

***Pooled Fund Study TPF-5(039)
FWD Calibration Center and
Operational Improvements***

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Topics to be covered

- ✿ Objective and goals of this study
- ✿ Project status/accomplishments
- ✿ Technical issues/problems
- ✿ Tentative calibration protocol
- ✿ Question for discussion

Project objective

To develop and implement long-term plans for FWD calibration centers, and to minimize the variability in pavement deflection data obtained with falling weight deflectometers

--- TPF-5(039) Website

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Goals



1. Modify the existing calibration procedure to be compatible with all FWD equipment on the market and in use by state highway agencies (FWDs able to impart a load of at least 6000#).
 - Evaluate the feasibility of streamlining the calibration process without reducing the accuracy and precision of the results obtained.
 - Evaluate the feasibility of automatic data acquisition triggering (*and automated reference deflection system movement compensation*) without reducing the accuracy and precision of the results obtained.

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Goals

2. Upgrade calibration hardware and software to be compatible with operating systems and computers that are current at the time of delivery.
 - The new software shall work with both SI and U.S. Customary units.



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Goals

3. Produce an upgraded and tested calibration system for use in the existing LTPP FWD Calibration Centers and non-LTPP calibration centers, and provide accompanying documentation and training to calibration center operators.



--- RFP DTFH61-04-R-00020, June 2004

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Additional Goal

4. Develop a calibration procedure that can be completed in 3 hours or less.

--- TAC, Albany, NY, April 2005



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Progress to date

- ✿ Re-established a working SHRP FWD calibration center at Cornell
- ⇒ April 2005
- ✿ Selected a 16-bit data acquisition board
- ✿ Selected a low-noise, durable accelerometer
- ✿ Conducted proof-of-concept tests
- ⇒ October 2005

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Progress to date

- ✿ Developed a database of calibration results according to the SHRP procedure
 - A standard of comparison for new procedures
 - ✿ Converted old DOS software to Visual Basic 6 (FWDREFCL)
 - ✿ Adapted the software to the new DAQ and accelerometer (WinFWDCal)
- ⇒ January 2006, with subsequent refinements

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Progress to date

- ✿ Developed a new software tool to convert FWD native output to PDX file format
 - Added task
 - ✿ Designed and evaluated multi-sensor stands to merge reference and relative calibration
 - Goal is to have position in the stand NOT be significant
- ⇒ April 2006

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Current activity

- ✿ Evaluate the new procedures, hardware and software with each brand of FWD
 - Dynatest, KUAB, JILS and Carl Bro
- ⇒ In progress
 - Expected completion by mid-May

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Remaining work



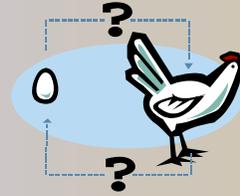
- ✿ Secure approval from COTR
- ✿ Distribute new equipment and software, and train center operators
- ⇒ Planned for late-July and early August
- ✿ Submit final report

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Chickens and eggs

- ✿ Hardware improvements
- ✿ Software improvements
- ✿ Procedural improvements

They are interrelated, and one begets the other ...



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A brief review of what we are doing
and why ...



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Three types of measurement errors

- ✿ Seating errors
 - Reduced by doing several unrecorded drops
- ✿ Random errors (repeatability)
 - Reduced by averaging several replicate drops
- ✿ Systematic error (bias)
 - Reduced by performing "SHRP" calibration
 - This is what we are working on in TPF-5(039)

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Typical FWD specification

"Deflections shall be accurate to ± 2 percent or ± 2 microns, whichever is larger."

- The ± 2 micron error is a random error, independent of the magnitude of the deflection
- The ± 2 percent error is a systematic error
- Whenever the deflection is 100 microns (4 mils) or larger, the systematic error would be larger than the random error

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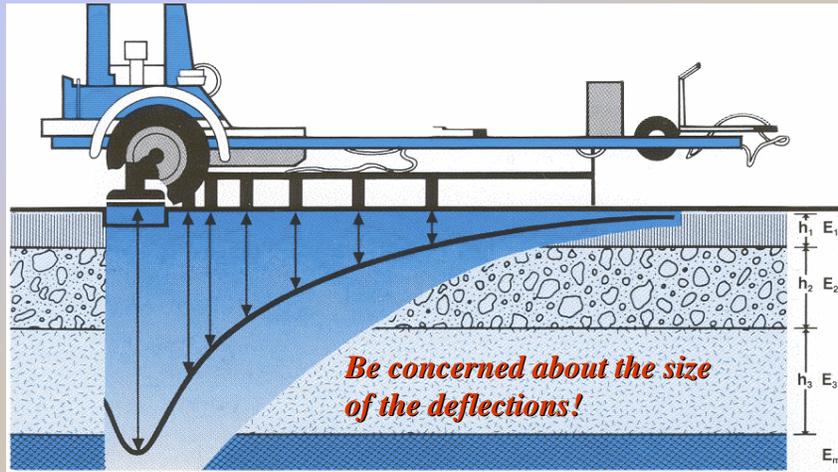
Observation

✿ If the systematic error is ± 0.3 percent, and the random error is $\pm 2\mu$, then the random error will be larger than the systematic error for all deflections up to 650μ (25 mils)

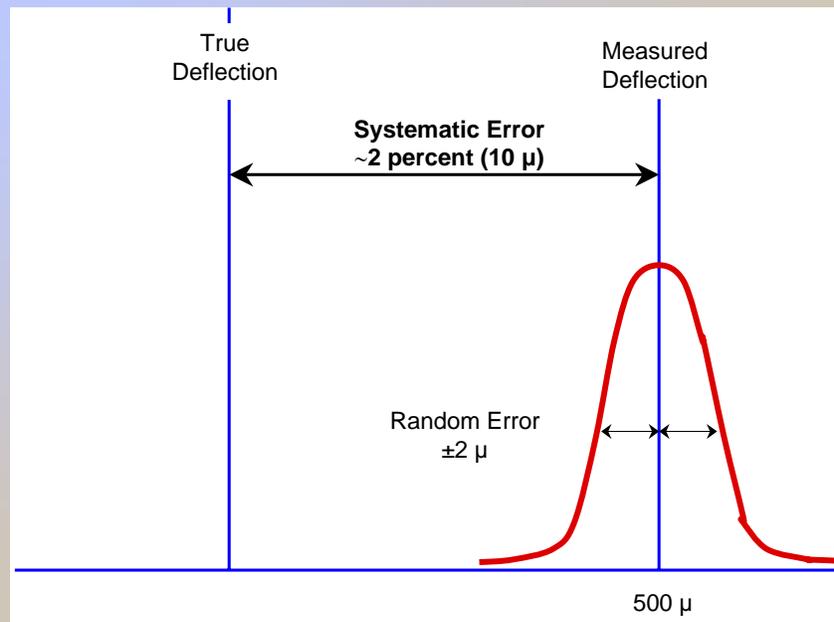
→ $2 \div 0.003 \approx 650$

→ Pavement deflections are not commonly greater than 650μ

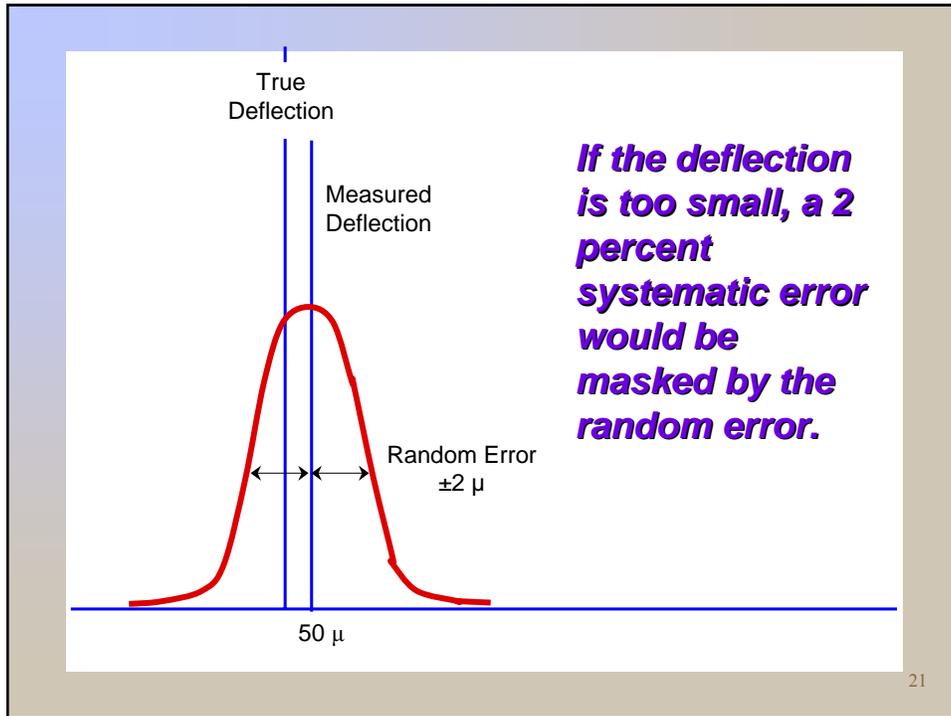
FWD Deflection Basin



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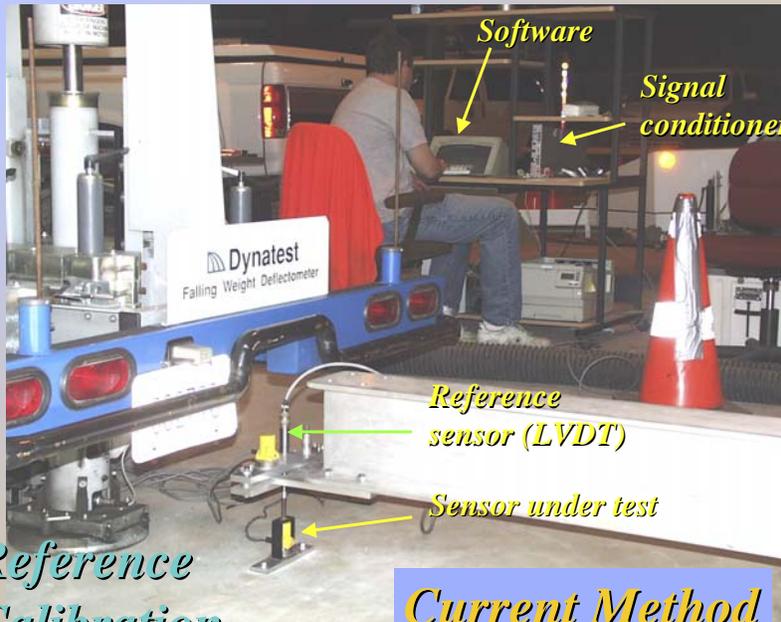


Conclusions

- ✿ It is necessary to continue to use a test pad that yields a 500 ± 100 micron (20 ± 4 mil) deflection for a 16,000 lb. load at a 20-inch offset from the FWD load plate.
- ✿ It is necessary to remove the deflection sensors from their holders.
 - Allows inspection and cleaning of sensors and cables



**5" fiber-reinforced concrete
6" crushed stone base
5' CBR 5 subgrade**



*Reference
Calibration*

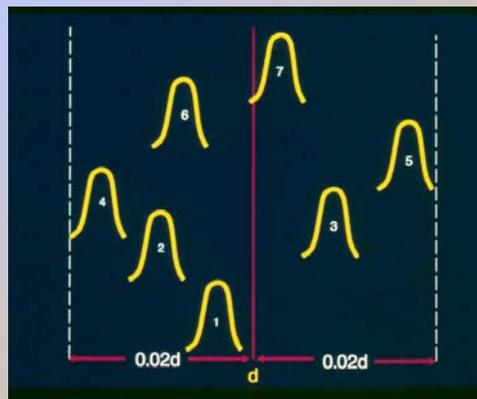
Current Method

Objective of reference calibration

- ✿ Assure that each sensor is random about correct deflection.
- ✿ Requires unbiased reference sensor and unbiased stand

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Sensor response after refcal



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*Relative
Calibration*



Current Method

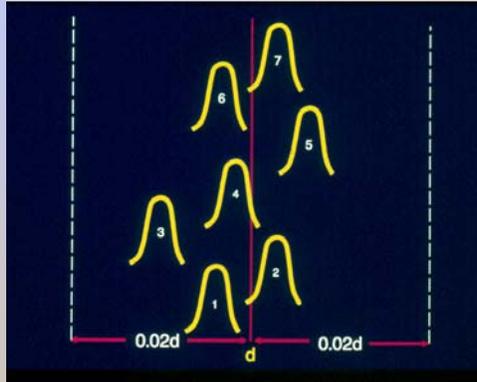
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Objective of relative calibration

- ✿ Collect a large number of observations of pavement response using all sensors
- ✿ Overall average is a good estimate of correct deflection
- ✿ Ratio of overall average to average for a single sensor is the calibration factor

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Sensor response after recal



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When everything goes well, the current SHRP procedure takes about six hours to complete ...

When things do not go well, it usually is due to maintenance problems with the FWD ...

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Ways to speed up the process

- ✿ Conduct reference calibration on all deflection sensors at the same time
 - Go to multisensor stand
- ✿ Eliminate the manual entry of FWD data in the reference system computer
 - Go to electronic transfer of data
- ✿ Eliminate rotation of sensors in the relative calibration procedure
 - Position in the stand must not be significant

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Accomplishments - speed

- ✿ So far we have got the procedure under two hours
- ✿ May be possible to get it close to one hour



(Applause)

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Accomplishments - software

- ✿ Windows-based software has been developed (WinFWDcal)
 - Modifications are required as changes in the calibration procedure are made
- ✿ File conversion software has been developed
 - Some required data are not in the FWD native output files
 - AASHTO's PDDX file format is not well defined
 - Electronic transfer of data using thumb drive

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Accomplishments - hardware

- ✿ Keithley model KUSB-3108 data acquisition board

- 16-bit board increases accuracy
- 15,000 samples per second
- "About triggering" developed
- Highly portable USB connection



- ✿ Silicon Designs model 2220 accelerometer

- Method for conversion of acceleration to displacement
- Method for calibration using Earth gravity
- Uses existing Vishay signal conditioner



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Accomplishments - hardware

- ✿ Multisensor stands developed

- One design for Dynatest, JILS and Carl Bro
- Second design for KUAB

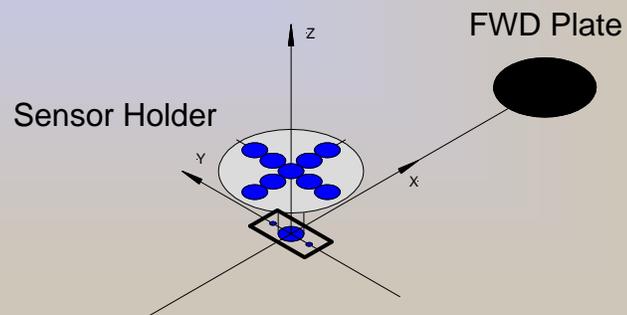
- ✿ Stand hold down method developed



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The "platter" design

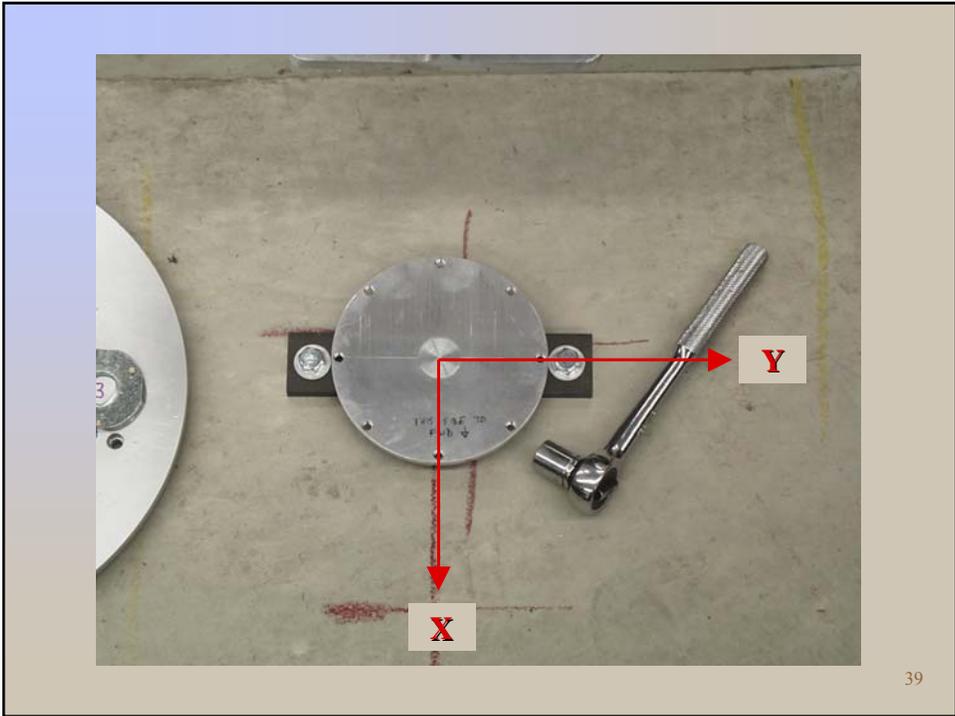
- ✿ Unsuccessful, but ...
- ✿ We learned a lot!



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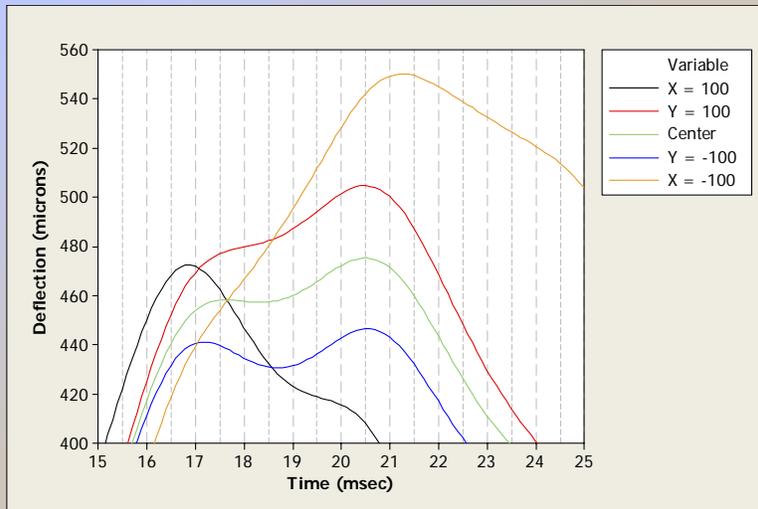
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Roll and pitch

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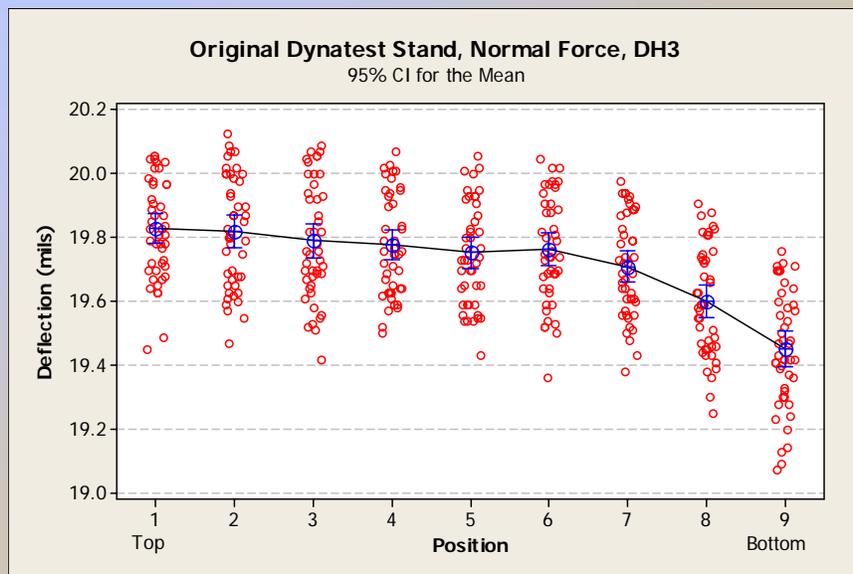
Problems with platter concept

- ✿ Roll and pitch excessive
- ✿ Simultaneous liquefaction of subsurface materials
- ✿ Could not cancel out the effect of position and set
- ✿ Not possible to use the concept – moved on to columnar design

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Manufacturers' Relative Calibration Stands



Problems with existing stands

- ✿ Position in the Dynatest stand was highly significant
- ✿ Stand was too flexible
- ✿ Similar findings for stands from Carl Bro and KUAB
- ✿ Decided to design a stiffer stand
 - Should be able to accommodate several types of deflection sensors

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Large Channel Stand



Ball Joint Base

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Large Channel Stand and Ladder Stand

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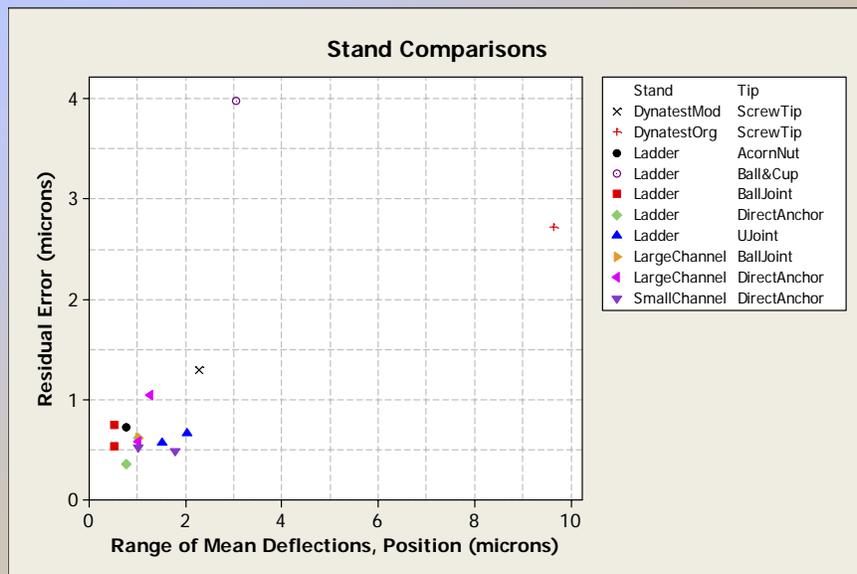


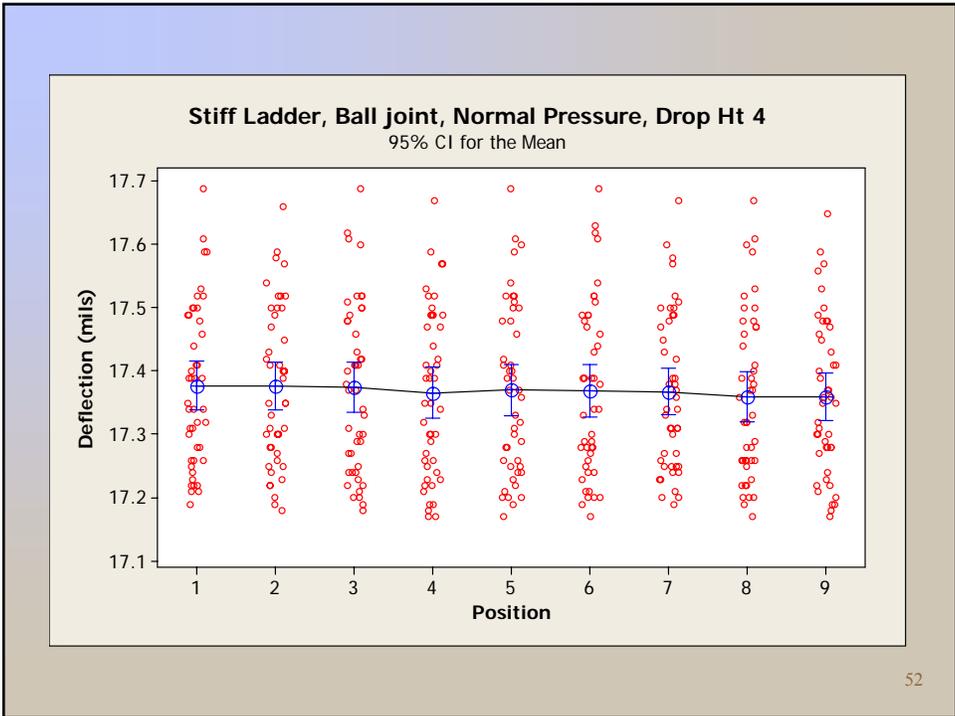
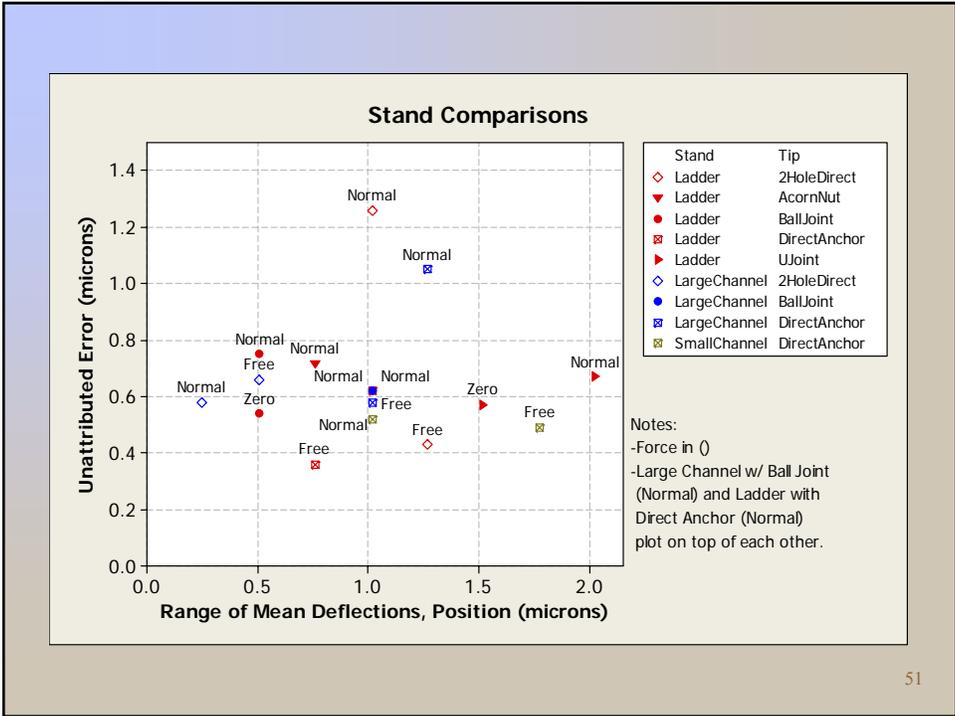
Ladder Stand

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Direct Anchor Base



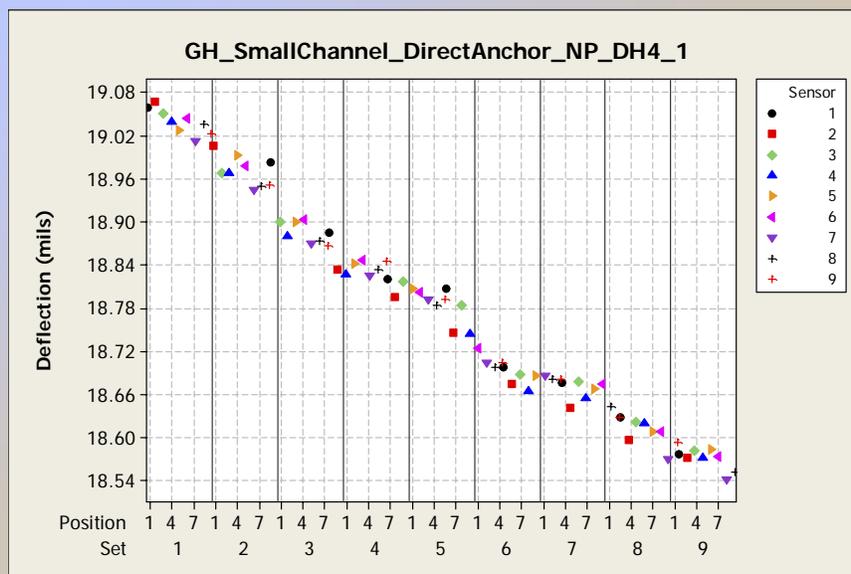


Observations



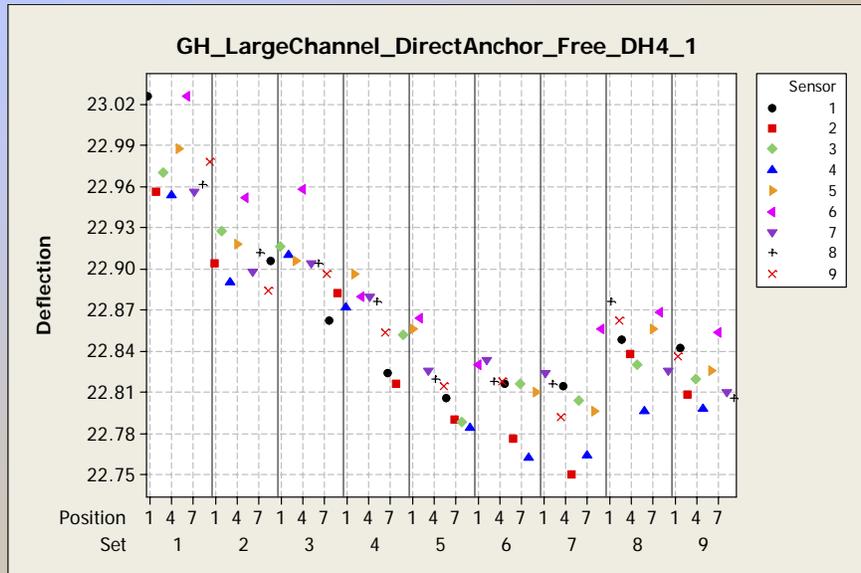
- Some combinations give very low error due to position (Range ~ 0.5 micron)
- Results are for a single type of FWD and one test pad/location
 - Currently gathering data for other FWDs
 - Too soon to declare complete success
- Statistics, used correctly, are a powerful tool to see very small differences in deflection response

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Each data point represents average of five drops per set

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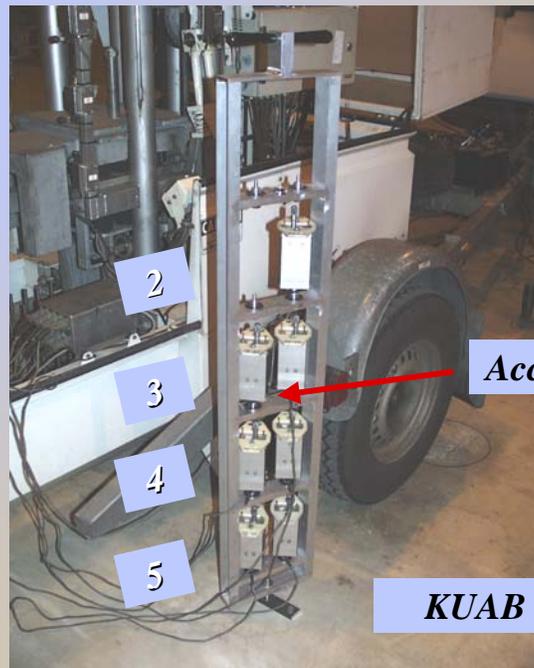


Relcal - Taking Sensor 1 from Position 1

Sources of error (differences)

- ✿ Geophone error
 - This is what we are calibrating for
- ✿ Position in stand error
- ✿ Set error
 - One set for each rotation of sensors
- ✿ Unattributed error
 - Error not attributed to the identified factors above
- ✿ Position and set do not influence calibration results if every sensor is in every position and every set

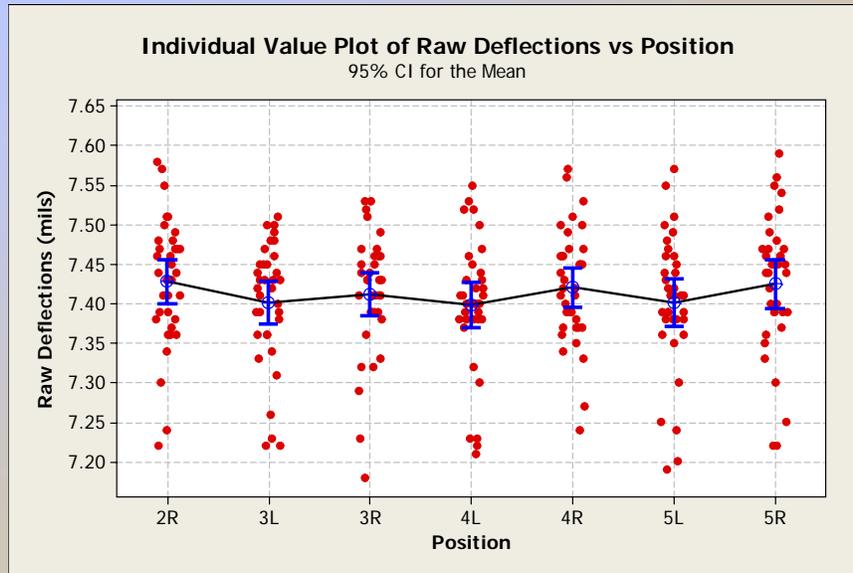
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Accelerometer

KUAB Stand

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Full rotation of sensors

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Analysis of Variance (KUAB stand)

| Source | N | SS | MS | F | P |
|--------|------------|--------|--------|------|-------|
| Shelf | 4 | .00394 | .00131 | 0.25 | 86.1% |
| Column | 2 | .01701 | .01701 | 3.24 | 7.3% |
| Set | 7 | .16145 | .02691 | 5.12 | 0.0% |
| Sensor | 7 | .00021 | .00004 | 0.01 | 100% |
| Error | <u>225</u> | 1.1971 | .00525 | | |
| Total | 245 | | | | |

Unattributed error = 0.072 mils (1.84 microns)

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Conclusions (KUAB stand)

- ✿ Reference cal factors were spot on
- ✿ Shelf level did not matter very much
 - 0.92 micron is barely "significant"
- ✿ Column position mattered a lot more
 - Rotate the stand to interchange the columns
- ✿ Effect of set was totally not random
- ✿ Unattributable error about as expected
 - 1.84 microns

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Lessons learned – reference calib.

- ✿ Accelerometer is an unbiased reference sensor, accurate to about 2-3 microns
 - Same as LVDT with allowable beam movement
- ✿ Place at mid-height of stand
- ✿ Position in stand adds a small amount of bias (~0.5 micron or less)
- ✿ Dynatest & JILS - Rotate sensors top-to-bottom to cancel out the bias
- ✿ KUAB stand – rotate columns right-to-left

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Lessons learned – relative calibration

- ✿ Difficult to get 500μ deflections at present locations on slab
- ✿ Move test point closer to edge of slab
- ✿ May not need to rotate sensors in stand, or only a top-to-bottom rotation
 - Put center sensors near middle of stand?
- ✿ Rotation provides a higher level of confidence in the results

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Lessons learned – general

- ✿ Necessary to attach stand to test pad



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Tentative calibration protocol

(subject to change)

- ✿ Load calibration procedure is unchanged
 - Increase calibration range to 25,000 pounds
- ✿ Perform reference and relative calibrations
 - Use accelerometer in reference calibration
 - Calibrate accelerometer on day of use by measuring Earth gravity (+1g and -1g)
 - Use multisensor stand(s) for refcal and relcal
 - Transfer data from FWD to calibration computer electronically

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Reference calibration

- ✿ Perform 18 to 24 drops using at least three load levels, an equal number of drops per load, achieving 500 ± 100 microns at the highest load level
 - 3x6, 3x7, 3x8, 4x5, 4x6 qualify
 - Use same sequence in load calibration
- ✿ Reverse sensors top to bottom in stand (KUAB:left to right) and repeat

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Relative calibration

- ✿ Perform 40 drops without rotation in stand, achieving 500 ± 100 micron deflections
 - No pause or minimum pause between drops
- ✿ Reverse sensors top to bottom in stand (KUAB:left to right) and repeat

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Data analysis



- ✿ Transfer data from FWD electronically
 - Use PDX file format
- ✿ Compute interim gain factors from recal
- ✿ Multiply interim gain factors times recal data
- ✿ Compute recal means ratios and final gain factors
- ✿ Transfer final gain factors to FWD computer

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Calibration factor

$$\text{Means Ratio} = \frac{\text{Overall Average Deflection}}{\text{Individual Sensor Avg. Deflection}}$$

$$\text{Final Gain} = \text{Sensor Original Gain} \times \text{Means Ratio}$$

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Quality assurance



- ✿ Do not exceed 4 g's during refcal drops
- ✿ Compare final gain factors to previous calibration results
 1. Accept results if factors have not changed more than 1 percent since last calibration
 2. Accept results if factors fall between 0.98 and 1.02
 3. Results are acceptable if *either* criterion is met.

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Quality assurance

- ✿ Issue certificate of calibration if all load and deflection sensors pass Criterion #1 or Criterion #2

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Calibration frequency

- ✿ Full calibration (all sensors) annually
- ✿ Relative calibration monthly
 - Assures detection of sensors going bad

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Further discussion



- ✿ Rotating sensors in the stand during relative calibration eliminates the chance that bias due to position will occur
- ✿ Would it make sense to offer two levels of calibration?
 - Level 1 – sensors rotated during relative cal.
 - Level 2 – sensors not rotated
 - Could make up to 30-40 minutes difference
 - Perhaps a small improvement in accuracy of gains

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Keep it simple

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