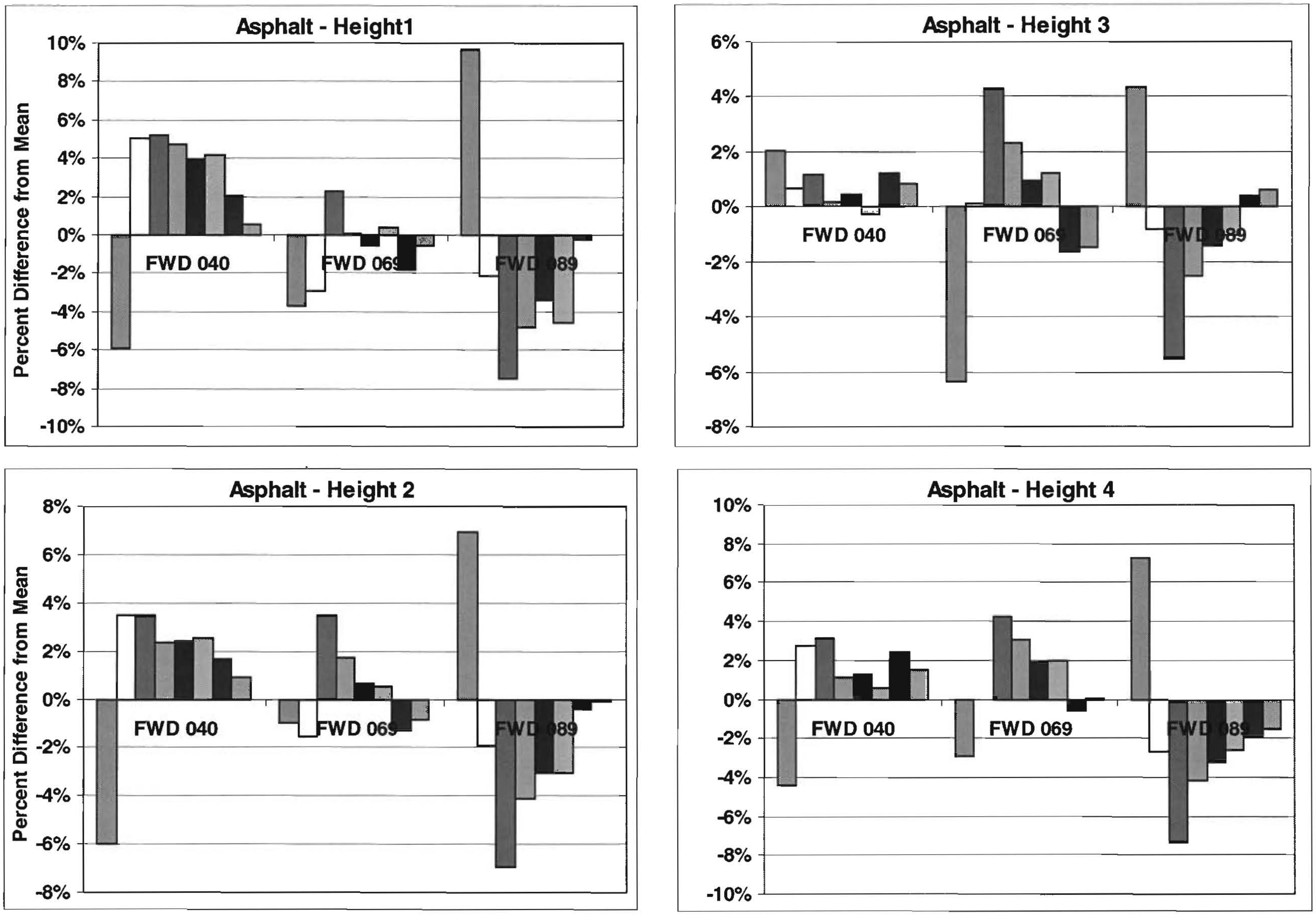
Overall Reproducibility - Before Calibration

	CONCRETE - Averages								ASPHALT - Averages							
Height1	LC	SD1	SD2	SD3	SD4	SD5	SD6	SD7	LC	SD1	SD2	SD3	SD4	SD5	SD6	SD7
FWD 040	-2.06%	3.92%	5.69%	2.43%	0.40%	-1.78%	-7.69%	-40.94%	-5.94%	5.01%	5.17%	4.71%	3.92%	4.21%	2.05%	0.55%
FWD 069	-7.85%	2.04%	3.03%	4.88%	5.77%	5.14%	8.16%	14.48%	-3.73%	-2.92%	2.31%	0.10%	-0.56%	0.37%	-1.84%	-0.56%
FWD 089	9.92%	-5.96%	-8.72%	-7.31%	-6.17%	-3.36%	-0.47%	26.45%	9.67%	-2.09%	-7.48%	-4.81%	-3.37%	-4.58%	-0.21%	0.01%
Height2	LC	SD1	SD2	SD3	SD4	SD5	SD6	SD7	LC	SD1	SD2	SD3	SD4	SD5	SD6	SD7
FWD 040	-4.22%	3.82%	4.52%	1.60%	-0.60%	-1.45%	5.42%	-26.04%	-5.97%	3.48%	3.47%	2.34%	2.43%	2.53%	1.68%	0.94%
FWD 069	-3.97%	1.60%	3.24%	5.04%	5.44%	6.80%	3.36%	13.27%	-0.95%	-1.54%	3.49%	1.75%	0.65%	0.53%	-1.30%	-0.85%
FWD 089	8.18%	-5.42%	-7.76%	-6.64%	-4.83%	-5.36%	-8.77%	12.77%	6.92%	-1.94%	-6.96%	-4.09%	-3.07%	-3.06%	-0.38%	-0.09%
Height3	LC	SD1	SD2	SD3	SD4	SD5	SD6	SD7	LC	SD1	SD2	SD3	SD4	SD5	SD6	SD7
FWD 040	2.99%	1.49%	2.06%	-0.69%	-1.83%	-1.27%	6.23%	-5.26%	2.03%	0.68%	1.19%	0.20%	0.47%	-0.23%	1.23%	0.86%
FWD 069	-8.54%	2.56%	4.26%	5.61%	5.03%	3.34%	-0.59%	-5.15%	-6.38%	0.11%	4.32%	2.33%	0.96%	1.24%	-1.64%	-1.46%
FWD 089	5.55%	-4.06%	-6.32%	-4.91%	-3.20%	-2.07%	-5.64%	10.41%	4.34%	-0.79%	-5.51%	-2.53%	-1.42%	-1.00%	0.41%	0.59%
Height4	LC	SD1	SD2	SD3	SD4	SD5	SD6	SD7	LC	SD1	SD2	SD3	SD4	SD5	SD6	SD7
FWD 040	-3.67%	3.71%	3.74%	1.61%	0.36%	1.22%	6.66%	-3.94%	-4.37%	2.74%	3.12%	1.10%	1.27%	0.62%	2.46%	1.51%
FWD 069	-3.58%	1.20%	3.24%	4.42%	3.66%	2.47%	-0.18%	-4.20%	-2.92%	-0.05%	4.22%	3.05%	1.93%	2.00%	-0.55%	0.01%
FWD 089	7.25%	-4.91%	-6.99%	-6.04%	-4.02%	-3.69%	-6.48%	8.14%	7.29%	-2.69%	-7.33%	-4.14%	-3.20%	-2.62%	-1.91%	-1.52%

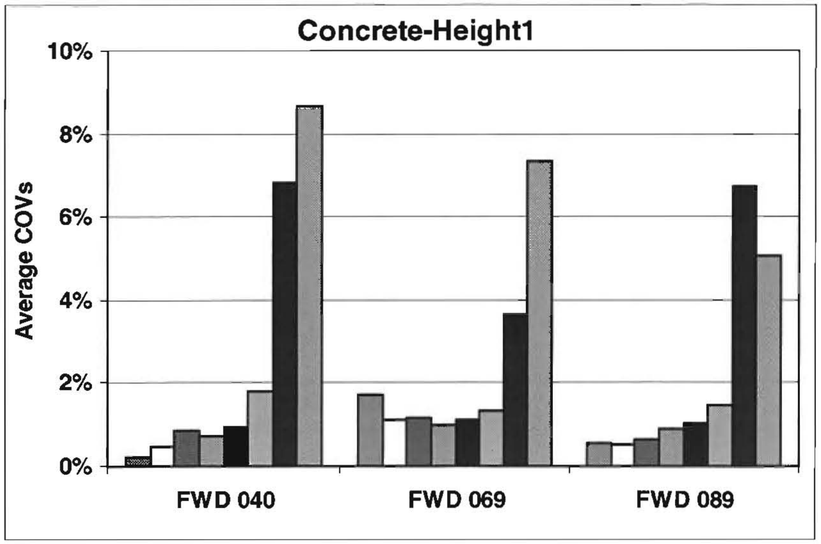
Overall Reproducibility - Before Calibration

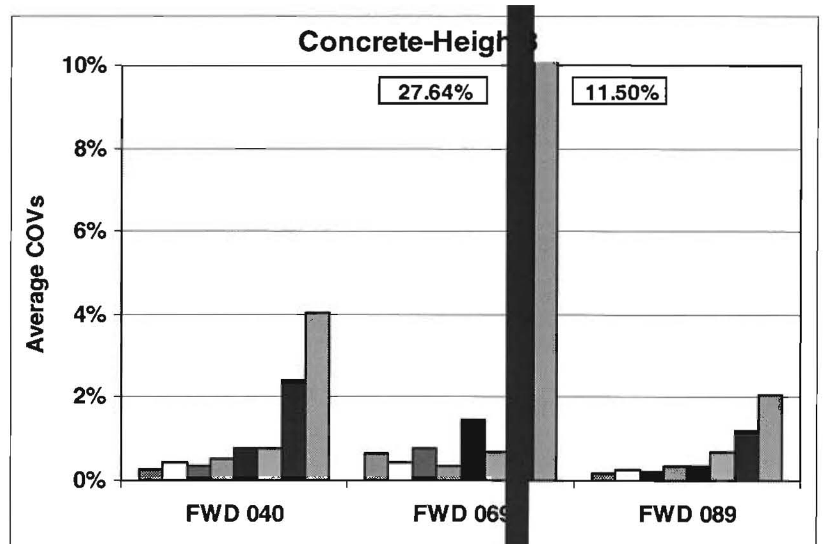


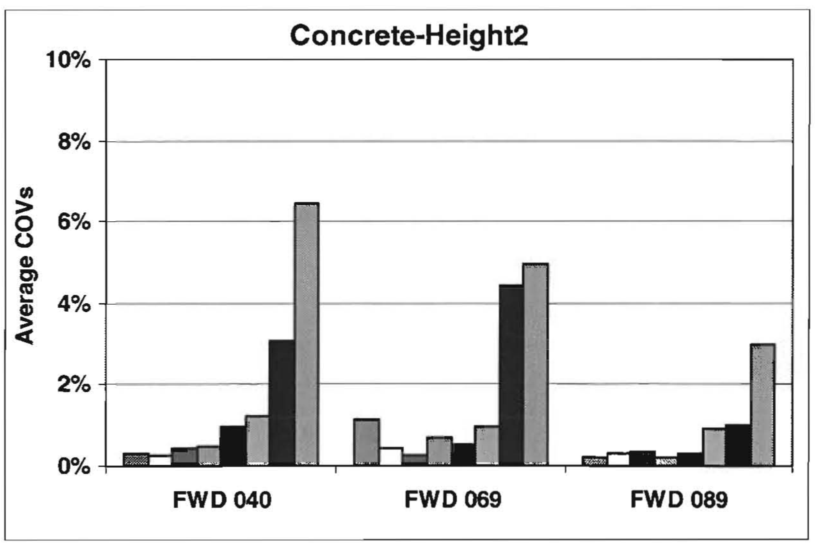
Overall Reproducibility - Before Calibration

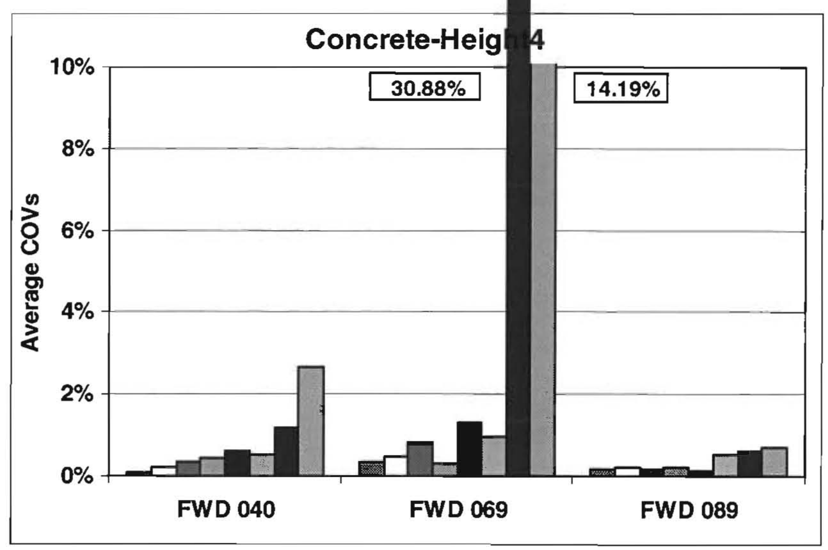


Overall Repeatability - After Calibration

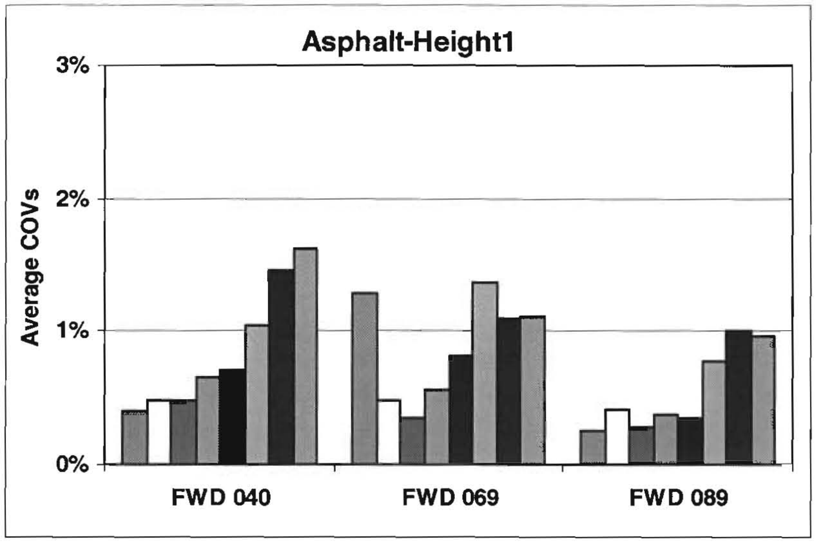


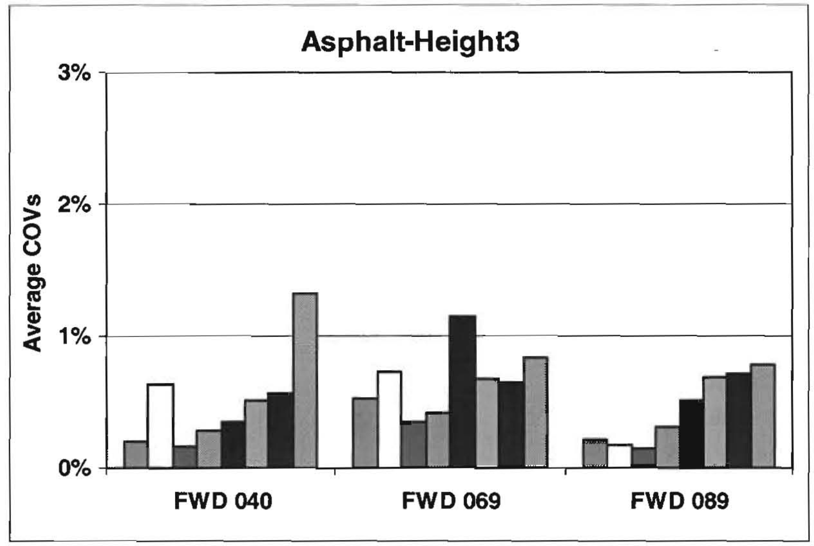


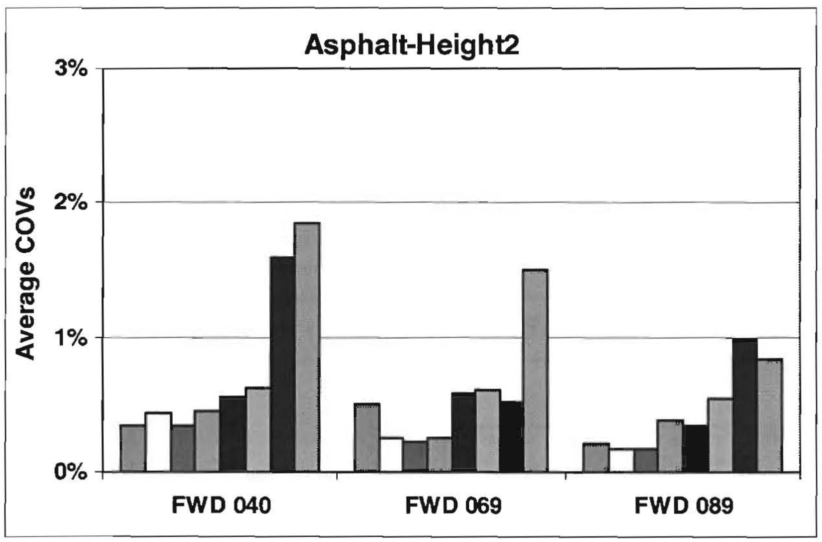


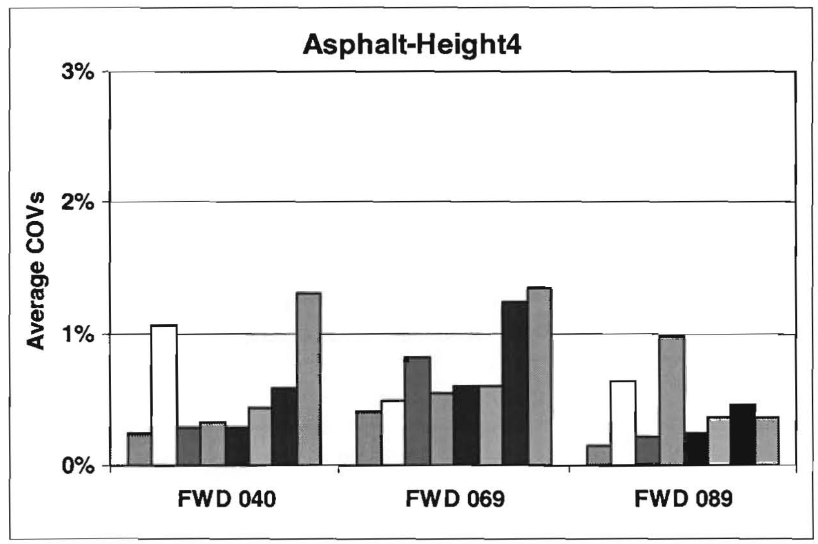


Overall Repeatability - After Calibration





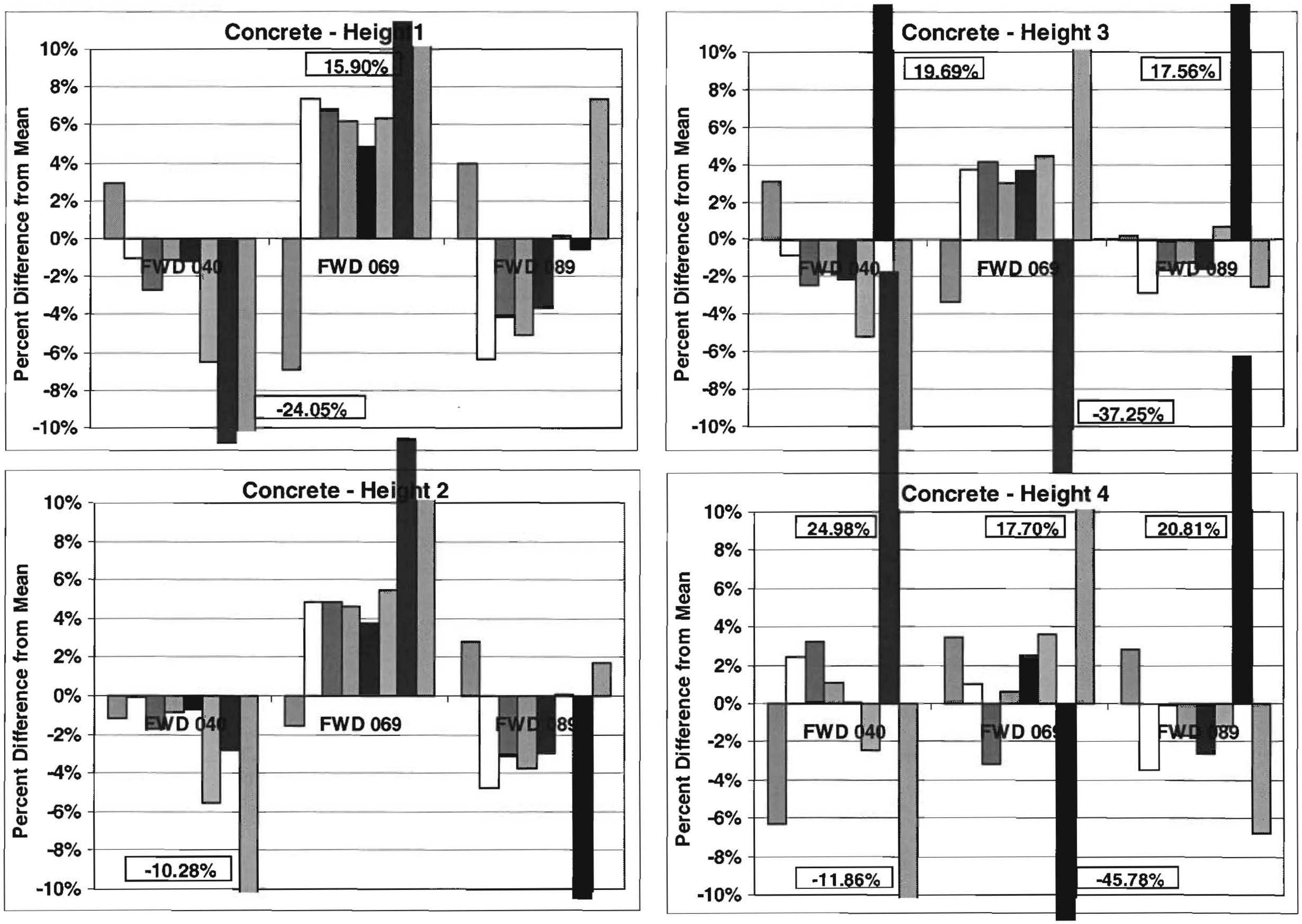




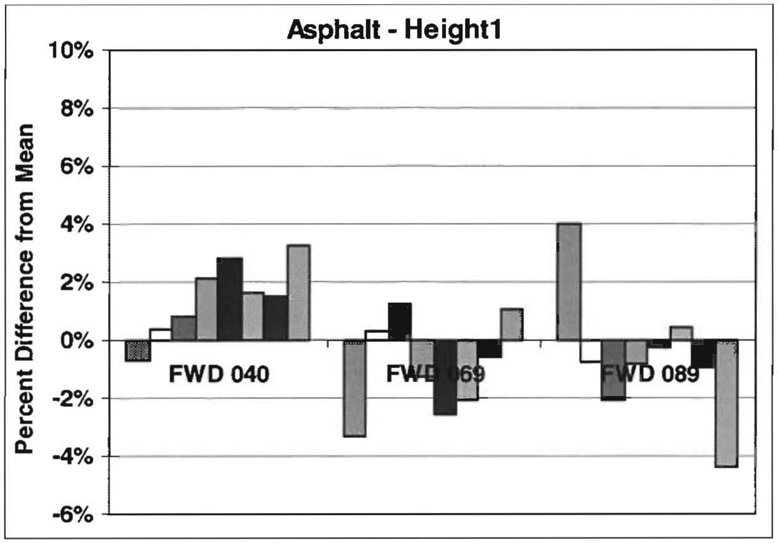
Overall Reproducibility - After Calibration

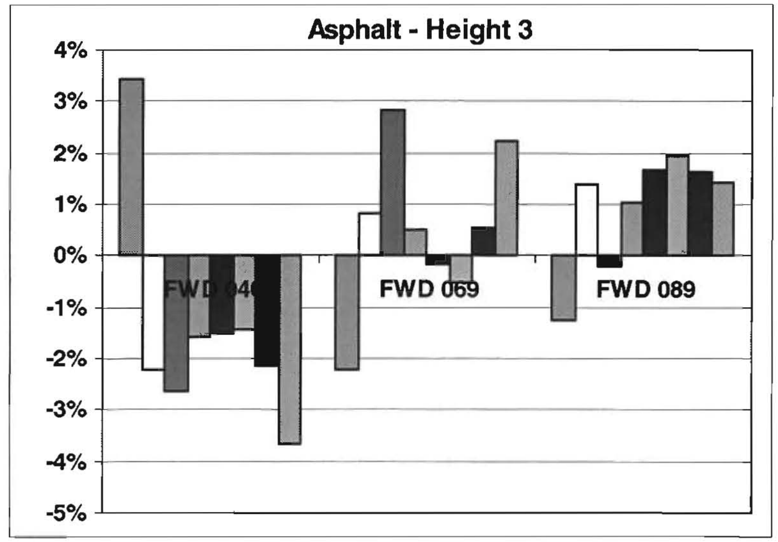
	CONCRETE - Averages								ASPHALT - Averages							
Height1	LC	SD1	SD2	SD3	SD4	SD5	SD6	SD7	LC	SD1	SD2	SD3	SD4	SD5	SD6	SD7
FWD 040	2.92%	-1.05%	-2.69%	-1.14%	-1.17%	-6.51%	-10.89%	-27.74%	-0.68%	0.39%	0.79%	2.10%	2.84%	1.63%	1.48%	3.27%
FWD 069	-6.92%	7.39%	6.82%	6.19%	4.83%	6.36%	11.44%	20.37%	-3.34%	0.33%	1.26%	-1.27%	-2.57%	-2.07%	-0.55%	1.09%
FWD 089	3.99%	-6.34%	-4.13%	-5.05%	-3.65%	0.15%	-0.55%	7.37%	4.02%	-0.72%	-2.05%	-0.83%	-0.27%	0.44%	-0.92%	-4.36%
Height2	LC	SD1	SD2	SD3	SD4	SD5	SD6	SD7	LC	SD1	SD2	SD3	SD4	SD5	SD6	SD7
FWD 040	-1.20%	-0.10%	-1.69%	-0.83%	-0.73%	-5.58%	-2.85%	-13.86%	-1.96%	-1.78%	-1.67%	-0.67%	-0.73%	-1.43%	-1.67%	-2.17%
FWD 069	-1.58%	4.85%	4.85%	4.61%	3.72%	5.47%	13.36%	12.12%	1.19%	1.27%	2.74%	0.85%	-0.21%	0.13%	0.87%	3.32%
FWD 089	2.78%	-4.75%	-3.16%	-3.78%	-2.98%	0.11%	-10.51%	1.75%	0.76%	0.51%	-1.07%	-0.18%	0.94%	1.30%	0.80%	-1.15%
Height3	LC	SD1	SD2	SD3	SD4	SD5	SD6	SD7	LC	SD1	SD2	SD3	SD4	SD5	SD6	SD7
FWD 040	3.13%	-0.88%	-2.48%	-1.71%	-2.14%	-5.17%	17.27%	-11.34%	3.44%	-2.23%	-2.63%	-1.56%	-1.51%	-1.44%	-2.16%	-3.66%
FWD 069	-3.33%	3.74%	4.11%	2.98%	3.67%	4.45%	-32.25%	13.86%	-2.20%	0.83%	2.83%	0.51%	-0.16%	-0.52%	0.53%	2.23%
FWD 089	0.20%	-2.86%	-1.62%	-1.26%	-1.53%	0.72%	14.98%	-2.52%	-1.24%	1.40%	-0.20%	1.05%	1.67%	1.96%	1.63%	1.43%
Height4	LC	SD1	SD2	SD3	SD4	SD5	SD6	SD7	LC	SD1	SD2	SD3	SD4	SD5	SD6	SD7
FWD 040	-6.28%	2.46%	3.21%	1.06%	0.05%	-2.42%	22.57%	-15.25%	-5.15%	-0.37%	0.24%	1.08%	0.75%	-2.67%	0.48%	-0.97%
FWD 069	3.48%	1.01%	-3.12%	0.59%	2.53%	3.59%	-40.75%	22.04%	2.48%	1.13%	1.87%	0.43%	-0.52%	0.93%	-0.96%	1.40%
FWD 089	2.81%	-3.48%	-0.09%	-1.66%	-2.59%	-1.17%	18.18%	-6.79%	2.67%	-0.76%	-2.11%	-1.51%	-0.23%	1.74%	0.48%	-0.43%

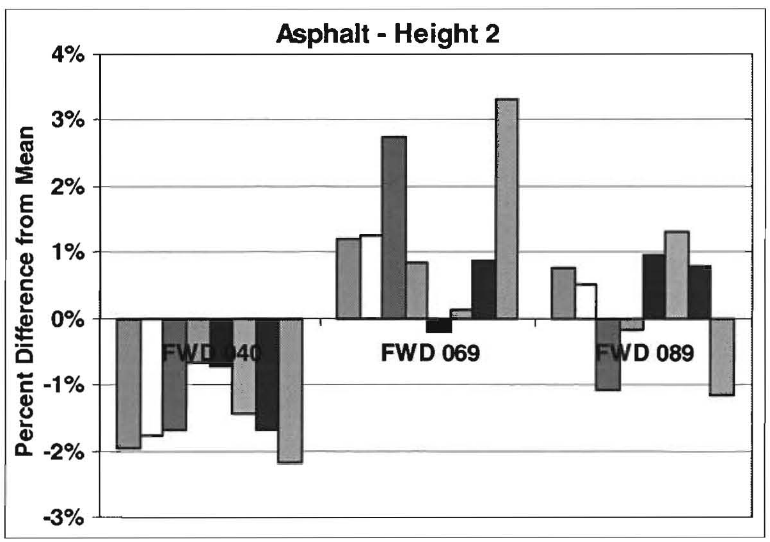
Overall Reproducibility - After Calibration

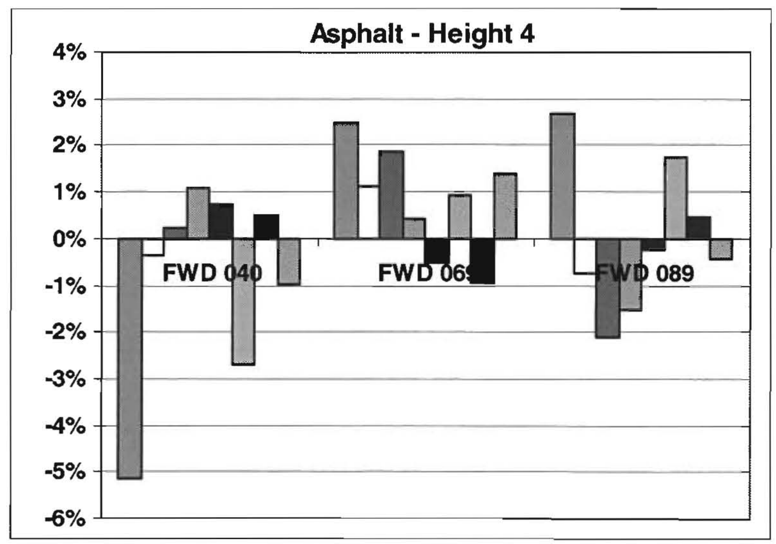


Overall Reproducibility - After Calibration

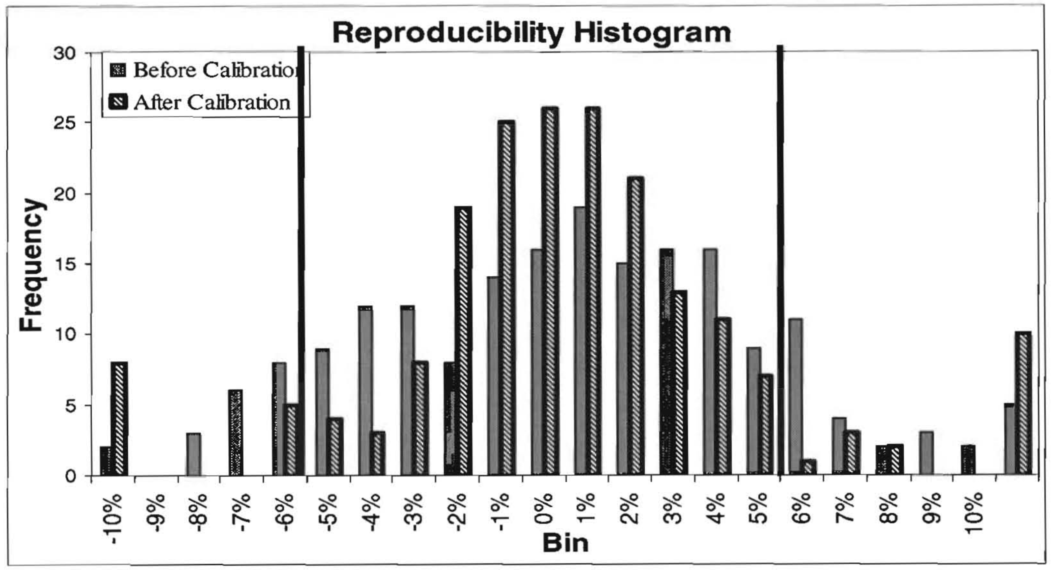




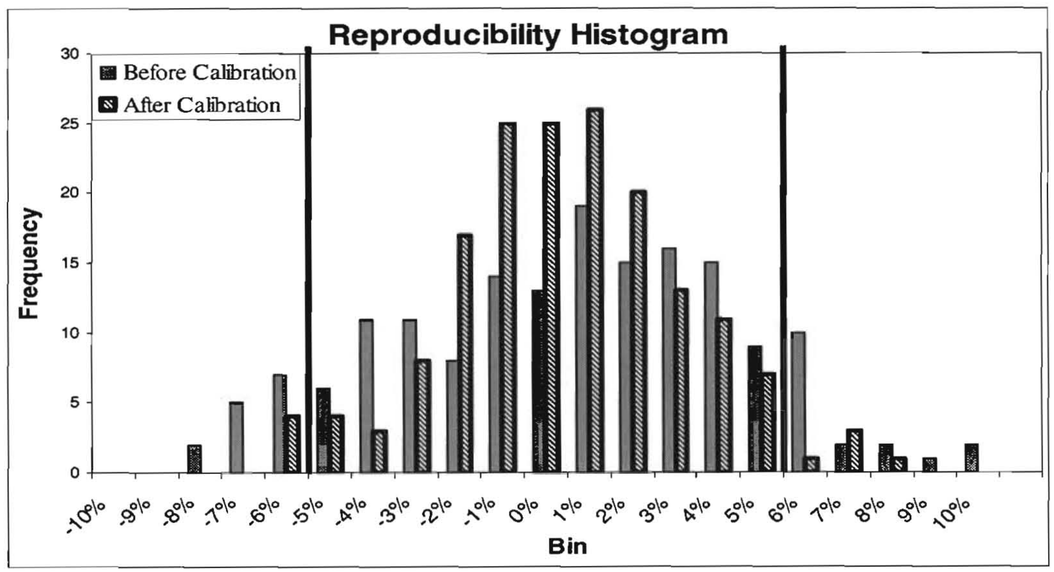




Data for Reproducibility Histogram All values considered		
Bins	**Before Cal**	**After Cal**
-10%	2	8
-9%	0	0
-8%	3	0
-7%	6	0
-6%	8	5
-5%	9	4
-4%	12	3
-3%	12	8
-2%	8	19
-1%	14	25
0%	16	26
1%	19	26
2%	15	21
3%	16	13
4%	16	11
5%	9	7
6%	11	1
7%	4	3
8%	2	2
9%	3	0
10%	2	0
	5	10



Data for Reproducibility Histogram Values below 1mil Removed		
Bins	**Before Cal**	**After Cal**
-10%	0	0
-9%	0	0
-8%	2	0
-7%	5	0
-6%	7	4
-5%	6	4
-4%	11	3
-3%	11	8
-2%	8	17
-1%	14	25
0%	13	25
1%	19	26
2%	15	20
3%	16	13
4%	15	11
5%	9	7
6%	10	1
7%	2	3
8%	2	1
9%	1	0
10%	2	0
	0	0



Appendix C

Complete Calibration Data

Comparison of FWD040 Deflections and Calibration Slab Geophones

	FWD SD1	LabVIEW CalGeo1	%Error	FWD SD2	LabVIEW CalGeo2	%Error	FWD SD3	LabVIEW CalGeo3	%Error	FWD SD4	LabVIEW CalGeo4	%Error	FWD SD5	LabVIEW CalGeo5	%Error	FWD SD6	LabVIEW CalGeo6	%Error	FWD SD7	LabVIEW CalGeo7	%Error
	8.09	8.16	0.83%	6.17	6.47	4.70%	4.33	4.37	0.92%	2.66	2.73	2.49%	1.58	1.58	0.19%	0.91	1.01	9.54%	0.60	0.68	12.28%
	8.09	8.21	1.41%	6.21	6.50	4.39%	4.35	4.40	1.18%	2.67	2.75	2.84%	1.59	1.60	0.44%	0.93	1.04	10.14%	0.59	0.70	16.19%
	8.10	8.15	0.56%	6.33	6.48	2.31%	4.31	4.41	2.18%	2.64	2.75	4.14%	1.58	1.58	0.19%	0.86	1.03	16.75%	0.57	0.70	18.45%
	8.04	8.21	2.08%	6.13	6.51	5.85%	4.31	4.43	2.77%	2.65	2.78	4.54%	1.58	1.61	1.80%	0.85	1.04	18.35%	0.63	0.71	10.89%
	8.16	8.21	0.57%	6.23	6.50	4.09%	4.40	4.41	0.23%	2.69	2.76	2.68%	1.61	1.60	-0.37%	0.95	1.02	7.23%	0.55	0.71	22.86%
Average	8.10	8.19	1.09%	6.21	6.49	4.27%	4.34	4.40	1.46%	2.66	2.75	3.34%	1.59	1.60	0.45%	0.90	1.03	12.43%	0.59	0.70	16.17%
Std Dev	0.04	0.03		0.08	0.01		0.04	0.02		0.02	0.02		0.01	0.01		0.04	0.01		0.03	0.01	
COV	0.53%	0.38%		1.21%	0.22%		0.88%	0.51%		0.72%	0.65%		0.82%	0.75%		4.84%	1.33%		5.16%	1.56%	
	11.37	11.52	1.26%	9.04	9.12	0.88%	6.11	6.19	1.26%	3.79	3.93	3.49%	2.26	2.31	2.25%	1.35	1.51	10.77%	0.87	1.04	15.94%
	11.42	11.51	0.76%	9.05	9.12	0.73%	6.16	6.19	0.44%	3.81	3.93	2.93%	2.28	2.31	1.17%	1.38	1.51	8.85%	0.85	1.05	18.66%
	11.37	11.44	0.65%	8.98	9.08	1.14%	6.13	6.21	1.27%	3.78	3.90	3.13%	2.26	2.29	1.48%	1.32	1.51	12.41%	0.91	1.03	11.82%
	11.35	11.44	0.80%	9.01	9.05	0.49%	6.14	6.18	0.71%	3.80	3.92	3.09%	2.28	2.30	0.74%	1.31	1.51	13.42%	0.91	1.04	12.50%
	11.39	11.47	0.71%	8.99	8.98	-0.16%	6.15	6.20	0.82%	3.81	3.89	1.96%	2.27	2.30	1.30%	1.29	1.48	13.01%	0.94	1.04	9.18%
Average	11.38	11.48	0.83%	9.01	9.07	0.62%	6.14	6.19	0.90%	3.80	3.91	2.92%	2.27	2.30	1.39%	1.33	1.51	11.69%	0.90	1.04	13.63%
Std Dev	0.03	0.03		0.03	0.06		0.02	0.01		0.01	0.02		0.01	0.01		0.04	0.01		0.04	0.01	
COV	0.23%	0.30%		0.34%	0.65%		0.31%	0.17%		0.34%	0.45%		0.44%	0.32%		2.66%	0.87%		3.99%	0.49%	
	14.33	14.49	1.08%	11.48	11.52	0.34%	7.84	7.87	0.41%	4.91	5.02	2.25%	2.98	3.00	0.77%	1.82	2.01	9.23%	1.20	1.38	12.79%
	14.32	14.47	1.02%	11.46	11.49	0.29%	7.83	7.88	0.58%	4.90	5.01	2.20%	2.97	2.99	0.74%	1.86	1.98	5.82%	1.20	1.38	13.11%
	14.30	14.52	1.54%	11.50	11.52	0.20%	7.83	7.87	0.52%	4.91	4.99	1.66%	3.01	3.00	-0.23%	1.86	2.00	6.86%	1.24	1.40	11.11%
	14.31	14.51	1.36%	11.46	11.50	0.32%	7.83	7.87	0.51%	4.91	5.00	1.88%	3.00	2.99	-0.27%	1.85	1.99	7.13%	1.23	1.37	9.96%
	14.30	14.48	1.23%	11.48	11.53	0.46%	7.83	7.84	0.17%	4.90	5.00	1.98%	2.98	3.01	1.06%	1.83	2.00	8.27%	1.21	1.36	10.90%
Average	14.31	14.49	1.25%	11.48	11.51	0.32%	7.83	7.87	0.44%	4.91	5.01	1.99%	2.99	3.00	0.41%	1.84	1.99	7.47%	1.22	1.38	11.58%
Std Dev	0.01	0.02		0.02	0.02		0.00	0.01		0.01	0.01		0.02	0.01		0.02	0.01		0.02	0.01	
COV	0.09%	0.15%		0.15%	0.15%		0.06%	0.17%		0.11%	0.23%		0.55%	0.28%		0.99%	0.55%		1.49%	1.03%	
	DATA REMOVED FROM ANALYSIS																				
	56.18	19.37	-190.08%	15.46	15.42	-0.28%	10.52	10.58	0.59%	6.65	6.77	1.74%	4.07	4.11	1.07%	2.54	2.79	8.80%	1.77	1.96	9.51%
	28.75	19.36	-48.50%	15.46	15.47	0.03%	10.50	10.62	1.17%	6.64	6.77	1.91%	4.05	4.15	2.34%	2.58	2.80	7.73%	1.69	1.95	13.16%
	19.22	19.37	0.77%	15.48	15.47	-0.10%	10.53	10.64	1.03%	6.65	6.78	1.92%	4.06	4.13	1.67%	2.56	2.79	8.08%	1.76	1.94	9.33%
	19.20	19.36	0.83%	15.48	15.47	-0.09%	10.53	10.64	1.01%	6.65	6.80	2.16%	4.06	4.11	1.19%	2.55	2.78	8.17%	1.73	1.95	11.37%
	19.30	19.38	0.40%	15.48	15.53	0.32%	10.56	10.68	1.08%	6.67	6.80	1.93%	4.07	4.15	2.00%	2.58	2.79	7.59%	1.76	1.95	9.93%
Average	28.53	19.37	-47.32%	15.47	15.47	-0.02%	10.53	10.63	0.97%	6.65	8.78	1.93%	4.06	4.13	1.66%	2.56	2.79	8.07%	1.74	1.95	10.66%
Std Dev	16.00	0.01		0.01	0.04		0.02	0.03		0.01	0.02		0.01	0.02		0.02	0.01		0.03	0.01	
COV	56.07%	0.04%		0.07%	0.26%		0.21%	0.32%		0.16%	0.23%		0.21%	0.47%		0.70%	0.28%		1.88%	0.32%	

Comparison of FWD069 Deflections and Calibration Slab Geophones

	FWD SD1	LabVIEW CalGeo1	%Error	FWD SD2	LabVIEW CalGeo2	%Error	FWD SD3	LabVIEW CalGeo3	%Error	FWD SD4	LabVIEW CalGeo4	%Error	FWD SD5	LabVIEW CalGeo5	%Error	FWD SD6	LabVIEW CalGeo6	%Error	FWD SD7	LabVIEW CalGeo7	%Error
	8.90	9.03	1.44%	7.01	7.01	0.04%	4.71	4.76	0.99%	2.92	2.96	1.32%	1.72	1.74	1.21%	0.99	1.13	12.31%	0.64	0.79	18.99%
	8.94	9.02	0.85%	7.04	7.03	-0.14%	4.72	4.77	1.01%	2.94	2.98	1.18%	1.74	1.76	0.85%	1.00	1.13	11.50%	0.65	0.79	17.93%
	8.68	8.99	3.46%	6.85	7.02	2.45%	4.57	4.72	3.18%	2.88	2.96	2.64%	1.69	1.75	3.21%	0.99	1.14	12.85%	0.65	0.80	18.34%
	8.57	8.98	4.52%	6.74	7.02	3.97%	4.50	4.72	4.62%	2.83	2.97	4.59%	1.67	1.75	4.41%	0.98	1.14	14.04%	0.61	0.79	23.17%
	8.81	8.93	1.39%	7.01	7.00	-0.10%	4.70	4.72	0.49%	2.93	2.95	0.71%	1.73	1.74	0.29%	1.03	1.12	8.20%	0.66	0.79	16.35%
Average	8.78	8.99	2.33%	6.93	7.02	1.25%	4.64	4.74	2.05%	2.90	2.96	2.09%	1.71	1.74	1.99%	1.00	1.13	11.79%	0.64	0.79	18.96%
Std Dev	0.15	0.04		0.13	0.01		0.10	0.02		0.05	0.01		0.03	0.01		0.02	0.01		0.02	0.00	
COV	1.76%	0.42%		1.87%	0.14%		2.14%	0.50%		1.56%	0.31%		1.70%	0.43%		1.93%	0.61%		3.00%	0.36%	
	11.17	11.28	0.93%	8.86	8.82	-0.44%	5.94	5.97	0.50%	3.76	3.76	0.11%	2.24	2.25	0.36%	1.33	1.46	9.09%	0.89	1.00	11.27%
	11.15	11.38	2.00%	8.88	8.87	-0.11%	5.90	5.99	1.55%	3.78	3.79	0.13%	2.24	2.26	0.71%	1.32	1.47	10.33%	0.88	1.02	14.06%
	11.23	11.24	0.12%	8.98	8.76	-2.53%	5.91	5.96	0.86%	3.84	3.75	-2.45%	2.26	2.24	-0.80%	1.35	1.46	7.22%	0.90	1.00	9.64%
	11.17	11.30	1.15%	8.93	8.84	-1.03%	5.89	6.00	1.78%	3.83	3.77	-1.51%	2.25	2.26	0.53%	1.34	1.45	7.84%	0.90	1.02	11.59%
	11.26	11.30	0.39%	8.96	8.82	-1.62%	5.92	5.97	0.87%	3.86	3.75	-2.99%	2.26	2.25	-0.58%	1.36	1.48	8.23%	0.91	1.02	10.96%
Average	11.20	11.30	0.92%	8.92	8.82	-1.14%	5.91	5.98	1.11%	3.81	3.76	-1.34%	2.25	2.25	0.04%	1.34	1.47	8.54%	0.90	1.01	11.51%
Std Dev	0.05	0.05		0.05	0.04		0.02	0.02		0.04	0.02		0.01	0.01		0.02	0.01		0.01	0.01	
COV	0.42%	0.44%		0.57%	0.46%		0.33%	0.26%		1.11%	0.43%		0.44%	0.35%		1.18%	0.81%		1.27%	1.22%	
	14.95	15.21	1.72%	12.04	11.89	-1.30%	7.86	8.07	2.64%	5.22	5.15	-1.44%	3.11	3.13	0.77%	1.91	2.09	8.70%	1.26	1.45	13.04%
	14.99	15.24	1.63%	12.11	11.94	-1.42%	7.88	8.10	2.73%	5.24	5.16	-1.65%	3.11	3.15	1.30%	1.91	2.10	9.18%	1.26	1.46	13.88%
	14.94	15.20	1.70%	11.99	11.88	-0.93%	7.88	8.09	2.55%	5.20	5.14	-1.23%	3.11	3.13	0.67%	1.87	2.09	10.53%	1.26	1.46	13.76%
	14.88	15.18	1.97%	24.06	11.89	-102.42%	7.87	8.05	2.25%	5.19	5.11	-1.49%	3.08	3.14	1.91%	1.89	2.09	9.57%	1.21	1.44	15.91%
	14.98	15.18	1.30%	12.00	11.87	-1.13%	7.94	8.08	1.67%	5.22	5.13	-1.77%	3.11	3.14	0.83%	1.92	2.07	7.38%	1.25	1.45	14.03%
Average	14.95	15.20	1.66%	14.44	11.89	-21.43%	7.89	8.08	2.37%	5.21	5.14	-1.51%	3.10	3.14	1.10%	1.90	2.09	9.07%	1.25	1.45	14.12%
Std Dev	0.04	0.03		5.38	0.03		0.03	0.02		0.02	0.02		0.01	0.01		0.02	0.01		0.02	0.01	
COV	0.29%	0.17%		37.24%	0.24%		0.40%	0.23%		0.37%	0.31%		0.43%	0.25%		1.05%	0.51%		1.74%	0.67%	
	DATA REMOVED FROM ANALYSIS																				
	18.00	18.34	1.84%	24.99	14.37	-73.86%	9.52	9.75	2.40%	6.30	6.23	-1.14%	3.77	3.83	1.67%	2.34	2.56	8.63%	1.55	1.80	13.94%
	17.89	18.49	3.25%	14.38	14.42	0.29%	9.65	9.82	1.70%	6.22	6.27	0.78%	3.77	3.83	1.64%	2.29	2.57	10.96%	1.49	1.78	16.10%
	18.11	18.45	1.83%	14.59	14.42	-1.16%	9.72	9.82	1.06%	6.32	6.26	-0.93%	3.81	3.83	0.55%	2.32	2.56	9.23%	1.52	1.78	14.61%
	18.01	18.31	1.64%	14.47	14.35	-0.85%	9.64	9.72	0.78%	6.30	6.19	-1.83%	3.80	3.82	0.50%	2.30	2.56	9.98%	1.56	1.77	11.76%
	18.15	18.49	1.83%	14.61	14.39	-1.54%	9.72	9.82	0.97%	6.35	6.27	-1.36%	3.82	3.83	0.24%	2.31	2.58	10.29%	1.55	1.78	13.07%
Average	18.03	18.42	2.08%	16.61	14.39	-15.40%	9.65	9.79	1.38%	6.30	6.24	-0.89%	3.79	3.83	0.92%	2.31	2.56	9.82%	1.53	1.78	13.90%
Std Dev	0.10	0.09		4.69	0.03		0.08	0.05		0.05	0.03		0.02	0.01		0.02	0.01		0.03	0.01	
COV	0.57%	0.46%			0.22%		0.85%	0.49%		0.76%	0.56%		0.61%	0.16%		0.83%	0.36%		1.88%	0.69%	

Comparison of FWD089 Deflections and Calibration Slab Geophones

	FWD	LabVIEW		FWD	LabVIEW		FWD	LabVIEW		FWD	LabVIEW		FWD	LabVIEW		FWD	LabVIEW		FWD	LabVIEW	
	SD1	CalGeo1	%Error	SD2	CalGeo2	%Error	SD3	CalGeo3	%Error	SD4	CalGeo4	%Error	SD5	CalGeo5	%Error	SD6	CalGeo6	%Error	SD7	CalGeo7	%Error
	6.87	6.50	-5.77%	5.37	5.49	2.19%	3.56	3.71	3.97%	2.19	2.30	4.74%	1.33	1.34	0.97%	0.80	0.85	5.33%	0.51	0.57	10.37%
	6.83	6.49	-5.19%	5.35	5.49	2.48%	3.55	3.73	4.77%	2.18	2.32	5.99%	1.31	1.35	2.75%	0.81	0.86	5.26%	0.48	0.57	15.64%
	6.90	6.57	-4.99%	5.37	5.51	2.54%	3.56	3.73	4.63%	2.23	2.33	4.33%	1.33	1.36	2.13%	0.80	0.85	5.77%	0.50	0.58	13.34%
	6.86	6.56	-4.65%	5.35	5.53	3.18%	3.59	3.74	3.91%	2.23	2.32	3.84%	1.32	1.33	0.75%	0.79	0.85	7.49%	0.48	0.57	16.23%
	6.95	6.67	-4.15%	5.41	5.51	1.87%	3.59	3.72	3.42%	2.19	2.32	5.56%	1.30	1.34	3.06%	0.78	0.84	7.47%	0.46	0.58	20.96%
Average	**6.86**	**6.56**	-4.95%	**5.37**	**5.51**	2.45%	**3.57**	**3.72**	4.14%	**2.20**	**2.32**	4.89%	**1.32**	**1.34**	1.93%	**0.80**	**0.85**	6.26%	**0.49**	**0.57**	15.33%
Std Dev	**0.05**	**0.07**		**0.02**	**0.02**		**0.02**	**0.01**		**0.02**	**0.01**		**0.01**	**0.01**		**0.01**	**0.01**		**0.02**	**0.01**	
COV	**0.66%**	**1.12%**		**0.46%**	**0.30%**		**0.52%**	**0.32%**		**1.09%**	**0.50%**		**0.99%**	**0.78%**		**1.43%**	**0.63%**		**4.01%**	**0.97%**	
	9.76	9.18	-8.34%	7.63	7.62	-0.17%	5.06	5.17	2.11%	3.11	3.23	3.74%	1.89	1.91	1.15%	1.16	1.22	4.53%	0.72	0.82	12.41%
	9.67	9.10	-6.22%	7.62	7.61	-0.13%	5.04	5.14	1.93%	3.12	3.22	3.02%	1.87	1.92	2.50%	1.13	1.23	8.06%	0.72	0.81	11.22%
	9.68	9.09	-6.51%	7.58	7.58	0.03%	5.00	5.14	2.76%	3.12	3.21	2.89%	1.85	1.89	2.27%	1.14	1.21	5.39%	0.70	0.81	13.69%
	9.61	9.18	-4.70%	7.59	7.54	-0.68%	5.03	5.11	1.47%	3.11	3.22	3.36%	1.87	1.88	0.64%	1.12	1.21	7.74%	0.67	0.80	16.04%
	9.59	9.08	-5.64%	7.56	7.56	0.04%	5.02	5.12	1.88%	3.10	3.21	3.28%	1.86	1.89	1.64%	1.13	1.21	6.53%	0.69	0.80	13.97%
Average	**9.66**	**9.13**	-5.88%	**7.60**	**7.58**	-0.18%	**5.03**	**5.13**	2.03%	**3.11**	**3.22**	3.26%	**1.67**	**1.90**	1.64%	**1.14**	**1.21**	6.46%	**0.70**	**0.81**	13.45%
Std Dev	**0.07**	**0.05**		**0.03**	**0.03**		**0.02**	**0.02**		**0.01**	**0.01**		**0.01**	**0.02**		**0.02**	**0.01**		**0.02**	**0.01**	
COV	**0.69%**	**0.54%**		**0.38%**	**0.43%**		**0.44%**	**0.48%**		**0.27%**	**0.29%**		**0.79%**	**0.80%**		**1.34%**	**0.75%**		**3.03%**	**1.15%**	
	12.86	12.26	-4.91%	10.15	10.16	0.14%	6.74	6.89	2.22%	4.23	4.36	2.87%	2.59	2.61	0.77%	1.58	1.70	7.11%	0.99	1.15	13.61%
	12.82	12.16	-5.44%	10.14	10.17	0.31%	6.72	6.90	2.67%	4.22	4.35	2.99%	2.57	2.61	1.53%	1.57	1.70	7.48%	1.00	1.14	11.97%
	12.81	12.24	-4.63%	10.13	10.15	0.22%	6.73	6.89	2.25%	4.20	4.35	3.47%	2.57	2.59	0.93%	1.58	1.69	6.34%	0.99	1.14	13.16%
	12.85	12.14	-5.82%	10.11	10.14	0.26%	6.74	6.88	2.08%	4.22	4.34	2.83%	2.56	2.63	2.55%	1.56	1.70	7.96%	1.01	1.13	10.93%
	12.80	12.14	-5.45%	10.11	10.16	0.44%	6.72	6.88	2.27%	4.20	4.34	3.31%	2.55	2.61	2.34%	1.56	1.69	7.53%	1.01	1.13	10.46%
Average	**12.83**	**12.19**	-5.25%	**10.13**	**10.16**	0.27%	**6.73**	**6.89**	2.30%	**4.21**	**4.35**	3.10%	**2.57**	**2.61**	1.62%	**1.57**	**1.69**	7.29%	**1.00**	**1.14**	12.03%
Std Dev	**0.03**	**0.06**		**0.02**	**0.01**		**0.01**	**0.01**		**0.01**	**0.01**		**0.01**	**0.01**		**0.01**	**0.01**		**0.01**	**0.01**	
COV	**0.20%**	**0.47%**		**0.18%**	**0.13%**		**0.15%**	**0.16%**		**0.32%**	**0.12%**		**0.58%**	**0.45%**		**0.64%**	**0.37%**		**1.00%**	**0.59%**	
	15.72	14.83	-6.02%	12.43	12.52	0.72%	8.29	8.47	2.10%	5.22	5.40	3.37%	3.23	3.27	1.10%	2.01	2.15	6.56%	1.30	1.44	9.91%
	15.71	14.89	-5.49%	12.42	12.50	0.60%	8.29	8.49	**2.39%**	5.22	5.38	3.01%	3.23	3.29	1.79%	2.00	2.13	6.10%	1.29	1.44	10.42%
	15.67	14.91	-5.11%	12.39	12.48	0.71%	8.28	8.46	2.13%	5.20	5.39	3.54%	3.22	3.24	0.62%	1.99	2.15	7.36%	1.28	1.44	11.17%
	15.71	14.92	-5.29%	12.39	12.48	0.75%	8.28	8.49	**2.42%**	5.21	5.41	3.64%	3.22	3.28	1.92%	1.98	2.13	6.82%	1.28	1.44	10.86%
	15.69	14.86	-5.60%	12.39	12.49	0.80%	8.28	8.47	2.23%	5.20	5.39	3.51%	3.21	3.26	1.50%	1.97	2.13	7.56%	1.28	1.44	11.30%
Average	**15.70**	**14.88**	-5.50%	**12.40**	**12.49**	0.71%	**8.28**	**8.48**	2.25%	**5.21**	**5.39**	3.41%	**3.22**	**3.27**	1.39%	**1.99**	**2.14**	6.88%	**1.29**	**1.44**	10.73%
Std Dev	**0.02**	**0.04**		**0.02**	**0.02**		**0.01**	**0.01**		**0.01**	**0.01**		**0.01**	**0.02**		**0.02**	**0.01**		**0.01**	**0.00**	
COV	**0.13%**	**0.25%**		**0.16%**	**0.13%**		**0.07%**	**0.16%**		**0.19%**	**0.19%**		**0.26%**	**0.60%**		**0.79%**	**0.55%**		**0.70%**	**0.20%**	

Appendix D

Complete Validation Data

Overall Reproducibility – After Calibration

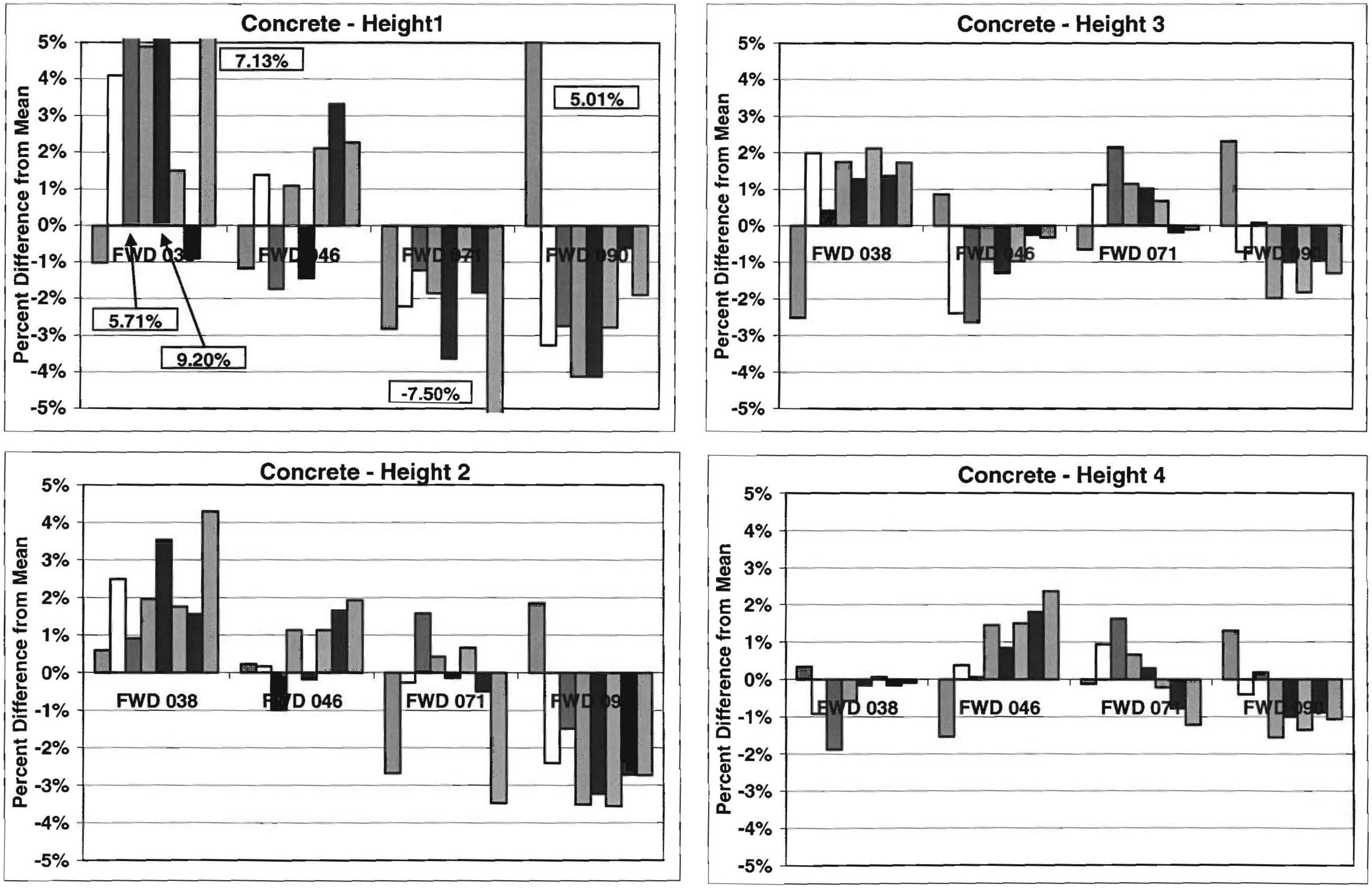
	CONCRETE - Averages								ASPHALT - Averages							
Height1	**LC**	**SD1**	**SD2**	**SD3**	**SD4**	**SD5**	**SD6**	**SD7**	**LC**	**SD1**	**SD2**	**SD3**	**SD4**	**SD5**	**SD6**	**SD7**
FWD 038	-1.01%	4.10%	**5.71%**	4.88%	**9.20%**	1.50%	-0.89%	**7.13%**	-1.19%	-1.06%	-0.02%	0.33%	2.45%	-0.06%	-2.78%	0.84%
FWD 046	-1.17%	1.39%	-1.74%	1.09%	-1.44%	2.12%	3.33%	2.27%	0.97%	-1.04%	-0.92%	3.78%	0.08%	2.98%	3.62%	4.37%
FWD 071	-2.83%	-2.21%	-1.22%	-1.85%	-3.63%	-0.85%	-1.83%	**-7.50%**	-3.32%	2.91%	2.18%	-0.27%	-2.64%	-1.22%	1.22%	**-6.19%**
FWD 090	**5.01%**	-3.27%	-2.75%	-4.12%	-4.13%	-2.77%	-0.60%	-1.90%	3.54%	-0.81%	-1.25%	-3.83%	0.11%	-1.69%	-2.05%	0.98%
Height2	**LC**	**SD1**	**SD2**	**SD3**	**SD4**	**SD5**	**SD6**	**SD7**	**LC**	**SD1**	**SD2**	**SD3**	**SD4**	**SD5**	**SD6**	**SD7**
FWD 038	0.59%	2.49%	0.91%	1.95%	3.54%	1.76%	1.56%	4.28%	-0.24%	0.50%	0.67%	1.19%	3.02%	2.97%	2.67%	3.88%
FWD 046	0.23%	0.17%	-1.00%	1.13%	-0.18%	1.13%	1.65%	1.93%	1.40%	-1.51%	-0.94%	2.79%	-0.86%	0.06%	0.37%	0.50%
FWD 071	-2.68%	-0.26%	1.58%	0.43%	-0.13%	0.67%	-0.50%	-3.48%	-2.04%	2.59%	1.87%	0.31%	-0.92%	-0.77%	-0.28%	-2.38%
FWD 090	1.85%	-2.41%	-1.48%	-3.51%	-3.22%	-3.56%	-2.72%	-2.73%	0.88%	-1.57%	-1.60%	-4.29%	-1.24%	-2.26%	-2.76%	-2.00%
Height3	**LC**	**SD1**	**SD2**	**SD3**	**SD4**	**SD5**	**SD6**	**SD7**	**LC**	**SD1**	**SD2**	**SD3**	**SD4**	**SD5**	**SD6**	**SD7**
FWD 038	-2.52%	1.99%	0.41%	1.74%	1.27%	2.12%	1.37%	1.74%	-3.39%	0.75%	1.36%	1.73%	3.02%	2.72%	2.04%	2.83%
FWD 046	0.86%	-2.40%	-2.64%	-0.91%	-1.30%	-0.97%	-0.25%	-0.32%	1.76%	-2.42%	-2.20%	0.88%	-2.34%	-1.66%	-1.36%	-1.31%
FWD 071	-0.65%	1.12%	2.15%	1.14%	1.02%	0.68%	-0.18%	-0.11%	-0.69%	3.30%	2.36%	1.15%	0.68%	1.02%	0.57%	-1.01%
FWD 090	2.31%	-0.72%	0.08%	-1.98%	-1.00%	-1.82%	-0.95%	-1.31%	2.33%	-1.63%	-1.51%	-3.76%	-1.36%	-2.09%	-1.24%	-0.51%
Height4	**LC**	**SD1**	**SD2**	**SD3**	**SD4**	**SD5**	**SD6**	**SD7**	**LC**	**SD1**	**SD2**	**SD3**	**SD4**	**SD5**	**SD6**	**SD7**
FWD 038	0.34%	-0.92%	-1.88%	-0.56%	-0.15%	0.06%	-0.15%	-0.08%	-0.17%	-0.90%	-0.65%	-1.00%	0.14%	-0.24%	0.40%	-1.61%
FWD 046	-1.53%	0.38%	0.07%	1.46%	0.85%	1.50%	1.81%	2.36%	-1.58%	1.16%	1.31%	4.33%	0.77%	1.54%	1.96%	2.71%
FWD 071	-0.12%	0.94%	1.62%	0.66%	0.30%	-0.21%	-0.77%	-1.22%	-0.84%	2.24%	2.32%	1.23%	1.71%	1.26%	0.16%	0.14%
FWD 090	1.31%	-0.40%	0.19%	-1.55%	-1.00%	-1.35%	-0.88%	-1.07%	2.59%	-2.51%	-2.97%	-4.57%	-2.61%	-2.57%	-2.51%	-1.24%

Overall Reproducibility – After Calibration

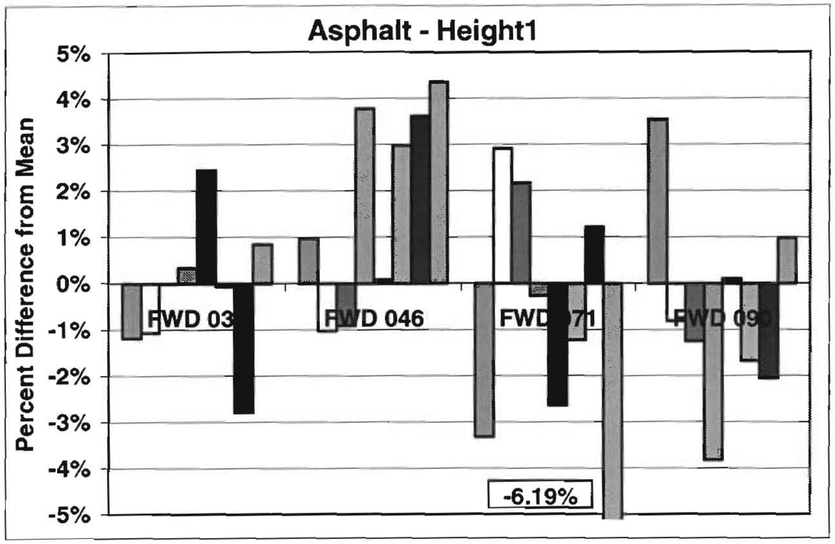
AvenueD - Averages

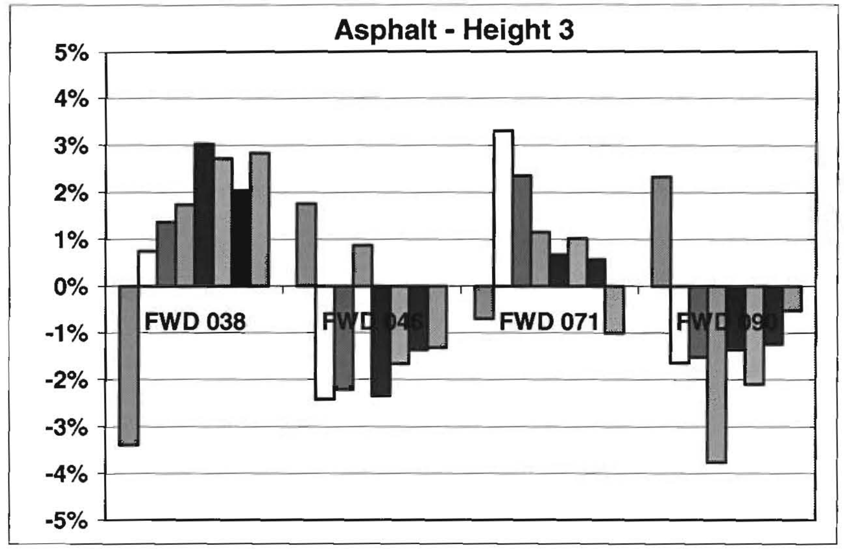
Height1	LC	SD1	SD2	SD3	SD4	SD5	SD6	SD7
FWD 038	-0.83%	-1.55%	-0.58%	-0.18%	0.31%	-1.02%	-1.88%	-0.86%
FWD 046	0.79%	-1.96%	-2.12%	0.48%	-1.08%	0.64%	1.38%	-0.55%
FWD 071	-4.13%	3.05%	2.01%	1.05%	-1.40%	-0.54%	-0.80%	0.00%
FWD 090	4.16%	0.47%	0.69%	-1.35%	2.17%	0.92%	1.30%	1.42%
Height2	**LC**	**SD1**	**SD2**	**SD3**	**SD4**	**SD5**	**SD6**	**SD7**
FWD 038	0.49%	-0.83%	0.25%	1.01%	1.23%	1.27%	0.42%	2.20%
FWD 046	1.29%	-1.83%	-2.15%	0.72%	-0.99%	0.24%	0.21%	-0.48%
FWD 071	-2.62%	2.70%	1.83%	1.13%	-0.44%	-0.84%	-0.53%	-2.32%
FWD 090	0.84%	-0.04%	0.07%	-2.86%	0.21%	-0.67%	-0.10%	0.60%
Height3	**LC**	**SD1**	**SD2**	**SD3**	**SD4**	**SD5**	**SD6**	**SD7**
FWD 038	-1.53%	0.49%	0.92%	1.45%	0.38%	1.73%	1.48%	0.63%
FWD 046	0.26%	-3.75%	-3.86%	-0.77%	-2.24%	-1.95%	-2.25%	-2.16%
FWD 071	-1.61%	3.08%	2.39%	1.86%	1.01%	0.54%	0.11%	0.73%
FWD 090	2.88%	0.18%	0.55%	-2.54%	0.85%	-0.32%	0.65%	0.81%
Height4	**LC**	**SD1**	**SD2**	**SD3**	**SD4**	**SD5**	**SD6**	**SD7**
FWD 038	0.49%	-1.46%	-1.53%	-1.44%	-1.96%	-0.64%	-0.21%	-3.34%
FWD 046	-0.85%	-0.25%	0.18%	3.19%	0.97%	1.29%	1.21%	1.76%
FWD 071	-1.88%	1.92%	2.72%	2.17%	1.74%	0.94%	0.46%	2.04%
FWD 090	2.24%	-0.20%	-1.37%	-3.92%	-0.76%	-1.58%	-1.46%	-0.46%

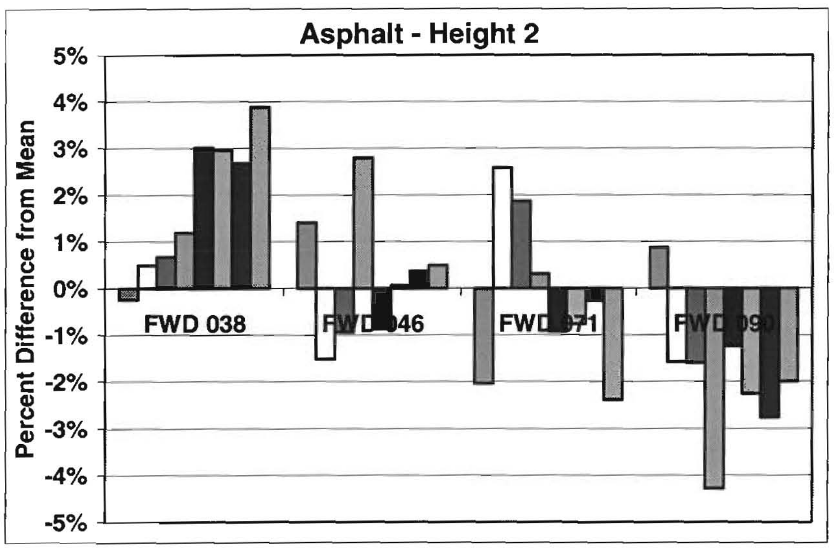
Overall Reproducibility – After Calibration

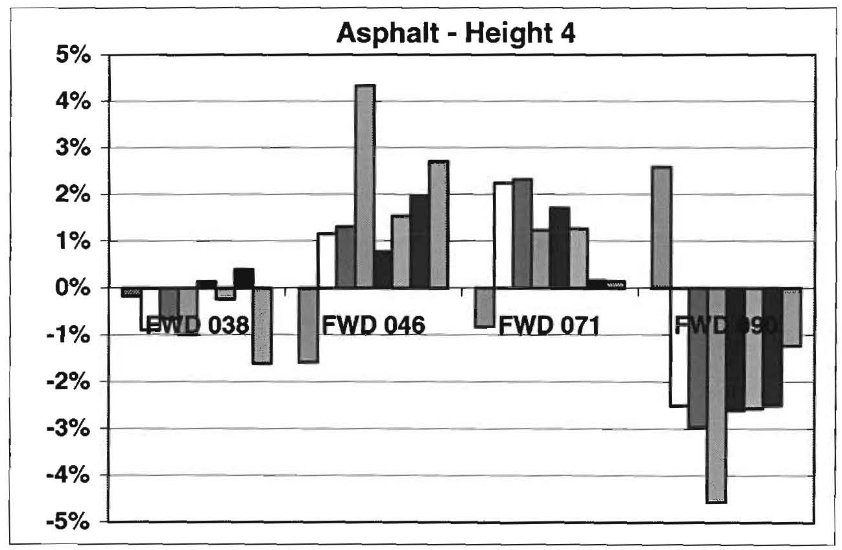


Overall Reproducibility – After Calibration









Overall Reproducibility – After Calibration