

**FALLING WEIGHT DEFLECTOMETER CALIBRATION: LOOKING BACK
TO THE FUTURE**

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ABSTRACT

As part of the Strategic Highway Research Program (SHRP), regional Falling Weight Deflectometer (FWD) calibration centers were established at locations in the United States in the early 1990s. After ten years of FWD calibrations, there is enough evidence to look back at FWD calibrations and review the SHRP FWD calibration protocols to determine possible changes and improvements. An analysis of FWD calibrations performed through 2000 at five FWD calibration centers in the United States determined some changes to FWD calibrations might be warranted. However, it is critical to balance the cost of implementation of new protocols versus the improvements these changes may provide to the quality of data collected with a FWD. The analysis also shows the need for annual calibrations to ensure FWDs meet existing standards for use. Based upon the results of the analysis and input from FWD users and operators from the US and Europe, proposed changes to the SHRP protocol were collected for review. This paper reviews the suggested changes and makes recommendations for more detailed analysis and priority for inclusion in revised calibration protocols.

CALIBRATION HISTORY

In the early 1990s, the United States Federal Highway Administration (FHWA) Strategic Highway Research Program (SHRP) contracted for the development of Falling Weight Deflectometer (FWD) calibration centers to ensure accuracy and precision of FWD data. The calibration protocol (*I*), developed by Lynne Irwin at Cornell University, took into account different problems that might exist with the calibration of FWDs. The calibration protocol focused on the parts of the FWD that could not easily be calibrated in the field or at a home base or that would require expensive equipment to perform the calibration.

Since the protocol calls for FWD calibration at a fixed location, regional FWD calibration centers were installed in the United States to limit the distance the FWD would need to travel to be calibrated. Five FWD calibration centers were installed as part of the initial development: four regional centers as part of the SHRP program and one private center in Florida. The regional centers continue to be operated by the State Departments of Transportation where they are located.

Additional SHRP-based FWD calibration centers currently exist in Kansas and Indiana in the United States, and in South Africa and Australia. Eight FWDs used to collect data for the Long Term Pavement Performance (LTPP) Program are calibrated annually at the four regional centers. Additional FWDs, owned by states, other public agencies, universities and private companies, are also calibrated at the various centers.

Table 1 - Initial Date of Calibration at Regional FWD Calibration Centers

FWD Calibration Center	Date of First Calibration
Nevada DOT (SHRP/LTPP)	1991
Minnesota DOT (SHRP/LTPP)	1992
Pennsylvania DOT (SHRP/LTPP)	1992
Texas DOT (SHRP/LTPP)	1992
Dynatest, Florida (Private)	1992

Shortly after the installation of the initial FWD calibration centers a users group of FWD owners, researchers, and operators in North America began holding an annual meeting to discuss FWD research, operations, and maintenance issues. In 1998, based on input from FWD owners and operators attending the FWD Users Group meetings (FWDUG), a recommendation was made to perform a historical analysis of calibrations. Initially, the goal was to determine the quality of the current calibration protocol. However, after an

initial review in 2000, an additional goal was added to include changes that might improve the protocol or make it more user-friendly.

SHRP Calibration

The SHRP calibration of the FWD concentrates on calibrating items that are difficult to calibrate in the field. Essentially, the only two items calibrated are the FWD's load cell and geophones.

Load Cell

The FWD load cell is calibrated against a reference load cell, which is calibrated to a very high accuracy using National Institute of Science and Technology (NIST) standards. The reference load cell should have an error of less than 0.3 percent over a range of 0-20,000 pounds (88kN) according to the SHRP protocol. The Cornell University Local Roads Program has performed every single reference load cell calibration and, in reality, almost all of the load cell calibrations have had an accuracy of 0.1 percent or better.

The FWD load cell is calibrated using multiple drops at four different load levels. A multiplier (gain) of the electrical signal from the FWD load cell is changed to match the output of the FWD load cell to the reference device. Statistical checks validate the results.

Geophones

The goal of geophone calibration is to have both high accuracy and high precision. To do this geophones are calibrated in a two-step process. The first step is a comparison to a reference Linear Variable Displacement Transducer (LVDT). The LVDT is a very accurate device calibrated before each FWD calibration, but has an error similar in magnitude to the geophones. Since the reference device (LVDT) is not substantially more precise than the geophones, the first part of the calibration only removes any bias in the geophones on the FWD. Therefore, the goal of the reference calibration is to ensure the output of the geophones after this step is random about the correct deflection. Again, four different load levels are used to provide a range for the calibration. The gain of each geophone is adjusted based upon the results of the reference calibration.

Once the geophone gains have been adjusted in the reference calibration, all of the geophones are subjected to the same deflection by stacking all of the geophones in a column. Since the average of all of the deflections are expected to be random about the correct value, a relative adjustment can be done to ensure the geophones are in calibration relative to each other. Essentially, the relative calibration (2) adjusts the gain of the geophones to increase the precision. This is accomplished by performing a large number of drops (35 for a 7 geophone FWD, 45 for a 9 geophone FWD) with each geophone sensing the same deflection. Using a Latin squares statistical design, the gain of the geophones are adjusted. Together with the reference calibration, the full calibration ensures the precision and accuracy of the geophones. Between the annual full

calibration, relative calibrations in the field are used to check the consistency of the geophones and to make minor adjustments.

SHRP CALIBRATION ANALYSIS

For the historical analysis, data were collected from the four regional FWD calibration centers as well as the Dynatest center. The newer FWD calibration centers were not included due to the small number of FWD calibrations performed at each center. Each center provided all available data. This data did not provide a complete set of all calibrations performed since record keeping was not complete nor standardized.

The analysis had several goals:

- Determine the quality of existing protocols
- Analyze the need to calibrate FWDs on an annual basis
- Examine the failure rates of the various components of FWDs with respect to the FWD calibration protocol

Three different statistical tests were performed on the data to check consistency versus time. First, for both load cells and geophones the average absolute change in the gain on the device from one year to the next was examined. This helped determine the value of annual calibrations. Second, the number of load cells and geophones that failed to meet the specifications in the protocol was examined. This determined if the protocol was catching devices that were out of specification as well as the long-term quality of the devices themselves. Finally, statistical comparisons were made for geophones and load cells which had been calibrated at multiple centers to determine the consistency between centers. The final gain settings should be independent of the center where the FWD was calibrated.

Historical Results

The FWD calibration data provided by the five FWD calibration centers included 626 calibrations of 126 different FWDs. The analysis of historical trends only examined those devices (load cells and geophones) that had been calibrated three or more times. The analysis concentrated on the final gain leaving the FWD calibration center. An effort was made to ensure no calibrations were missed for a given device but this cannot be confirmed.

Load Cells

164 different load cells were included in the data provided. Table 2 shows the number of calibrations performed for the various load cells.

Table 2 - Load Cell Calibrations

Calibrated	Load cells	Calibrations
Once	53	53
Twice	23	46
3 or more	88	527
Total	164	626

For load cells with three or more calibrations, the average change in the final gain between calibrations is 0.09 percent. This results in an error of 14 lbs for a 16,000 lbs load (0.061 kN for a 71 kN load). This error is well below the sensitivity of the FWD and reference load cells.

Examining the number of load cells that had a final gain factor of less than 0.98 or greater than 1.02, a total of 108 (20.5 percent) load cell calibrations failed to meet this criteria. The histogram in Figure 1 shows the distribution of the final gain factors. Even though this criteria is not in the SHRP protocol, this number seemed unacceptably high so a secondary analysis of the data was undertaken.

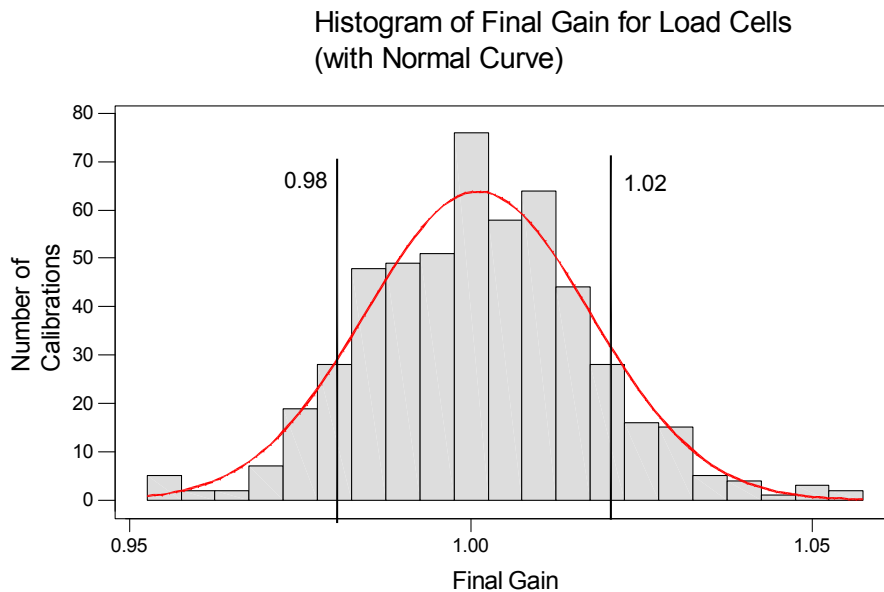


Figure 1 - Final Gain Factor for Load Cells

Analysis of Load Cell Trends The secondary analysis looked at the long-term trends of the load cell final gain. There are several possibilities for the long-term trend of the final gain of different load cells. Figure 2 shows five different load cells that illustrate the different trends.

Final Gain Load Cells

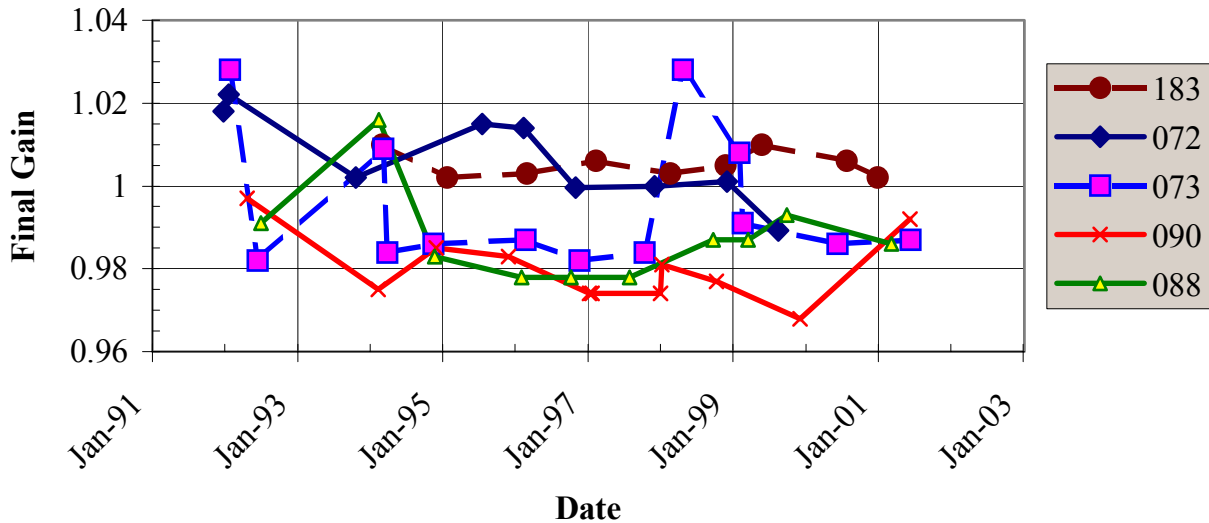


Figure 2- Historical Trends in Final Gain for Selected Load Cells

- Stable load cell versus time (43 load cells of the 88 examined) – i.e. Load Cell #183**

Load cell 183 shows a fairly constant final gain versus time. The gain is well within the 0.98 to 1.02 range. Such a load cell may not need to be calibrated as often as some others but it takes several annual calibrations to be sure a load cell is stable. Calibrations need to be performed often enough to detect when the load cell fails or begins to behave in an unstable manner.

- General trend of final gain versus time (9 load cells) – i.e. Load Cell #072**

Load cell 072 is stable but has a long-term trend toward a decreasing final gain. The trend may be upwards or downwards but from one year to the next there is no major change that would invalidate any data taken with the FWD. This kind of load cell definitely needs to be calibrated on an annual basis to ensure the accuracy of any results from the FWD.

- Dramatic change from one year to the next (13 load cells) – i.e. Load Cell #073**

Load cell 073 shows several dramatic changes from one calibration to the next. Possible reasons for the large changes included: improper calibration; damage to the load cell; or major change in the response of the load cell. The data alone

cannot determine which of the possibilities is actually causing the change. This kind of load cell needs to be calibrated regularly to catch any anomalies.

- **Relatively stable versus time but with an offset (19 load cells) – i.e. Load Cell #090**

Some load cells are relatively stable over time but do not fall in the 0.98 to 1.02 final gain range. If, instead of looking at an absolute gain around 1.00, the relative change in gain versus the average gain over the life of the load cell is examined, these load cells never deviate from a two percent change about the average. If a load cell left the manufacturer with an offset in the gain factor, the load cell, while stable, would have a relatively high or low gain factor. Many of the load cells appear to be stable but with an offset.

- **Dramatic change from one year to the next with an offset – (4 load cells) – i.e. Load Cell #088**

Finally, a few load cells showed a combination of the offset and dramatic change from one year to the next. With the exception of a single calibration, load cell 088 was stable. The one spike for load cell 088 may actually be the only calibration that needs to be carefully examined.

Relative change in the final gain If, instead of the absolute final gain, the relative change versus the average final gain is examined, the number of load cell calibrations with a deviation of more than 2 percent drops from 108 (20.5 percent) to 32 (6.1 percent). This distribution is shown in Figure 3. This confirms the load cells are generally stable and the calibration protocol is able to catch any major changes in the final gain.

The frequency of calibration needs to be set often enough to ensure that good load cells are never out of calibration and load cells that need to be replaced are examined as soon as feasible. Due to the low expected change from year to year, there is no need to calibrate more than once each year. However, the analysis shows there is a need to calibrate the load cells on an annual basis to catch anomalies. Waiting two years between calibrations would increase the likelihood of an anomalous load cell being used when it should be replaced. It is recommended load cells be calibrated once each year.

Histogram of Relative Gain Change,
with Normal Curve

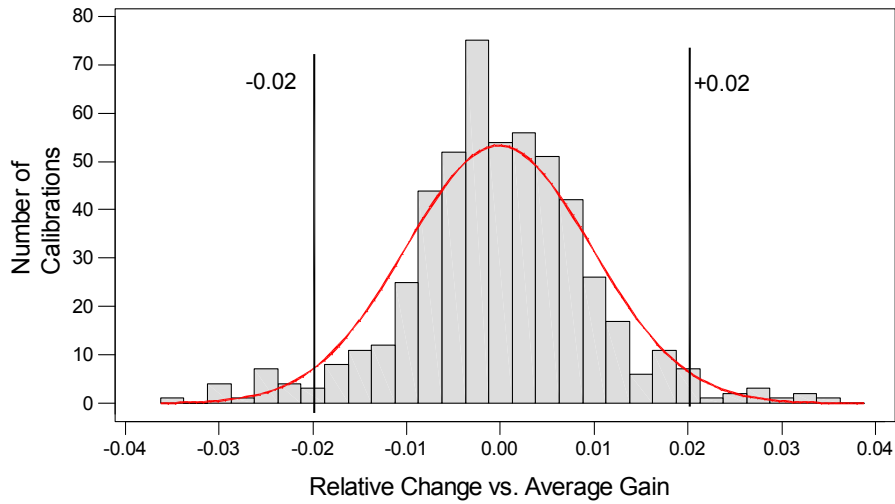


Figure 3 - Relative Gain for Load Cells

Multiple FWD Calibration Center Calibrations Twenty-four of the load cells were calibrated at least three times and at more than one of the five FWD calibration centers in the study. An analysis of variance (ANOVA) test (Table 3), calculated using MINITAB statistical software (3) shows no statistical difference between any of the centers.

A Tukey (4) pairwise comparison analyzes different treatment levels to determine if a treatment level is statistically different versus another treatment level. Table 4 shows this comparison, run with MINTAB statistical software, to detect if there is any difference between each given pairs of centers with respect to the final gain of the load cells. The hypothesis is the centers are independent. If the probability is greater than 0.05, we can not reject the hypothesis. The results show no statistical difference between the centers. Load cell calibration is independent of the center performing the calibration.

Table 3 - ANOVA Test on Load Cell Final Gain

Analysis of Variance for Load Cell, using Adjusted SS for Tests						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Center	4	0.0017208	0.0004423	0.0001106	1.48	0.211
Load Cell	23	0.0104920	0.0104920	0.0004562	6.11	0.000
Error	129	0.0096267	0.0096267	0.0000746		
Total	156	0.0218395				

Table 4 - Tukey Testing of Load Cell Final Gain

Tukey Simultaneous Tests for Load Cells Comparing FWD Calibration Centers				
Response Variable Load Cell				
All Pairwise Comparisons among Levels of Center				
Center = North Central subtracted from:				
Level	Difference	SE of		Adjusted
Center	of Means	Difference	T-Value	P-Value
Dynatest	-0.002303	0.003731	-0.617	0.9721
N. Atlantic	-0.002806	0.003142	-0.893	0.8990
Southern	-0.004152	0.004304	-0.965	0.8705
Western	-0.008839	0.003983	-2.219	0.1792
Center = Dynatest subtracted from:				
Level	Difference	SE of		Adjusted
Center	of Means	Difference	T-Value	P-Value
N. Atlantic	-0.000503	0.003301	-0.152	0.9999
Southern	-0.001848	0.003383	-0.546	0.9822
Western	-0.006536	0.003354	-1.948	0.2974
Center = N. Atlantic subtracted from:				
Level	Difference	SE of		Adjusted
Center	of Means	Difference	T-Value	P-Value
Southern	-0.001345	0.003693	-0.364	0.9962
Western	-0.006033	0.003493	-1.727	0.4213
Center = Southern subtracted from:				
Level	Difference	SE of		Adjusted
Center	of Means	Difference	T-Value	P-Value
Western	-0.004687	0.003523	-1.330	0.6728

Geophones

The data provided show that 1014 geophones have been calibrated at the five FWD calibration centers with 537 of the geophones being calibrated three or more times. Table 5 shows the number of calibrations performed for the various geophones.

For geophones with more than three calibrations, the average change from one calibration to the next is 0.58 percent. This results in an error of 0.092 mils for a 16 mil deflection (2.31 μm for a 400 μm deflection). This error is just above the sensitivity of the geophones (0.08 mils or 2 μm).

Table 5- Geophone Calibration

Calibrated	Geophones	Calibrations
Once	290	290
Twice	187	374
3 or more	537	2954
Total	1014	3618

Examining the number of geophones that had a final gain less than 0.98 or greater than 1.02, a total of 77 (2.60 percent) of the geophone calibrations failed to meet this criteria. Figure 4 shows the distribution of the final gain factors. The SHRP protocol recommends any sensor with a gain outside the range of 0.98 to 1.02 should be repaired or replaced. However, geophones may fail the final gain criteria and still be acceptable due to either a stable geophone with an offset in the gain factor, or a final gain just outside the acceptable range. In both cases, it is assumed that the other calibration criteria have been met. It is also assumed the owner of that the FWD made the decision to continue using the geophone even though it does not meet the calibration protocol.

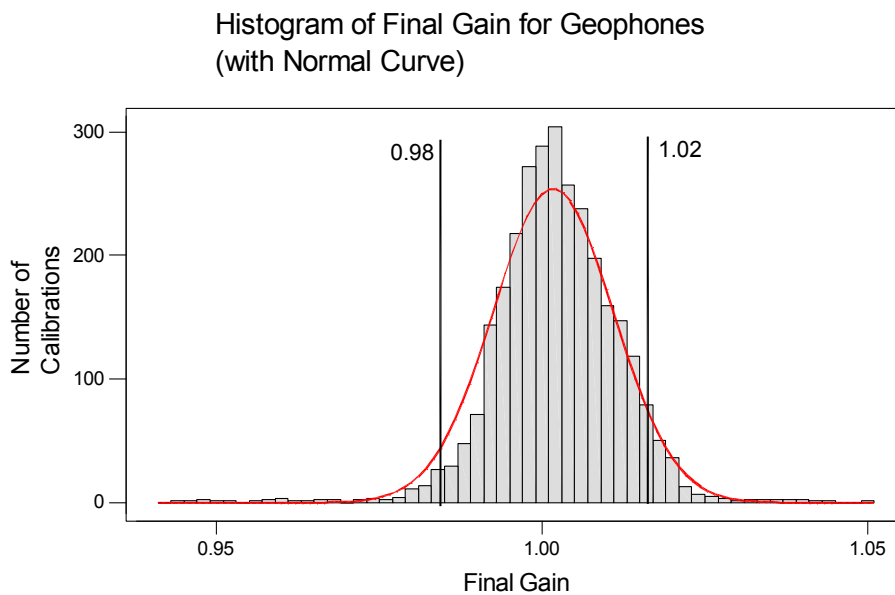


Figure 4 - Final Gain for Geophones

Only 39 geophones accounted for the 77 calibrations that failed to meet the 0.98 to 1.02 final gain factor. Eleven of the 39 geophones in question appear to have an offset in the gain factor but the data alone are not conclusive. It is also likely these geophones need to be removed from service.

Multiple FWD Calibration Center Calibrations A total of 175 geophones were calibrated at least three times and at more than one of the five FWD calibration centers in the study. An ANOVA test was performed using MINITAB and shows a statistical

difference between the centers. Additional statistical testing may help determine if the difference is critical.

A Tukey pairwise comparison between the centers also shows a difference between the centers. The North Atlantic FWD calibration center at the Pennsylvania Department of Transportation (Pennsylvania) appears to provide a different result than all the other four FWD calibration centers. Additionally, the Dynatest and Southern (Texas) FWD calibration centers appear to provide differing results.

Table 6- ANOVA Test on Geophone Final Gain

Analysis of Variance for Sensor Final Gain, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Center	4	0.0036126	0.0016900	0.0004225	14.58	0.000
Sensor #	174	0.0464258	0.0464258	0.0002668	9.21	0.000
Error	829	0.0240184	0.0240184	0.0000290		
Total	1007	0.0740568				

Data mining found three possible reasons for the difference:

- The data provided did not overlap in time. For example, the data from the Dynatest FWD calibration center begins in late 1997. Since the Dynatest FWD calibration center is commonly used by FWDs that are being reconditioned, changes to the hardware and software of the FWD while at the Dynatest FWD calibration center may have resulted in an gain offset that shows up as a variation between the FWD calibration centers.
- There is, indeed, a difference between the FWD calibration centers. If the LVDT used to calibrate the geophones has a systematic difference between the centers, then the resulting calibrations will have a difference in the final gain.
- The results are statistically different but not practically different. The statistical power of the tests are greater than 99 percent in both cases, but the worst case expected difference in the final gain is 0.0053. This results in an error of only 0.085 mils for a 16 mil deflection (2.12 μm for a 400 μm deflection).

Table 7- Tukey Testing of Geophone Final Gain

Tukey Simultaneous Tests

Response Variable Sensor Final Gain				
All Pairwise Comparisons among Levels of Center				
Center = North Central subtracted from:				
Level	Difference	SE of		Adjusted
Center	of Means	Difference	T-Value	P-Value
Dynatest	0.001883	0.000801	2.349	0.1296
N. Atlantic	-0.003457	0.000742	-4.660	0.0000
Southern	-0.000567	0.000885	-0.641	0.9683
Western	-0.000315	0.001055	-0.299	0.9983
Center = Dynatest subtracted from:				
Level	Difference	SE of		Adjusted
Center	of Means	Difference	T-Value	P-Value
N. Atlantic	-0.005340	0.000740	-7.221	0.0000
Southern	-0.002450	0.000708	-3.462	0.0049
Western	-0.002198	0.000860	-2.556	0.0788
Center = N. Atlantic subtracted from:				
Level	Difference	SE of		Adjusted
Center	of Means	Difference	T-Value	P-Value
Southern	0.002890	0.000810	3.568	0.0033
Western	0.003142	0.001032	3.043	0.0198
Center = Southern subtracted from:				
Level	Difference	SE of		Adjusted
Center	of Means	Difference	T-Value	P-Value
Western	0.000252	0.000893	0.2822	0.9986

If there is a difference between the centers, it may be possible to correct this problem in the future by changing the protocol. Two possible suggested changes to the protocol that may detect any existing systematic variation in the calibration are the use of historical analysis or a dynamic calibration of the LVDT.

Conclusions to Calibration Analysis

Generally, the current SHRP FWD calibration protocol is very effective and does a very good job of ensuring FWD are calibrated to a very high standard. Some changes to FWD calibrations may be warranted to help detect possible changes between FWD calibration centers and improve the ease of FWD calibration. However, there is a need to balance the cost of new procedures versus the value.

The current protocol does a good job of detecting damaged sensors, but more rigorous checks may keep some load cells and geophones from passing the calibration. Finally, calibrations are needed on an annual basis to be sure the results from the FWD are as accurate and precise as possible.

PROTOCOL IMPROVEMENTS

At FWDUG meetings in 2000 and 2001 as well as the first European FWDUG meeting in 2001, attendees were asked for input and ideas for improvement or problems with the current FWD calibration protocol. Additional information about possible FWD calibration methods was gleaned from the COST (Information and Technology Centre for Transport and Infrastructure) Action 336 – Task Group #3 ‘Calibration of Falling Weight Deflectometers (5). This Task Group’s main task was to prepare procedures for FWD calibration to be used in Europe. The Task Group did a very thorough analysis and provided many suggestions not provided by others.

Protocol Suggestions

Below is the list of the suggested improvements gathered from the various sources. A short paragraph describes the reason for the suggestion. All suggestions were accepted to be sure no good suggestion was ignored.

Load Cells

- **Increase range for FWD load cell calibration;**
- **Build heavy weight load cell for Heavy Weight Deflectometers (HWDs)**

The existing range of the reference load cells only allows calibration up to 20,000 pounds (88 kN), which does not allow heavy weight deflectometers (HWDs) to be calibrated over their full range. This may increase errors in the load reading at the upper end of the FWD’s and HWD’s working range.

- **Build load cell with 18 inch (450 mm) diameter**

In a similar vein to the previous suggestion, this would allow calibration with the larger load plates of the HWD.

- **Place reference load cell into hole so FWD plate is flush with slab**

The calibration of the load cell can create problems for the FWD since the geophones may be suspended in air during the load cell calibration. The computer programs for the FWD may generate an error when the geophones are suspended. A simple alternative that does not require removing the geophones from their holders is to place a wooden beam underneath the geophones.

Geophones

Geophone Reference Calibration

- **Moveable bracket for LVDT**

The existing bracket makes it difficult to align the LVDT at the zero balance point. A modified design developed by the FWD calibration center in Indiana may meet the requirements of the calibration protocol. The FHWA has recently procured four devices for the four regional FWD calibration centers.

- **Automate reference calibration**

This suggestion entails updating the current FWD calibration computer software (6) to read data from the FWD directly into the reference calibration program. This would add efficiency to the current reference calibration procedure and eliminate the possibility of human error due to mistyped values, which is an issue with the current version of the software. A unified output format, as discussed at the North American FWDUG meeting in 2001, would also make this suggestion a much easier programming task.

- **Measure beam movement directly**

During reference calibration of the geophones it is important to be sure that the concrete isolation block does not experience vibrations too early. Currently, this is done using a geophone from the FWD under calibration. It is awkward and requires some special apparatus with certain model FWDs. Use of an independent sensor to directly sense the movement of the beam is currently under development.

- **Better isolation on concrete**

The SHRP FWD calibration centers have had to move the concrete isolation block at least once and in some cases three times in the last 10 years. Some of the block movements have been due to failures of the concrete pad, but some have been due to isolation issues between the concrete pad and the isolation block. If a better scheme could be found to control isolation, the centers would save time and the probability of isolation errors may decrease.

- **Redesign geophone holder to accommodate different styles of geophones**

The geophone holder currently accommodates Dynatest and Kuab model geophones. The other major manufacturers would like to have accommodation of their geophones at the centers. It is expected, currently, that the manufacturer will provide any special holders.

- **Deflection sensor reference calibration verification using a vibration table**

The use of a vibration table to calibrate the geophones has the appeal of portability. In addition, this suggestion provides the ability to attempt to calibrate the geophone without removing it from the FWD. However, in reality, the vibration table can only calibrate the geophone in the vibrations range used during the calibration.

Geophone Relative Calibration

- **Ensure relative calibration stand is vertical**

Currently a small level bubble at the top of the relative calibration stand is the only method used to ensure that the stand is vertical. It is sometimes difficult to see and may not work as well as intended, especially while testing in the field. It is actually more critical that the geophones are at the same angle for every single drop during the relative calibration. The bubble does an adequate job here, but better techniques may be available.

- **Develop a shorter stand for the KUAB geophone relative calibration**

The relative calibration stand for the KUAB FWD is fairly tall and awkward. A shorter stand would be advantageous. Attempts have been made to have two columns of geophones in a single stand, but it is difficult to support the stand at the bottom. Multiple points touching the ground may result in variations in the deflections the various geophones detect.

- **Develop a relative calibration stand with down pressure**

Applying down pressure seems to reduce the error within the calibration. The key is to develop a calibration stand that applies consistent pressure.

- **Universal Relative Calibration software (7)**

This suggestion is very similar to the idea of automated reference calibration. A universal format of data output from FWDs, such as the AASHTO Pavement Deflection Data Exchange (PDDX) format (8), will facilitate the ability of this suggestion to be implemented.

- **Develop quicker relative calibration**

The current protocol for relative calibration takes approximately 15 to 30 minutes to perform because it involves between 35 and 45 load drops in addition to shifting the sensors through the calibration stand. In the field, this can be very difficult especially if weather conditions are not favorable. A shorter or faster procedure would increase the likelihood that relative calibrations are performed during the year as required in the calibration protocol.

Geophone Calibration In-place

- **Servo-accelerometer in axis with geophones;**

- **Geophone in axis with geophones**

The concept for both suggestions is to develop a way to calibrate geophones in place without removal from the FWD. The difficulty in both cases is one of the underlying assumptions in calibration. For a reference device to calibrate another device it needs to have an accuracy and precision on the order of one magnitude greater than the device under calibration. Since the error of a geophone is approximately 1 to 2 microns, any device used to calibrate the geophone in a single operation must have an error of 0.1 to 0.2 microns. No current devices meet this criterion. There is the real concern that deflections further away from the load plate will be so small as to be impossible to

calibrate.

Other Components

- **Pavement temperature probe;**
- **Infrared temperature sensor;**
- **Odometer/distance measurement;**
- **Verification of sensor offsets (By physical measurement)**

All four of the suggestions come from the European FWD calibration protocol. Currently, there is no accepted procedure in the United States for calibrating these components of the FWD. The suggestion was made to include each of these components as a part of the annual calibration performed at the FWD calibration centers. In addition, each component could be calibrated during the year as needed at the home facility of the FWD.

- **Routine voltage check of electronics**

Low voltages can result in inaccurate deflectometer measurements. A routine voltage check, performed both at the FWD calibration center and the home facility, will reduce or eliminate this problem. The FWD calibration centers ask for this to be done prior to arrival at the center, but it is not in the actual protocol.

- **Clean and maintain FWD (load plate, bleed air)**

Maintenance of the FWD is imperative to good operation and data collection. However, maintenance prior to calibration is not currently part of the calibration protocol. To ease the burden on the FWD calibration centers and to expedite the calibration process, the protocol should be amended to include a checklist of maintenance activities that must be performed by the FWD owner/operator prior to calibration.

FWD Calibration Centers

- **Develop concrete block design to allow easier access for KUAB FWDs**

The design layout of a KUAB FWD, with the load plate near the front of the trailer, makes it difficult to get the proper deflections on the concrete slab without difficult maneuvering of the FWD or utilization of a large load. A concrete block design that allows easier access of the KUAB FWDs would facilitate calibration.

- **Change sensitivity method for the KUAB FWDs**

Currently the sensitivity method for KUAB FWDs involves detection of vibration of the falling mass as it is released. It is not always successful and can be very frustrating to both the center operator and the FWD operator. The suggestion to *measure the beam movement directly* will also solve this particular problem.

- **Dynamic calibration of LVDT**

Since the LVDT is being used in a dynamic mode, it may be more accurate to calibrate the LVDT in a dynamic mode using a simple device similar to a tuning fork with different magnitudes and frequencies.

- **Check linearity of LVDT**

At least one FWD calibration center's reference LVDT had damage that may have resulted in a non-linear response. A simple statistical test could be added to check for this possibility and alert the center operator.

Computer Software

- **Read FWD data into calibration computer**

If the data from the load cell, reference and relative calibrations could be read directly from a file produced by the FWD, the possibility of human error would decrease.

- **Develop universal reporting procedure**

All four of the regional FWD calibration centers, as well as the State and private centers have their own reporting format. Although they all report the same information, the way the data is reported varies. If the data output were part of the computer program, the historical analysis described earlier would have been much easier. Finally, a universal procedure would help ensure all centers were providing a consistent level of service.

- **Display historical data**

Historical data is useful in the calibration process to identify drastic changes that may occur due to failure of a geophone or an error in calibration. A display of the historical data could immediately alert the FWD calibration center operator to such an error. However, computer programming the historical data is a major obstacle in implementation.

- **Metrication**

Current calibration software programs use U.S. Customary units only. However, at least one FWD is manufactured to utilize only metric units. In this case, during calibration the user must recalculate the metric data into U.S Customary units. This takes time, increases error, and, in the case of relative calibration, may cause the calibration to be skipped due to the time to perform the calculation. Computer software could be programmed to use dual units.

- **Use polynomial (non-linear) regression for the gain settings**

The use of non-linear regression to set the gains would decrease errors if the load cells and geophones are non-linear. However, the FWD manufacturers would need to make modifications to the control software to allow the inclusion of additional calibration coefficients.

Other Issues

- **Develop reference test pads to calibrate FWDs in place**

The concept is to develop a reference pad that could be used to calibrate the entire FWD without removing any geophones. The error of the response of the pad would need to be only 0.1 microns to be able to be used independently.

- **Develop a portable calibration system**

This problem is really a subset of calibrating the geophones in place. In the current design, the load cell and relative calibrations are portable if a laptop is used as the calibration computer. The relative calibration is independent of the need to have special hardware other than the calibration stand.

- **Look at the whole time-history (pulse length)**

It is known that different FWDs have different pulse lengths. Measuring the length of the pulse provides another data input from the FWD. Also, if the shapes of the load or deflection pulses are incorrect then any dynamic analysis of the data will obviously be incorrect. This effort would require a tremendous amount of data collection, and there is no evidence the pulse shape of the calibration devices and the FWD devices are different.

- **Use history in statistical checks**

The historical analysis mentioned earlier is just a review by the operator. A statistical check of the historical analysis could be used to alert the center operator to check the device under calibration. The difficulty is in developing a statistical test that would alert the operator without creating false positive results.

- **Short-term repeatability**
- **Long-term repeatability**
- **FWD group field calibration**
- **FWD field calibration**

All four of these suggestions are described in the European COST 336 – Task Group #3 calibration protocol. The first two examine data from a single FWD. The other two are group exercises that are more in the realm of verifications than calibrations.

RECOMMENDATIONS

It is not the goal of this paper to make recommendations for specific changes in the protocol. The goal of this portion of the paper is to provide a list of the suggestions based on input from the FWD calibration centers and FWD users that should be examined in more detail for possible inclusion in FWD calibration. Each of the FWD calibration centers and manufacturers in the United States was provided with a list of the suggestions. The authors' recommendations utilize many of their comments.

Below is a prioritized list of the authors' suggestions for further examination. High priority suggestions should be cost effective and are worthy of inclusion in the protocol. Medium priority suggestions can be divided into three categories: those that would be useful but are costly, those that are currently beyond existing technologies, and those that may not improve the quality of the calibration. Medium priority suggestions would benefit from additional research. Low priority suggestions will not be likely to improve either the accuracy or the ease of FWD calibration.

High Priority for Change/Inclusion

Load Cells

- None

Geophone Reference Calibration

- Automate reference calibration
- Moveable bracket for LVDT
- Measure beam movement directly

Geophone Relative Calibration

- Universal Relative Calibration software

Computer Software

- Read FWD data into calibration computer
- Develop universal reporting procedure

Other Components

- Pavement temperature probe
- Infrared temperature sensor
- Odometer/ distance measurement
- Verification of sensor offsets
- Routine voltage checks of electronics
- Clean and maintain FWD (load plate, bleed air)

FWD Calibration Centers

- Change sensitivity method for the KUAB FWDs

Medium Priority for Change/Inclusion (More research is needed)

Load Cells

- Increase range for FWD load cell calibration
- Build heavy weight load cell for HWDs
- Build load cell with 18 inch (450 mm) diameter

Geophones Reference Calibration

- Better isolation on concrete
- Redesign geophone holder to accommodate different styles of geophones

Geophone Relative Calibration

- Ensure relative calibration stand is vertical
- Develop a shorter stand for the KUAB geophone relative calibration
- Develop a relative calibration stand with downpressure
- Develop quicker relative calibration

Geophone Calibration In-place

- Servo-accelerometer in axis with geophones
- Geophone in axis with geophones

FWD Calibration Centers

- Develop concrete block design to allow easier access for KUAB FWDs
- Dynamic calibration of LVDT
- Check linearity LVDT

Computer Software

- Display historical data
- Metrication

Other Issues

- Develop a portable calibration system
- Look at whole time-history (pulse length)
- Short-term repeatability
- Long-term repeatability

Low Priority for change/ inclusion

Load Cells

- Place reference load cell into hole so FWD plate is flush with slab

Geophone Reference Calibration

- Deflection sensor reference calibration verification using a vibration table

Computer Software

- Use polynomial (non-linear) regression for gain setting

Other Issues

- Develop reference test pads to calibrate FWDs in place
- Use history in statistical checks
- FWD group field calibration
- FWD field calibration

CONCLUSION

The SHRP FWD calibration protocol is a mature standard that has been used successfully for over ten years. A historical analysis of the results from the calibrations shows the protocol succeeds in the primary goal of ensuring FWDs that are calibrated provide consistent data and are as accurate and precise as possible. Like any protocol, some changes to the FWD calibration may be warranted. Specifically, changes may help detect possible differences between FWD calibration centers and improve the ease and efficiency of FWD calibrations. Input from the European and United States FWD users shows there are lots of possible suggestions for FWD calibration protocol enhancements and changes. A balance between what is possible and what is worthwhile will reduce the number of changes that are actually put into practice. Items that could be implemented quickly or that would be likely to improve the calibration of FWDs are the highest priority.

The highest priority items are listed below:

Load Cells

- None

Geophone Reference Calibration

- Automate reference calibration
- Moveable bracket for LVDT

- Measure beam movement directly
- Geophone Relative Calibration
- Universal Relative Calibration software
- Computer Software
- Read FWD data into calibration computer
 - Develop universal reporting procedure
- Other Components
- Pavement temperature probe
 - Infrared temperature sensor
 - Odometer/ distance measurement
 - Verification of sensor offsets
 - Routine voltage checks of electronics
 - Clean and maintain FWD (load plate, bleed air)
- FWD Calibration Centers
- Change sensitivity method for the KUAB FWDs

The next steps will be to work with the European and U.S. FWD Users' Groups to develop an action plan to determine the cost and effort of implementing the items in the high priority list. A procedure will then have to be developed for amending the SHRP protocol.

The items categorized as medium and low priority will require further research as to their cost effectiveness and overall benefit to the calibration procedures. This activity may again fall to the FWD Users' Groups. However, sources for funding need to first be identified and a concentrated effort needs to be developed for each item in the list. The limited availability of additional funding may preclude in-depth research.

FWD calibration centers have been an extremely successful product of the SHRP program and continue to benefit FWD users and researchers by ensuring that FWD data is as accurate and precise as possible. After a decade in operation, the SHRP FWD calibration protocol has shown it works. As with any protocol, it may need improvements in order to take advantage of lessons learned and to remain on top of changing technology.

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