SHRP-P-652

Falling Weight Deflectometer Relative Calibration Analysis

PCS/Law Engineering

Strategic Highway Research Program
National Research Council
Washington, DC 1993

SHRP-P-652
Contract P-001

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August 1993

key words:
calibration
deflection testing and backcalculation
falling weight deflectometer
FWD
LTPP AC

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350/NAP/893

Acknowledgments

The research described herein was supported by the Strategic Highway Research Program (SHRP). SHRP is a unit of the National Research Council that was authorized by section 128 of the Surface Transportation and Uniform Relocation Assistance Act of 1987.

The development of this program was sponsored by the Strategic Highway Research Program for use in the Long-Term Pavement Performance (LTPP) Studies. Technical contributions were provided by Dr. Lynne Irwin, Cornell University and Consultant to SHRP. Version 1 of the program was written by Mr. Scott Rabinow of PCS/LAW Engineering, Beltsville, Maryland. Version 2 of the program was written by Mr. Raj Basavaraju and Mr. Gary E. Elkins of Nichols Consulting Engineers.

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Abstract

Non-destructive deflection testing with Falling Weight Deflectometers (FWDs) is a critical element of the pavement monitoring effort for the Long-Term Pavement Performance (LTPP) test sections of the Strategic Highway Research Program. Data obtained through this testing serves as the primary mechanism for assessing structural conditions within each LTPP test section.

For the LTPP deflection data to serve its intended purpose, the deflection testing must be conducted consistently, and with accurately calibrated FWDs. This report documents the FWDCAL software, which was developed to help ensure that the latter need is met.

SHRP FWD testing procedures require that the FWDs used be calibrated on a regular basis. One aspect of this requirement is monthly relative calibration of the FWD deflection measurement system. This process involves stacking the deflection sensors, one above another, in a special stand, so that all will simultaneously measure the deflection of the pavement at the same point. By rotating the sensors through the positions in the stand, and repeating the testing, a data set is obtained which can be analyzed to: (1) determine an appropriate multiplier for each sensor, so that all will provide identical data; and (2) statistically partition the measurement errors in the data to the major sources of error, as a check on the acceptability of the calibration data. The FWDCAL software documented in this report was developed to perform these analyses.

Purpose

The purpose of this document is to explain the background and use of the revised FWD relative calibration analysis computer program, **FWDCAL Version 2.0**, developed for the Strategic Highway Research Program (SHRP) for use by the Long Term Pavement Performance (LTPP) Regional Coordination Offices (RCO). The **FWDCAL Version 2.0** program automates the analysis of the results of the relative calibration test procedure performed on the Falling Weight Deflectometer (FWD) geophones. The program performs the following functions:

- Checks FWD relative calibration data file for compliance with the LTPP test setup requirements.
- Calculates new relative gain factors for each geophone.
- Checks the ratios between the existing and new relative gain factors to determine if they are within the established tolerances.
- Performs an analysis of variance on the data to determine the statistical significance of key test factors.
- Provides a statistical summary of the test results.
- Provides guidance to the user on needed gain changes or further testing needs.

The following new capabilities have been added to the **FWDCAL Version 2.0** program:

- Computes the gains factor for a replacement sensor.
- Processes up to three data sets in the same file.
- Computes the average new relative gain factor from relative calibration tests performed as a part of the SHRP Reference calibration procedure. All three data sets must be in the same file.
- Processes data sets produced by Version 10 and Version 20 of the Dynatest FWD operating system software.
- Ability to process multiple data sets in separate files without exiting the program.

The program displays the results on the screen and writes them to an output file for subsequent printing.

Background

The LTPP program uses the Dynatest Model 8000 Falling Weight Deflectometer (FWD) to measure the deflection response of the test pavement structures. The **FWDCAL** computer program was developed to automate the analysis of the results of the relative calibration performed with this device.

Relative calibration is a technique used to verify and adjust the response of each of the deflection sensors, geophones on a Dynatest FWDs, so that equivalent measurements are obtained when the sensors are subjected to the same displacement. A direct result of this procedure is the determination of a set of multipliers necessary to keep the measurements derived from the deflection sensors equivalent.

In the relative calibration procedure all deflection sensors are placed in a stand which is held vertical on a point located near the load plate so that all sensors are subjected to the same deflection. The measurements consist of subjecting the sensors to a five drop load sequence, then rotating the positions of the sensors in the stand, placing the stand on the same point and repeating the drop sequence. This process is repeated until all sensors have been tested in each position in the stand. The position of the sensors in the stand are rotated to serve as a check on proper conduct of the test and cancel out any effect of stand position on the results.

The most basic analysis of the data collected in a relative calibration test consists of the following:

1. Calculating the ratio of overall mean deflection of all sensors for all drops to the mean deflection of each sensor for all drops. This is called the means ratio.

2. Computing the new gain value, which is the product of the means ratio times the existing gain value.

In addition, the following statistical analyses are used as aids in evaluating the validity of the relative calibration test and in investigating anomalous results:

A. Latin Square, analysis of variance (ANOVA). This determines the statistical significance of sensor, set and position on the test results.

B. Summary statistics:
- mean, standard deviation and coefficient of variation of the deflection response of **all** sensors for all drops.
- mean, standard deviation and coefficient of variation of **each** sensor for all drops.
- mean, standard deviation and coefficient of variation of all sensors by **position** in the stand.
- mean deflection of each sensor and average of for all sensors for each drop set.
- mean load for each drop set.
- mean, standard deviation and coefficient of variation of the load for all drops.

C. Cochran homogeneity variance test. This statistical test is used to determine if the variance of each deflection sensor's response across all drops is equivalent.

The standard LTPP relative calibration procedure is presented in Appendix A.

Program Description

The **FWDCAL Version 2.0** program contains three analysis options:

1. Standard Analysis
2. Replace Geophone Analysis
3. Reference-Relative Calibration.

The Standard Analysis is designed for use in interpreting the results when a relative calibration is performed as a stand-alone procedure such as for routine checks (e.g. monthly). The Replace Geophone Analysis is used when one of the geophones is replaced without an immediate Reference calibration. In the Replace Geophone Analysis, the response of the replacement geophone is not included in the computation of the overall average mean response of all geophones. The Reference-Relative Calibration is designed to be used for the relative calibration performed in conjunction with the SHRP **Reference** calibration procedure. This analysis option computes the average new gain setting for a series of three tests.

The program is written in Microsoft® QuickBasic™ 4.5. It uses a proprietary file selection routine written by PCS/LAW Engineering. It also utilizes commercial routines written by Crescent Software for the menu's and windows. A listing of the **FWDCAL Version 2** program is presented in Appendix B. The routines from Crescent Software are not included in the listing.

All of the analyses follow the same basis steps which consist of FWD data file input, gains table, latin square ANOVA, summary statistics, and program output. These topics are described in the following sections.

FWD Data File Input

Each Dynatest FWD data file consists of header information and data block(s). The first 37 lines of the Dynatest data file contains the header information. An example is shown in Table 1. The second part of the data file, known as the data block, consists of the loads, deflections, temperatures and station information. A data file can contain multiple data block sets, referred to as data sets, in a file that contains only one header block.

Table 1. Example of Dynatest FWD header block.

Line No.	File Contents
	Column
	111111111122222222223333333333444444444455555555556666666666777777777778
	12345678901234567890123456789012345678901234567890123456789012345678901234567890
1	R80 73 8906065806068936F10
2	700031018002-05875568.6303111 6
3	150 0 203 305 457 610 914 1524 5.9 0 8 12 18 24 36 60
4	C:\FWD\DATA\ .FWD
5	
6	S -28 27 23 38 80 73 Heights ....
7	S -28 27 23 74 80 73 Heights ....
8	808.207227303730-.005 -.005
9	18 15 3.5 5 2 15 2 8
10	Ld 110 1.014 92
11	D1 801 .987 1.059
12	D2 802 .986 1.093
13	D3 803 .985 1.066
14	D4 804 .983 1.045
15	D5 805 .985 1.126
16	D6 806 .981 1.108
17	D7 807 .983 1.059
18	D0 808 1 1.079
19	D0 809 1 1.089
20	D0 810 1 1.130
21	OPERATOR NAME
22	11020600........................
23	0 0 0 0 ....
24	*
25	
26	
27	*
28	....
29	16388 -4839 0 ....32 0 ......
30	123P45678P90123P45678P90123P45678P90123P45678S..................................
31	DDDP44444P44444P44444P44444P44444P44444P44444P1111111111111111444444444444444444
32	....
33	....*****.*****.*****.*****.*****.*****.*****.**********************************
34	....
35	....
36	RELATIVE CALIBRATION............
37	*

The program is terminated if any of the following conditions are found during the checks performed on the header block:

- The Dynatest FWD operating software is not either edition 10 or 20.
- If the number of sensors is not equal to 7.
- If there are less than 46 total active drops indicated on line 30. The number of active drops is determined by the column number of the first period (.) found on line 30.
- If there are not 5 repeat drops for each drop set.

Other information determined from the header block and used by the program include:

- Units for data collection, English or Metric
- Data collection date
- FWD serial number
- Deflection sensor gain settings
- Operators' names

The FWD data block consists of a repeating series of lines defining the test sequence of five repeat drops for each position arrangement. The first line in the data block identifies the location (station) of the test, the character "S" always occupies the first column in this line. The lines following are the data recorded for each drop. If English units are used, the load and deflection data are written twice on the same line, once in metric and then in English units. If metric units are used, only the metric measurements are present. An excerpt from a Dynatest FWD relative calibration data block in English units is shown in Figure 1.

File Contents

```
                                    Column
          11111111112222222222333333333344444444445555555555666666666677777777778
12345678901234567890123456789012345678901234567890123456789012345678901234567890

S    -28            27 23 I61626    80  73  Heights ..........................
1596 441 443 442 443 443 442 441 25360 17.37 17.44 17.40 17.43 17.42 17.42 17.38
1580 452 452 452 452 451 452 452 25104 17.78 17.78 17.78 17.79 17.77 17.80 17.79
1593 459 460 460 460 460 460 459 25312 18.07 18.12 18.11 18.12 18.12 18.10 18.07
1586 465 467 466 466 467 466 465 25208 18.31 18.37 18.35 18.36 18.38 18.36 18.32
.    .   .   .   .   .   .   .    .     .     .     .     .     .     .     .
.    .   .   .   .   .   .   .    .     .     .     .     .     .     .     .
.    .   .   .   .   .   .   .    .     .     .     .     .     .     .     .
.    .   .   .   .   .   .   .    .     .     .     .     .     .     .     .
1434 512 512 515 513 512 512 512 22784 20.16 20.15 20.26 20.18 20.17 20.16 20.16
1407 508 510 510 510 510 509 509 22360 20.00 20.07 20.09 20.06 20.09 20.03 20.04
1381 505 504 506 505 505 504 505 21936 19.88 19.86 19.93 19.90 19.87 19.86 19.88
1380 503 502 506 503 502 503 503 21928 19.79 19.77 19.93 19.82 19.78 19.81 19.80
1365 503 503 505 503 504 503 503 21696 19.79 19.81 19.88 19.82 19.82 19.81 19.80
EOF
```

Figure 1. Excerpt from a Dynatest FWD relative calibration data block.

Gains Table

The relative gain settings for a Dynatest FWD are multipliers used to refine the deflection sensor calibration. The manufacturer generally sets these gains to 1.000. The FWD operating program allows the user to adjust these gain settings in the range 0.980 to 1.020. The primary result of the analysis on the relative calibration test data is the computation of new deflection sensor gain settings so that all sensors produce equivalent results. The determination of the need to change gain settings is based on the amount of difference between the sensor responses. This information is provided by the **FWDCAL** program in the gains table.

The gains table contains the following information:

Sensor Number - This is the sensor number read from the header block. This number should correspond to the position or channel that the sensor is connected to on the FWD.

Sensor Serial Number - This is the sensor serial number read from the header block. Each sensor has an serial number assigned by the manufacturer. This number is used by the FWD operating program to determine the proper processing parameters for each sensor.

Existing Gain Factor - This is the current gain setting read from the header block.

Means Ratio - This is the computed ratio of the average response of all sensors to the response of each individual sensor. A tolerance range is set for this number to indicate the need for adjustment of the gain factor.

New Relative Gain - This is the new relative gain factor computed from the results of the test. This is the number that would be entered into the FWD operating program if the gain factors need to be changed.

The overall mean deflection response is computed as follows,

$$\bar{X}_O = \sum_{i=1}^{NumSens} \sum_{k=1}^{NumSets} \sum_{l=1}^{NumReps} \frac{\delta_{ikl}}{(NumSens \times NumSets \times NumReps)} \tag{1}$$

where,

$\bar{X}_O$ = average deflection for all sensors.

NumSens = Number of sensors, 7 for SHRP FWD.

NumSets = Number of drop sets, 7 for SHRP relative calibration test. This should be equal to the number of sensors and number of positions in the stand.

NumReps = Number of repeat drops for each drop set, 5 for SHRP relative calibration test.

δ_{ikl} = deflection for sensor i, drop set k, and repeat drop l.

The mean deflection response for each sensor is computed as,

$$\bar{X}_i = \sum_{k=1}^{NumSets} \sum_{l=1}^{NumReps} \frac{\delta_{ikl}}{(NumSets \times NumReps)} \tag{2}$$

where,

$\bar{X}_i$ = Average deflection for sensor *i*.

The means ratio for each sensor is,

$$R_i = \frac{\bar{X}_O}{\bar{X}_i} \tag{3}$$

where,

R_i = The means ratio of sensor *i*.

The new relative gain factor is computed as,

$$G_{FN\,(i)} = G_{FE\,(i)} \times R_i \tag{4}$$

where,

$G_{FN(i)}$ = The new relative gain factor for sensor *i*.

$G_{FE(i)}$ = The existing relative gain factor for sensor *i*.

The values of the means ratio are compared against a tolerance range of 1.000 ± 0.003. If the means ratio falls outside of this range a YES is displayed in the out of limit tolerance column in the gains table. The new relative gains are compared against a range from 0.980 to 1.020, which corresponds to the manufacturer's specified 2% tolerance. If a new relative gain value falls outside of this range, a YES is displayed in the out of limit 2% range column. The other messages displayed by the program are discussed in the program output portion of this document.

It is important to note that the geophones on a Dynatest FWD must be in the position indicated in the FWD operating software. If the position of a geophone is switched on the FWD a change must be made in the geophone set-up table in the operating program. Otherwise the program will use the wrong gain and amplification factors for the geophone.

Latin Square ANOVA

The SHRP relative calibration procedure was designed in such a way that a statistical analysis of variance (ANOVA) procedure could be run on the results. The purpose of this procedure is to provide a tool for evaluating the validity of the relative calibration test and as an aid in interpreting its results. The results of the ANOVA indicate only statistical significance relative to the amount of unexplained variation present in the data set. By themselves, the ANOVA results do not necessarily indicate the need for a sensor gain change, that a test was not valid, or that a repeat test is needed. The ANOVA results must be evaluated relative to the information provided in the gains table and the summary statistics. **Statistical** significance in the ANOVA results do not necessarily imply **engineering** significance.

In the Latin Square ANOVA of the relative calibration test, *F* statistics are computed for each main effect (position, set, and sensor). The computed *F* values are compared to the critical *F* statistic (2.14 corresponds to the 5% confidence level). If a computed *F* values is less than the critical *F* statistic, then the the effect is judged **not** to be statistically significant. If the computed *F* value is greater than the critical *F* statistic, then the effect is indicated as being statistically significant and instructional messages are displayed in the output. These messages are based the results of both the gains table and the ANOVA. These messages are discussed in the program output portion of this document. The details of the Latin Square experiment design layout and computations are presented in Appendix C.

Summary Statistics

A following summary statistics are produced by the program to aid in interpretation of the relative calibration test results.

- Mean deflection of each sensor and the average for all sensors for each drop set.
- Mean, standard deviation and coefficient of variation of **each** sensor for all drops.

- Overall mean, standard deviation and coefficient of variation of the deflection response of **all** sensors for all drops.
- Mean, standard deviation and coefficient of variation of all sensors by **position** in the stand.
- Mean load for each drop set.
- Mean, standard deviation and coefficient of variation of the load for all drops.

The coefficient of variation is the standard deviation divided by the mean times 100.

These statistics can be helpful in interpreting the results of a relative calibration test. For example, the systematic variation in the load between drop sets can be directly observed. This can be the cause for the significance of drop set in the ANOVA. The cause for some anomalous results can also be easily identified. For example, it is easy to detect if effect of one out of range sensor on the overall mean is causing another sensor to be indicated as out of range.

A test is performed on the significance of the variance between deflection sensors. This test is performed to determine if the variation in the response of a sensor is much greater than the other geophones. This can occur even though the mean response is the same as the other sensors. Cochran's test for the homogeneity of variances is used.

The Cochran statistic is

$$g = \frac{Largest\ S_i^2}{\sum_{i=1}^{NumSens} S_i^2} \tag{5}$$

where

$$S_i^2 = \frac{(NumSets \times NumReps) \sum_{k=1}^{NumSets} \sum_{l=1}^{NumReps} \delta_{ikl}^2 - \left(\sum_{k=1}^{NumSets} \sum_{l=1}^{NumReps} \delta_{ikl} \right)^2}{(NumSets \times NumReps)(NumSets \times NumReps - 1)} \tag{6}$$

S_i^2	=	sample variance for deflection response of sensor i for all drops.
NumSets	=	Number of drop sets.
NumReps	=	Number of repeat drops in each drop set.

To determine significance the computed g value is compared against the critical g_α. If $g > g_\alpha$, then the hypothesis of equal variances is rejected. For 7 sensors and 35 measurements, $g_{0.05} = 0.2326$. This procedure provides a test on the homogeneity of the sensor variance and also provides an indication of which sensor has the greatest variance. The results of this test are only printed if the computed g value is in the critical region.

Program Output

The program output is organized into the following screens/pages:

- Gains Table
- ANOVA Table
- Deflection Input Data
- Summary Statistics

An example of the four page output file from the program is shown in Figures 2 - 5. The output file created by the program has a name that consists of the original data file name with an extension of the form ".C$\varkappa\eta$", where:

$\varkappa$ = indicates the type of analysis:
S for standard analysis,
G for replace geophone analysis, and
R - for Reference-relative calibration

η = the last character in the data file name extension, for example it would be the (1) in the file name 59092289.RC1.

The program writes the output files to the same directory as the FWD data files specified in Control Screen 1. This file can be printed external from the program using the DOS PRINT command or by importing it into a text editor or word processing program and then printing.

The following information read from the input data file header block is printed on every page:

- FWD Serial Number
- Data of Calibration
- Data File Name
- Operator Name
- Data Set # of #. This indicates the data set number when multiple data blocks are included in a file with only one header block. For a single data set in the file, Data Set 1 of 1 will be displayed.

SHRP FWD Relative Calibration - Gains Table

FWD SN: 8002-061 Calibration Date: 05-31-91
Data File Name : 61053191.RC3 Data Set 1 of 1
Operator : RICK SMITH

Sensor #	Sensor S/N	Existing Gain Factor	Means Ratio	New Relative Gain	Out of Limit Tolerance	Out of Limit 2% Range
1	840	0.986	1.0011	0.987	NO	NO
2	838	0.990	0.9961	0.986	YES	NO
3	833	0.989	1.0015	0.990	NO	NO
4	834	0.990	1.0030	0.993	YES	NO
5	835	0.993	1.0018	0.995	NO	NO
6	3013	0.994	0.9980	0.992	NO	NO
7	837	0.993	0.9985	0.992	NO	NO

* Warning: At least one sensor is outside the tolerance limit.
  Verify these results with additional tests!

* RESULTS INDICATE THAT THE SENSOR GAINS SHOULD BE RESET.

SHRP FWD Relative Calibration - Gain adjustments

Results of this test indicate the possible need to adjust the gains. This should be confirmed with a repeat test.

Gain adjustment should be performed when the New Gain Factors for two independent calibrations are within +/- 0.002 of each other.

Gain adjustments should be made ONLY to the out of range geophone(s).

After adjusting any gain setting, the relative calibration test must be repeated to confirm that all sensors are within tolerance.

Figure 2. Example print of output file for the Gains Table.

```
            SHRP FWD Relative Calibration - Latin Square ANOVA Table
FWD SN: 8002-061                                  Calibration Date: 05-31-91
Data File Name : 61053191.RC3                            Data Set  1  of  1
Operator : RICK SMITH

     Variation      Sum of       Degrees of   Mean         Computed   Critical
     Source         Squares       Freedom     Square          f           f
     -----------    ---------   ----------    ---------    --------   --------
     Position       9.40E-02         6        1.57E-02       0.43       2.14
     Set            1.96E+00         6        3.26E-01       8.88       2.14
     Sensor         4.34E-01         6        7.23E-02       1.97       2.14
     Error          8.29E+00       226        3.67E-02
     TOTAL          1.08E+01       244

Gain adjustments are indicated, and drop set is statistically significant at
the 5% level. 'Set' significance may be due to warming of the buffers or
consolidation of pavement materials during the test. A repeat calibration,
after conditioning the FWD buffers with 50 drops from height 3, is required
to confirm the need for gain adjustments. If the deflections from the last 10
drops vary by more than 1 mil (25.4 microns), repeat the calibration at a
new location.
```

Figure 3. Example print of output file of the ANOVA Table.

Relative Calibration - Input Data

FWD SN: 8002-061 Calibration Date: 05-31-91

Data File Name : 61053191.RC3 Data Set 1 of 1

Operator : RICK SMITH

Set #	Drop #	Load lbf	Df1	Df2	Df3	Df4	Df5	Df6	Df7
			Deflections, 0.001 inches [mils]						
1	1	22,064	18.12	18.22	18.05	18.00	18.04	18.09	18.10
1	2	22,088	18.12	18.13	18.05	17.96	18.04	18.09	18.10
1	3	22,032	18.50	18.59	18.47	18.46	18.54	18.52	18.53
1	4	22,032	18.07	18.09	18.05	17.96	18.04	18.09	18.10
1	5	22,088	17.99	17.97	17.96	17.83	17.91	17.91	17.98
2	1	22,080	18.63	18.68	18.60	18.58	18.54	18.61	18.62
2	2	22,048	18.24	18.30	18.26	18.17	18.12	18.22	18.23
2	3	22,088	17.95	18.01	17.96	17.83	17.83	17.95	17.93
2	4	22,040	18.03	18.09	18.05	17.92	17.95	18.00	18.06
2	5	22,008	18.29	18.38	18.30	18.17	18.21	18.30	18.32
3	1	22,048	18.07	18.22	18.09	18.08	18.04	18.09	18.15
3	2	22,136	18.58	18.80	18.68	18.67	18.67	18.74	18.71
3	3	21,984	18.29	18.51	18.34	18.33	18.29	18.39	18.36
3	4	22,152	17.99	18.18	18.05	18.00	18.00	18.09	18.06
3	5	22,048	17.99	18.18	18.05	18.00	18.00	18.04	18.10
4	1	22,048	18.54	18.63	18.55	18.58	18.50	18.61	18.58
4	2	22,104	18.71	18.84	18.77	18.75	18.71	18.79	18.75
4	3	22,000	18.24	18.34	18.22	18.25	18.21	18.35	18.28
4	4	22,072	18.37	18.47	18.39	18.42	18.42	18.48	18.45
4	5	21,992	18.16	18.26	18.17	18.17	18.12	18.30	18.19
5	1	22,072	18.12	18.22	18.09	18.17	18.08	18.22	18.19
5	2	22,000	18.29	18.34	18.30	18.33	18.25	18.35	18.36
5	3	21,984	18.16	18.30	18.17	18.25	18.16	18.26	18.28
5	4	22,048	18.12	18.22	18.17	18.21	18.12	18.26	18.23
5	5	22,000	18.33	18.43	18.30	18.42	18.29	18.44	18.41
6	1	22,040	18.12	18.22	18.05	18.04	18.16	18.17	18.15
6	2	22,080	18.20	18.22	18.09	18.12	18.12	18.22	18.19
6	3	21,984	18.29	18.30	18.22	18.17	18.25	18.30	18.32
6	4	21,952	18.41	18.43	18.34	18.33	18.37	18.44	18.41
6	5	21,928	18.07	18.09	18.01	17.96	18.04	18.13	18.06
7	1	22,008	18.12	18.22	18.13	18.04	18.25	18.22	18.19
7	2	22,008	18.03	18.13	18.01	17.96	18.12	18.17	18.15
7	3	21,920	18.33	18.38	18.30	18.25	18.37	18.39	18.36
7	4	22,032	18.29	18.43	18.26	18.21	18.42	18.39	18.41
7	5	21,952	18.20	18.30	18.17	18.12	18.29	18.30	18.28

Figure 4. Example print of output file of input file listing.

Relative Calibration - Summary Statistics

FWD SN: 8002-061 Calibration Date: 05-31-91

Data File Name : 61053191.RC3 Data Set 1 of 1

Operator : RICK SMITH

	Load	Df1	Df2	Df3	Df4	Df5	Df6	Df7	Df1-7
Set 1 Avg	22,061	18.16	18.20	18.12	18.04	18.11	18.14	18.16	18.13
Set 2 Avg	22,053	18.23	18.29	18.23	18.13	18.13	18.22	18.23	18.21
Set 3 Avg	22,074	18.18	18.38	18.24	18.22	18.20	18.27	18.28	18.25
Set 4 Avg	22,043	18.40	18.51	18.42	18.43	18.39	18.51	18.45	18.44
Set 5 Avg	22,021	18.20	18.30	18.21	18.28	18.18	18.31	18.29	18.25
Set 6 Avg	21,997	18.22	18.25	18.14	18.12	18.19	18.25	18.23	18.20
Set 7 Avg	21,984	18.19	18.29	18.17	18.12	18.29	18.29	18.28	18.23

Overall Statistics

	Load	Df1	Df2	Df3	Df4	Df5	Df6	Df7	Df1-7
Average	22,033	18.23	18.32	18.22	18.19	18.21	18.28	18.27	18.25
Std Dev	54	0.19	0.21	0.20	0.23	0.21	0.21	0.20	0.210
COV, %	0.25	1.06	1.13	1.12	1.27	1.16	1.15	1.09	1.15

Position in Stand

	1	2	3	4	5	6	7
Avg Df	18.26	18.25	18.25	18.22	18.22	18.24	18.28
Std Dev	0.20	0.20	0.22	0.23	0.21	0.22	0.20
COV, %	1.09	1.09	1.22	1.24	1.16	1.20	1.12

Figure 5. Example print of output file of summary statistics.

Gains Table

The gains table displays the following information:

- Existing gain settings read from the input file data block.
- The computed means ratio for each sensor.
- The new relative gain factor based on the test results.
- Indicates if the means ratio for a sensor is out side the range of 1.000 ± 0.003.
- Indicates if the new relative gain factor is outside the 2% range of 0.980 - 1.020.

The following messages are printed:

- If one of the means ratios is out side of the tolerance limit:

  * Warning: At least one sensor is outside of the tolerance limit.
  Verify these results with an additional test!
  RESULTS INDICATE THAT THE SENSOR GAINS SHOULD BE RESET.

- If one of the means ratios is outside the tolerance range then the following message is shown on a separate screen displayed after the ANOVA output screen and is printed on the gains table in the output file:

  SHRP FWD Relative Calibration - Gain Adjustment

  Results of this test indicate the possible need to adjust the gains.
  This should be confirmed with a repeat test.

  Gain adjustment should be performed when the New Gain Factors for two independent calibrations are within +/- 0.002 of each other.

  Gain adjustments should be made ONLY to the out of range geophone(s).

  After adjusting any gain setting, the relative calibration test must be repeated to confirm that all sensors are within tolerance.

- If one of the New Relative Gain factors are outside the 2% range:

  * Warning: At least one sensor is outside the 2% range limit.
  Notify Supervising Engineer after verifying with additional tests!

- If the replace sensor analysis is selected, and if the means ratio is outside the tolerance range, then for the replaced sensor:

  * Means Ratio for Sensor No. #### is outside the tolerance range.
  * New Relative Gain for REPLACED Sensor No. #### is ?.???

  Where the serial number is indicated as #### and the new gain factor ?.??? in the example message above)

- If the replace sensor analysis is selected, and if the means ratio is inside the tolerance range, then for the replaced sensor (indicated as #### in the example message below):

  * Means Ratio for Sensor No. #### is within the tolerance range.
  * New Relative Gain for Sensor No. #### is ?.???

  An example gains table output is displayed in Figure 2.

In these messages, the user, who is assumed to the FWD operator, is advised to contact the supervising engineer prior to making any gain changes. This serves to notify the responsible supervisor that the results of the tests indicate that the gains need to be adjusted and to provide a check on the determination of the new gain factors to be input into the FWD operating computer program. The gains table is the primary determinant of the need to change gains. Because it is possible to obtain abnormal results from a single test, if a gain change is indicated then it is prudent to verify the results with another test. The resulting new relative gain factor from the two tests should be in close agreement. If inconsistent results are obtained, then additional tests should be performed after sources for the inconsistencies are investigated. Significant or frequent changes in the gain factors may indicate the need for a Reference calibration or the presence of abnormalities in the FWD electronics.

ANOVA Table

For each source of variation, the ANOVA table displays the following information:

- Sum of squares
- Degrees of freedom
- Mean Square
- Computed *F*
- Critical *F*

The messages printed on the ANOVA table are conditional on the results of the tolerance checks in the gains table and the significance of the variation sources determined in the ANOVA. For each combination of results a separate message is printed as specified in Table 2 for situations when all of the means ratios are within tolerance, and Table 3 when a means ratio is outside the tolerance range. In these tables, a Y indicates the effect was significant.

The message shown in Table 2 instructs the user to contact the supervising engineer if the situation occurs where the means ratios are within the tolerance limits for all sensors and sensor, set, and position are all significant. This unlikely situation can occur when the mean square error term has a very small value, less than 1.0×10^{-3}. The data set should be reviewed for potential anomalies. It can be expected that in this situation the coefficient of variation for all deflections will be less than 0.5%. If very good repeatability (low coefficient of variation) is found between sensors and all measurements, then the calibration should be accepted as valid and no changes made to the gain factors.

An example ANOVA Table output produced by the program is shown in Figure 3.

Table 2. Messages when gain ratios are within the tolerance range.

Set	Sen	Pos	Message
Y	N	N	No gain adjustments are indicated, but drop set is statistically significant at the 5% level. This can be due to warming of the buffers or consolidation of pavement materials during the test. Review the data carefully. If anything appears suspect, repeat the calibration after conditioning the FWD buffers with 50 drops from height 3. If the deflections from the last 10 drops vary by more than 1 mil (25.4 microns), repeat the calibration at a new location.
Y	Y	N	Sensor and drop set are statistically significant at the 5% level, but gain adjustments are not indicated. Review the data carefully. If anything appears suspect, repeat the calibration after conditioning the FWD buffers with 50 drops from height 3. If the deflections from the last 10 drops vary by more than 1 mil (25.4 microns), repeat the calibration at a new location.
Y	N	Y	Set and stand position are statistically significant at the 5% level, but gain adjustments are not indicated. Examine the data carefully. If anything appears suspect, repeat the calibration after conditioning the FWD buffers with 50 drops from height 3. When doing the calibration, extra care should be taken to properly seat the geophones and hold the stand vertically with moderate downward pressure. If deflections for the last 10 drops vary by more than 1 mil (25.4 microns) repeat the calibration at a new location.
Y	Y	Y	Set, sensor, and stand position are statistically significant at the 5% level. Although gain changes are not indicated, these results are suspect. A repeat calibration is required after conditioning with 50 drops at height 3. Extra care should be taken to properly seat the geophones and hold the stand vertically with moderate downward pressure. If deflections for the last 10 drops vary by more than 1 mil (25.4 microns) repeat the calibration at a new location. If this message appears in subsequent tests, contact your supervising engineer for further instructions.
N	N	N	Results indicate that no gain adjustments are needed.
N	Y	N	Sensor is statistically significant at the 5% level, but gain adjustments are not indicated. Test results should be carefully reviewed. If anything appears suspect, repeat the calibration. Otherwise, these results are acceptable.

Table 2. Messages when gain ratios are within the tolerance range (Contd.).

Set	Sen	Pos	Message
N	N	Y	Gains do not needed to be adjusted, but stand position is statistically significant at the 5% level. This may be caused by failure to keep the stand vertical, or improper seating of the geophones. In the future, care should be taken to ensure that the geophone bases are clean and well seated, and the stand is kept vertical with moderate downward pressure.
N	Y	Y	Sensor and stand position are statistically significant at the 5% level, but gain adjustments are not indicated. Review calibration results carefully. If anything appears suspect, repeat the calibration, taking care to ensure that geophone bases are clean and properly seated, and the stand is kept vertical with moderate downward pressure.

Table 3. Messages when a gain ratio is outside of the tolerance range.

Set	Sen	Pos	Message
Y	N	N	Gain adjustments are indicated and drop set is statistically significant at the 5% level. 'Set' significance may be due to warming of the buffers or consolidation of pavement materials during the test. A repeat calibration, after conditioning the FWD buffers with 50 drops from height 3, is required to confirm the need for gain adjustments. If the deflections from the last 10 drops vary by more than 1 mil (25.4 microns), repeat the calibration at a new location.
Y	Y	N	Gain adjustments are indicated. Sensor and drop set are statistically significant at the 5% level. A repeat calibration, after conditioning the FWD buffers with 50 drops at height 3, is required to confirm the need for gain adjustments. If deflections for the last 10 drops vary by more than 1 mil (25.4 microns) repeat the calibration at a new location.
Y	N	Y	Gain adjustments are indicated. Set and stand position are statistically significant at the 5% level. A repeat calibration, after conditioning the FWD buffers with 50 drops at height 3, is required to confirm the need for gain adjustments. When doing the calibration, extra care should be taken to seat the geophones properly, and hold the stand vertically, with a moderate level of downward pressure. If deflections for the last 10 drops vary by more than 1 mil (25.4 microns) repeat the calibration at a new location.
Y	Y	Y	Gain adjustments are indicated. Set, sensor, and stand position are statistically significant at the 5% level. A repeat calibration is required after conditioning the FWD buffers with 50 drops at height 3 for adjustments. When doing the calibration, extra care should be taken to properly seat the geophones, and hold the stand vertically, with a moderate level of downward pressure. If deflections for the last 10 drops vary by more than 1 mil (25.4 microns) repeat the calibration at a new location.
N	N	N	Gain adjustments are indicated. A repeat calibration is required to confirm the need for adjustments.
N	Y	N	The gain ratios and the statistical results indicate that gain adjustments are needed. A repeat calibration is required to confirm the need for gain adjustments.

Table 3. Messages when a gain ratio is outside of the tolerance range (Contd.).

Set	Sen	Pos	Message
N	N	Y	Gain adjustments are indicated. Stand position is statistically significant at the 5% level. A repeat calibration is required to confirm the need for gain adjustments. Care should be taken to ensure that the géophone bases are clean, firmly seated, and that the stand is held vertically with moderate downward pressure.
N	Y	Y	Gain adjustments are indicated. Sensor and Stand position are statistically significant at the 5% level. A repeat calibration is required to confirm the need for gain adjustments. Care should be taken to ensure that the geophone bases are clean, firmly seated, and that the stand is held vertically with moderate downward pressure.

Deflection Input Data

An echo listing of the deflection and load data read as input is provided to assure the user that the information was correctly read. This information is included only in the output file and is not accessible while running the FWDCAL program. An example listing of the deflection input data is shown in Figure 4.

Summary Statistics

An example of the summary statistics output is shown in Figure 5. This information is only included in the output file and is not accessible while running the program.

Program Operation

The **FWDCAL** is an interactive program which queries the user for the required information. The user program control interface consists of the following screens:

Control Screen 1 - Select Analysis Type
Control Screen 2 - FWD Data File Selection
Control Screen 3 - Select Geophone Replaced
Control Screen 4 - Display Results on Screen

The following three output screens are produced which display the results of the analysis and user messages:

Output Screen 1 - Gains Table
Output Screen 2 - ANOVA Table
Output Screen 3 - Gain Change Instructions
Output Screen 4 - Average New Gain Factors

These screens plus instructions on program installation and starting are discussed in the following sections.

Program Installation and Starting

The program is self contained in the file **FWDCAL2.EXE**. The program is not copy protected. The basic hardware requirement is an IBM® Personal Computer or IBM®-Compatible computer with at least 384 kilobytes (K) of available memory and minimum of 360K disk-drive capacity. A hard disk and 640K of memory are recommended. The program must be run under the DOS environment.

Two copies of the program should be made on two other disks to serve as a working and intermediate backup. The program distribution disk should be stored with other computer software backups. For a computer with a hard disk, the installation process consists of copying the program onto the desired directory or subdirectory. This can be done by using the change directory command to make the destination directory the current directory. Then issuing the DOS command:

COPY <drive>:FWDCAL2.EXE /V

where <drive> corresponds to the floppy disk drive containing the disk with the **FWDCAL2.EXE** program file. The /V switch verifies that the program was properly copied.

The program can be started by typing:

<Drive>:<Path> **FWDCAL2**

where,

<Drive>: - Specifies the name of the hard disk drive or floppy disk drive containing the **FWDCAL2.EXE** program file.

<Path> - Specifies the route the computer is to follow through the directory structure to locate the directory which contains the **FWDCAL2.EXE** program file.

If the current directory contains the **FWDCAL2.EXE** file, or if the directory containing the program is included in the PATH statement in the AUTOEXEC.BAT file, the program can be started by typing **FWDCAL2** at the command prompt.

Since the directory that the program is started from becomes the default directory in the FWD Data File Selection screen, Control Screen 2, it is convenient to start the program from the directory and or disk drive containing the FWD data file.

Control Screen 1 - Select Analysis Type

Control screen 1 is used to select the analysis type the program will run or can be used to exit the program after completing an analysis. This screen is shown in Figure 6. To select the desired analysis press the up and down arrow keys to highlight the desired choice and then press the <Enter> key. The <Home> and <End> keys can be used to jump to the first or last choice on the menu, respectively. The analysis types are:

Standard Analysis	-	The standard analysis is for use in interpreting the results of routine relative calibration tests not conducted in conjunction with the Reference calibration test.
Replace a Geophone	-	This analysis is used when one of the geophones is replaced or in the instance that the user wishes to exclude the effect of a specified geophone from the computation of the overall mean deflection response. In this analysis the response of the replacement geophone is not included in the computation of the overall average mean response of all geophones.
Reference-Relative Calibration	-	This analysis is designed to be used for the relative calibration performed in conjunction with the SHRP **Reference** calibration procedure. This analysis option computes and displays the new relative gain factor for a series of three tests and the average gain factor from the tests. All three data blocks for the tests **must** be contained in the same file.

The standard analysis and replace geophone analysis can be run on data files containing 1, 2, or 3 data blocks in the same file. After the analysis type is selected, the program reads the data file. If multiple relative calibration data blocks are found, the program displays a message indicating how many data blocks were found. For data files containing multiple data blocks, the program simply cycles through the program and treats each data block separately. The results are written to the same output file.

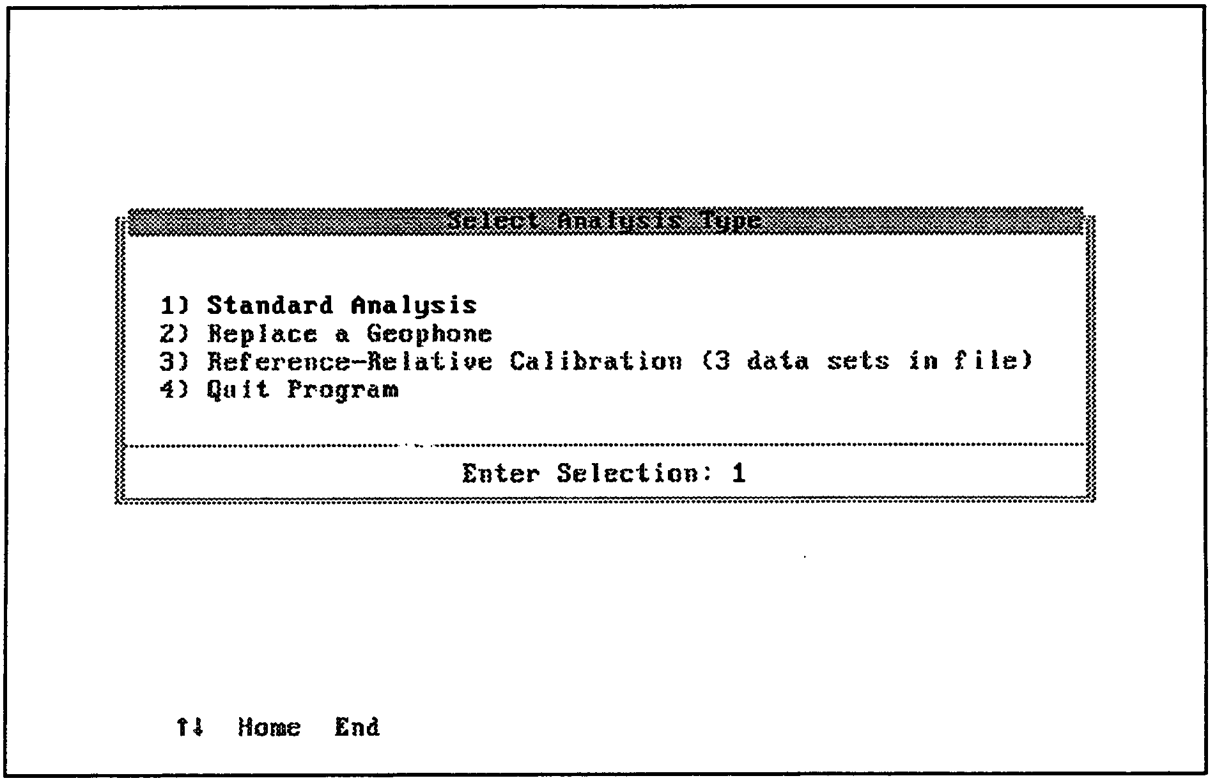

Figure 6. Select analysis control screen.

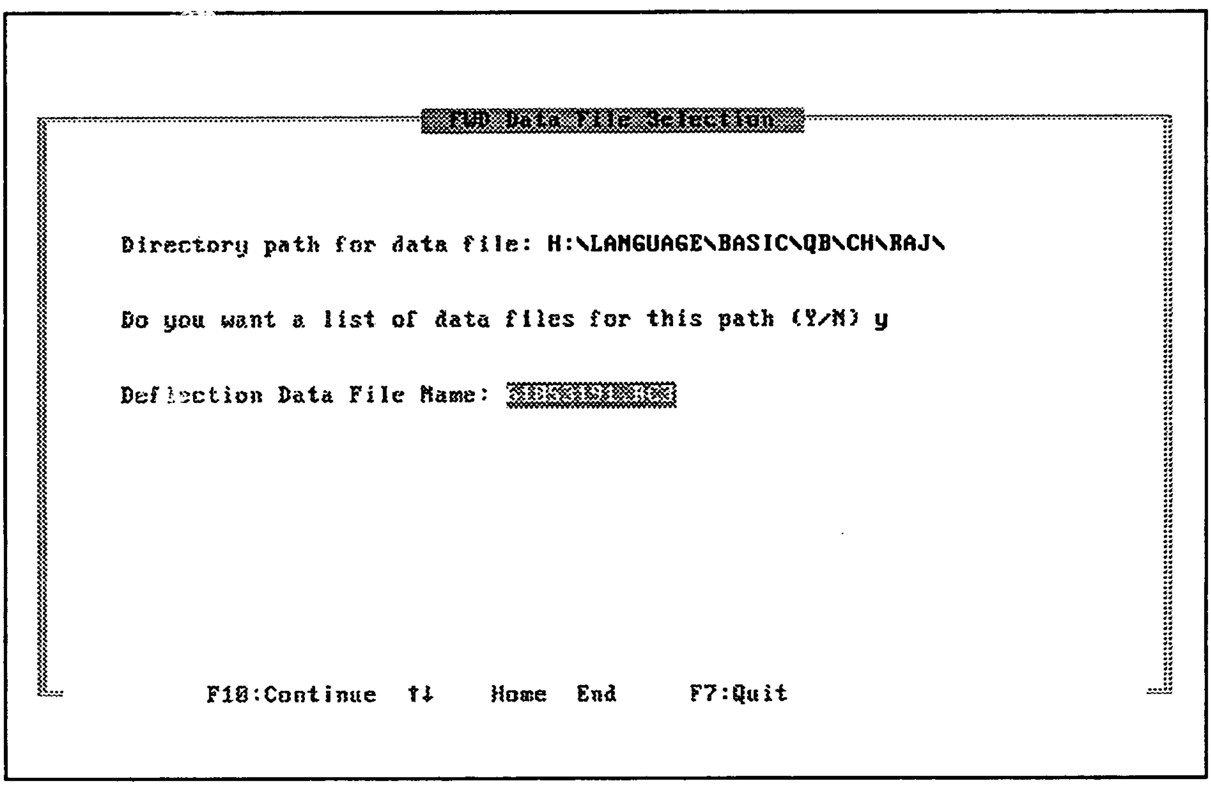

Figure 7. File selection control screen.

Control Screen 2 - FWD Data File Selection

The FWD File Selection screen is used to select the file to be analyzed. This screen is shown in Figure 7. This can be done by entering all of the information in the entry fields 1 and 2, or using field 2 to obtain a listing of the files in the directory indicated in field 1.

Field 1: Directory path for data file - the path to the desired FWD data files may be entered in this field by typing the full drive and path name (assumes default drive if no drive is specified) or by pressing <Enter> for the current directory. Nothing will be displayed in this field if the default current directory is used. The path does not require a backslash as the last character. If an error is detected when attempting to change to an invalid or nonexistent directory, an error message will appear on the screen.

Field 2: Show a list of files - a yes/no question that allows the user to select the file to be analyzed from the list of data files in the specified directory. If the response is (Y)es, then the user is placed in the directory list window and arrow keys are used to highlight a file in the list that can be selected by pressing <Enter> (<Return> on some keyboards). <PgUp> and <PgDn> can also be used to move backwards or forwards one page at a time, where such a quantity of files exists. <Esc> allows the user to exit the file list without selecting a file.

Field 3: Data file name - If a file was selected from the list of files in the directory specified in field 1, its name will appear in this field. If the field is blank, enter the file name. If the file does not exist, an error message will appear on the screen.

Once the data file has been specified, use the <F10> key to continue program operation. The up and down arrow keys can be used to change between the entry fields. The <Home> key can be used to jump to the first entry field and the <End> key to the last field. The <F7> key can be used to terminate the program.

Control Screen 3 - Select Geophone Replaced

This screen is displayed only if the replace geophone analysis is selected. This screen displays the list of geophone serial numbers read from the header block in the data file. The up and down arrow keys are used to highlight the replaced geophone. The selection is made by pressing the <Enter> key. The user is also given the option of exiting the program or indicating that no geophone was replaced. The <Home> and <End> keys can be used to jump to the first or last entry in the menu, respectively. An example of this screen is shown in Figure 8.

Control Screen 4 - Display Results on Screen

Field 1: Output file name - the name of the output file is shown . The output file name consists of the original file name with the extension ".C$\varkappa\eta$", where:

$\varkappa$ = indicates the type of analysis:
- **S** for standard analysis,
- **G** for replace geophone analysis, and
- **R** - for Reference-relative calibration

η = the last character in the data file name extension, for example it would be the (1) in the file name 59092289.RC1.

Field 2: If a Y is entered, the Output Screens 1 and 2 are displayed to show the Gains Table and the ANOVA Table on the screen.

The program writes the output files to the same directory as the FWD data files indicated in Control Screen 1. The output file naming convention was created so that the output files from multiple relative calibration tests performed on the same day using the SHRP relative calibration file naming convention, would not over write each other. The input file should always contain a unique character in the right most digit of the file name extension. An example of this control screen is shown in Figure 9.

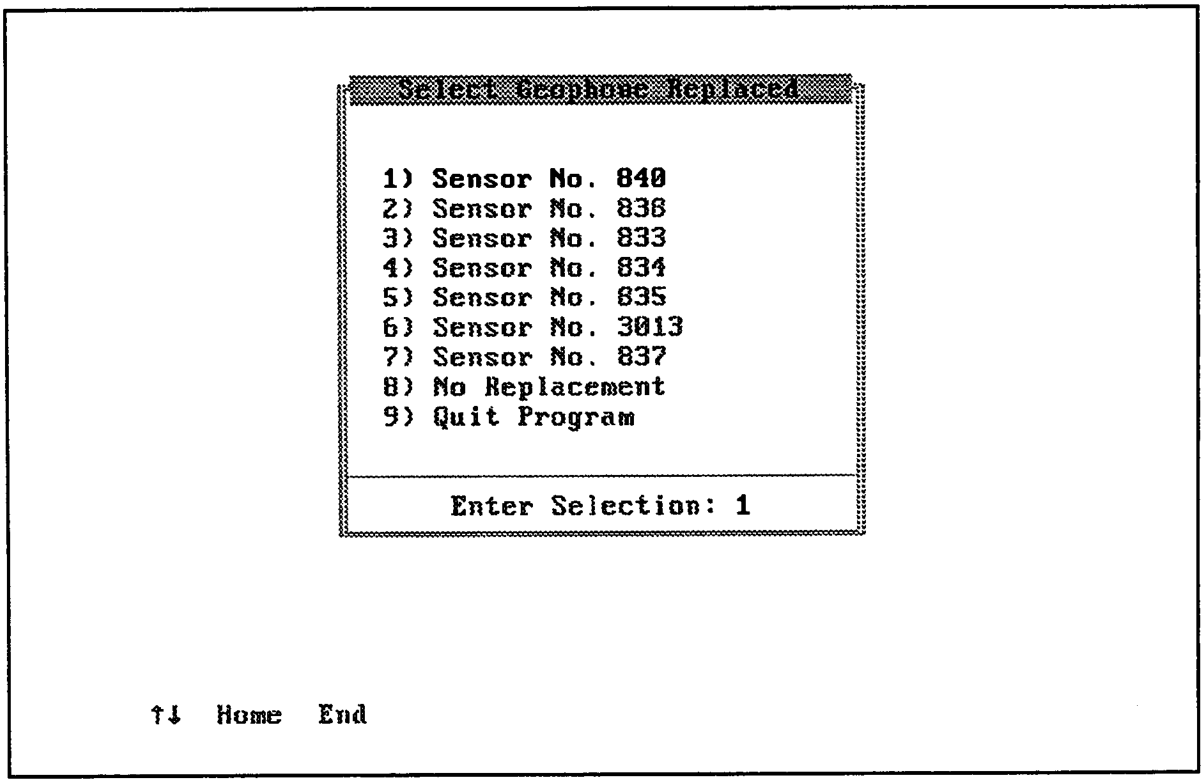

Figure 8. Select replaced geophone control screen.

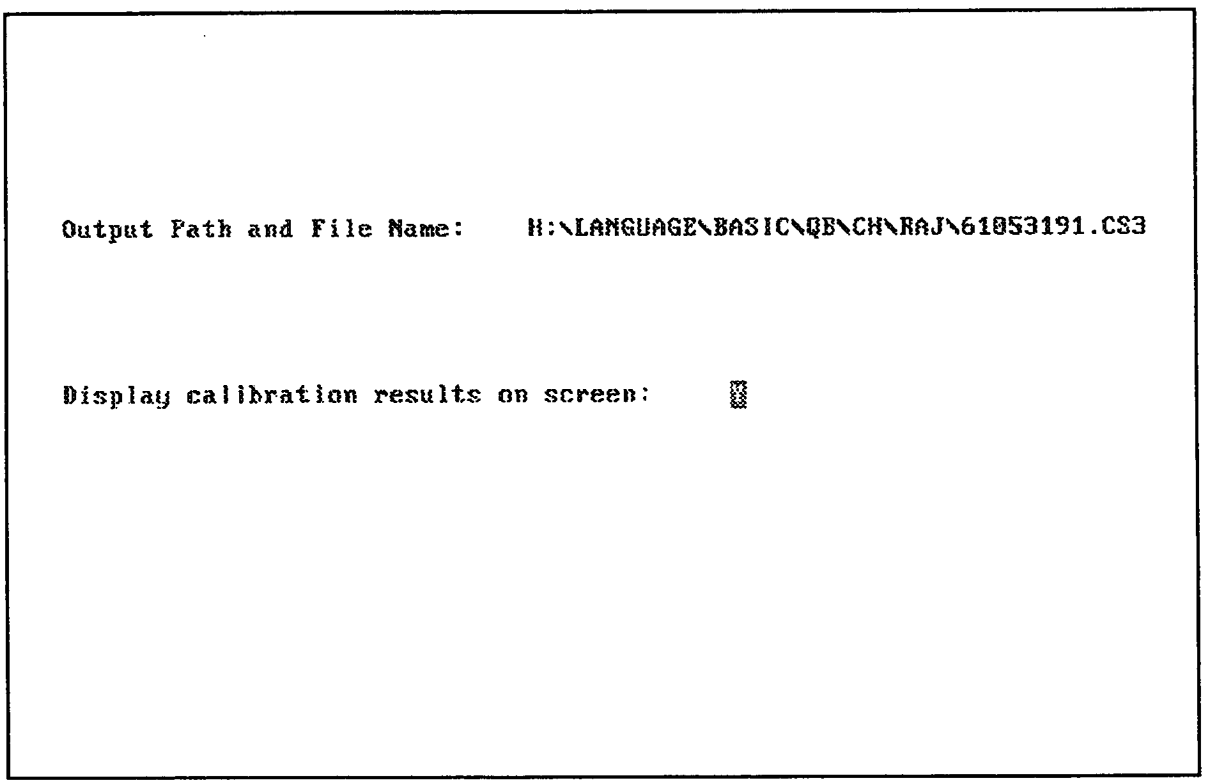

Figure 9. Display results control screen.

Output Screen 1 - Gains Table

If a (Y)es is selected to display the results on the screen in field 2 on Display Results Control Screen, then the Gains Table is displayed on the screen. In this screen, the user has the option of press <Page Down> or <PgDn> to display the ANOVA Table, or <Esc> to exit the output screens. An example of the Gains Table screen is shown in Figure 10. An explanation of the information and summary of the user messages presented in the Gains Table is discussed in the program output section of this document.

Output Screen 2 - ANOVA Table

The results of the ANOVA is displayed after the <PgDn> key is pressed in the Gains Table screen. In this screen the user has the option of pressing <PgUp> or <Page Up> to return to the Gains Table screen, or <Esc> to exit from the result table screens. An example of the ANOVA Table screen is shown in Figure 11. An explanation of the information and summary of the messages presented in the ANOVA Table is discussed in the program output section of this document.

Output Screen 3 - Gain Change Instructions

This screen is always displayed if one of the means ratio for a sensor is outside of the tolerance limit. The user is not given a choice of displaying this screen. To exit this screen, the user must hit any key. The contents of this screen are shown in Figure 12.

Output Screen 4 - Average New Gain Factors

This screen is only displayed for the results of a Relative-Reference type of analysis. This screen shows the computed new relative gain factors for each of the three repeat relative calibration tests, and the average of the tests. An example is shown in Figure 13.

SHRP FWD Relative Calibration – Gains Table

FWD SN: 8002-061 Calibration Date: 05-31-91
Data File Name : 61053191.RC3 Data Set 1 of 1
Operator : RICK SMITH

Sensor #	Sensor S/N	Exitisting Gain Factor	Means Ratio	New Relative Gain	Out of Tolerance	Limit 2% Range
1	840	0.986	1.0011	0.987	NO	NO
2	838	0.990	0.9961	0.986	YES	NO
3	833	0.989	1.0015	0.990	NO	NO
4	834	0.990	1.0030	0.993	YES	NO
5	835	0.993	1.0018	0.995	NO	NO
6	3013	0.994	0.9980	0.992	NO	NO
7	837	0.993	0.9985	0.992	NO	NO

* Warning: At least one sensor is outside the tolerance limit.
Verify these results with an additional test!
* RESULTS INDICATE THAT THE SENSOR GAINS SHOULD BE RESET.

PgDn to ANOVA Table Esc to exit results screens

Figure 10. Gains table output screen.

SHRP FWD Relative Calibration – Latin Square ANOVA Table

FWD SN: 8002-061 Calibration Date: 05-31-91
Data File Name : 61053191.RC3 Data Set 1 of 1
Operator : RICK SMITH

Variation Source	Sum of Squares	Degrees of Freedom	Mean Square	Computed f	Critical f
Position	9.40E-02	6	1.57E-02	0.43	2.14
Set	1.96E+00	6	3.26E-01	8.88	2.14
Sensor	4.34E-01	6	7.23E-02	1.97	2.14
Error	8.29E+00	226	3.67E-02		
TOTAL	1.08E+01	244			

Gain adjustments are indicated and drop set is statistically significant at the 5% level. 'Set' significance may be due to warming of the buffers or consolidation of pavement materials during the test. A repeat calibration, after conditioning the FWD buffers with 50 drops from height 3, is required to confirm the need for gain adjustments. If the deflections from the last 10 drops vary by more than 1 mil (25.4 microns), perform the calibration at a new location.

PgUp to Gains Table Esc to exit results screens

Figure 11. ANOVA table output screen.

SHRP FWD Relative Calibration - Gain adjustments

FWD SN: 0002-061 Calibration Date: 05-31-91
Data File Name : 61053191.RC3
Operator : RICK SMITH

Results of this test indicate the possible need to adjust gains.
This should be confirmed with a repeat test.

Gain adjustment should be performed when the new gain factors from two independent calibrations are within ±0.002 of each other.

Gain adjustments should be made ONLY to the out of range geophone(s).

After adjusting any gain setting, the relative calibration test should be repeated to confirm that all sensors are within tolerance.

Press any key to continue

Figure 12. Sensor gain adjustment message.

SHRP FWD Relative Calibration - Average Gains Table

FWD SN: 0002-061 Calibration Date: 05-08-91
Data File Name : TEMP3SET.RC1 Average Means and Gains for 3 data Sets
Operator : RICK SMITH

			New Relative Gain			
Sensor #	Sensor S/N	Existing Gain Factor	Set 1	Set 2	Set 3	Average
1	840	0.986	0.991	0.991	0.991	0.991
2	836	0.990	0.987	0.987	0.987	0.987
3	833	0.989	0.992	0.992	0.992	0.992
4	834	0.990	0.991	0.991	0.991	0.991
5	835	0.993	0.991	0.991	0.991	0.991
6	3013	0.994	0.991	0.991	0.991	0.991
7	837	0.993	0.993	0.993	0.993	0.993

Press any key to continue

Figure 13. Reference-relative calibration average new gain factor screen.

Function Keys

Table 4 presents a summary of the action of selected function and control keys the program uses in the various control screens. The function keys which are active are shown at the bottom of each screen.

Table 4. Function key summary.

Keys	Function
<F10>	Continue - the <F10> key is used to continue the program once all entries have been made in Control Screen 2.
<Esc>	ESCAPE - returns the user to field 2 in Control Screen 2 from the file list without selecting a file. It is also used to exit from the output screens.
<PgDn>,<PgUp>	PAGE DOWN or PAGE UP - used in the directory window if more than 20 files are present, to move from one page of the list to the next/previous page, or in output screens to move from the Gains Table to/from the ANOVA Table.
< ↑ >,< ↓ >	ARROW KEYS - these keys allow the user to move from one field to another on the data entry screens, as well as to move from file to file in the directory window. When more than one page of files are available in the directory window, pressing < ↓ > on the last row of the window places the cursor on the first row of the next page of the list. Pressing < ↑ > when on the top line of a second or subsequent pages will move the cursor to the bottom line of the previous page in the list.
<Home>, <End>	HOME or END - these keys allow the user to quickly move to the first or last field within the data entry screen menu, as well as the first or last file in the current page of the directory window.
<Space Bar>	SPACE BAR - the <Space Bar> key is used to exit the various warnings or errors that appear at the bottom of the data entry screen.
<CR>,<Enter> < ↵ >	CARRIAGE RETURN or ENTER - used to accept a data input value once it has been entered or selected.
<F7>	QUIT - used to exit the program in the File Selection Screen.

Anomalous Results

Depending on the results of the calibration analysis procedure, a number of scenarios exist for the case of apparently "bad" or anomalous data. For all scenarios, the first two remedial steps should consist of reviewing the echo print of the input data to identify any irregular or unusual conditions. If a problem exists in the header block or data format, another possibility might be to review the contents of the input file using a text editor and correct any format inconsistencies and then repeat the analysis.

As suggested in the user messages contained in the ANOVA table, several possible sources of abnormal results from the relative calibration test include:

- Failure to keep the stand vertical with moderate downward pressure applied. This typically results in position being statistically significant.

- Systematic change in the applied load to the pavement. Typically the load will decrease during the conduct of the test. This can be due to a change in the resiliency of the buffers or a change in the pavement structure. Remedial actions include further "conditioning" of the buffers with additional drops, or movement to a new location. This condition can be detected by inspection of the change in the load level between drop sets and the occurrence of set being statistically significant.

- Failure to place the stand in the exact same point. This can result in set and/or position being statistically significant.

- Failure to properly set the geophones in the center of holders in the stand. Cleaning the base of the geophones or greater care in setting them in the stand are two remedial approaches.

- Switching the position of the electrical connections, or "channels", of the geophones on the FWD without making the change in the FWD computer operating program. For example is sensor 7 is plugged into the channel 6 connection. In this case the operating program will not use the correct gain and analogue to digital conversion factors for the specific geophone. This is the reason why geophones can not be used on other FWDs without a modification to the operating computer software from Dynatest. The position of the geophone connections on the FWD should be compared against the positions shown in the operating computer program.

- Frayed, cracked or worn sensor wires and loose sensor connections can be a source of inconsistent results. Care should be taken not to remove a geophone from its holder by pulling on the lead wire since this can damage the connection.

Technical Assistance

If further technical assistance is required in the use of this program, please contact Cheryl Richter at FHWA LTPP Division (703) 285-2183 or Nichols Consulting Engineers, Reno Nevada (702) 329-4955.

Appendix A

SHRP FWD Calibration Protocol

SHRP FWD CALIBRATION PROTOCOL
April 1993

INTRODUCTION

This document describes the procedure for calibration of falling weight deflectometers (FWD) which was originally developed by the Strategic Highway Research Program (SHRP). This protocol is now administered by the Long-Term Pavement Performance (LTPP) Division in the Federal Highway Administration.

The procedure is written primarily for use with the Dynatest falling weight deflectometer, however it can also be used with the KUAB FWD. Due to differences in the design of the KUAB certain details are not applicable. Special procedures for the calibration of KUAB FWDs are included in Appendix B. It may be possible to use the procedure for other types of FWDs with minor modifications of the hardware and of the data acquisition software. The procedure is <u>not</u> applicable to the calibration of cyclic loading and other types of pavement deflection testing equipment.

In this procedure, the deflection and load transducers from the FWD are first calibrated individually against independently-calibrated reference devices. This is called "reference calibration," and it is performed at a LTPP Regional Calibration Center, or any other properly equipped location. The calibration of the FWD deflection sensors is further refined by comparing them to each other in a process referred to as "relative calibration". Relative calibration is done as a final step that accompanies reference calibration, and it can also be carried out alone, at any suitable location. There is no corresponding relative calibration procedure for the load measurement system.

The procedure results in calibration factors which are entered into the FWD software as multipliers. When the FWD measurements are multiplied by the calibration factors the result is a measurement which has been corrected to agree with the calibration instrumentation. It is necessary that there be a place in the FWD software to enter the calibration factors. That is the responsibility of the FWD manufacturer.

To use this procedure Dynatest FWDs must have Version 10 or higher software. Earlier versions do not have the pause feature and do not allow programming the required number of drops in the test sequence. Furthermore, it is not possible to leave the load plate down, as is called for in this procedure. Thus, Dynatest FWDs must be upgraded to Version 10 or higher software *before* calibration.

FREQUENCY OF CALIBRATION

Reference calibration should be performed at least once per year, or as soon as possible after a sensor has been replaced on the FWD.

Relative calibration should be performed on the deflection sensors at least once per month. It should also be performed immediately after a deflection sensor is replaced.

PERSONNEL

FWD System Operator
Calibration System Operator

REFERENCE CALIBRATION PROCEDURE

Equipment Preparation

The FWD should be in good operating condition prior to performing reference calibration. Particular attention should be paid to cleaning the magnetic deflection sensor bases to insure that they seat properly. Also verify that the FWD load plate is firmly attached to the load cell. In the event that the load plate is loose, the lower bolts should be tightened to a torque of 7.5 lbf-ft and set with Locktite before proceeding. (**Note:** This torque requirement is applicable to the Dynatest FWDs. For non-Dynatest FWDs consult the manufacturer.) All electrical connectors should be inspected and, if necessary, cleaned and firmly seated.

The FWD should be at room temperature. If the FWD has been outdoors at a very low or a very high temperature, sufficient time should be allowed for it to equilibrate to room temperature. It is recommended that a series of warm-up drops be performed immediately prior to beginning calibration, to assure that the rubber buffers have been thoroughly warmed up.

Set the FWD mass and drop heights to produce loads within ± 10 percent of 6, 9, 12, and 16 kips (27, 40, 53, and 71 kN). For the Dynatest FWD, it is possible to be within this tolerance for the highest load, and yet to have the drop height set too high. *Before* placing the reference load cell under the load plate, and with the mass positioned at drop height four (the highest position), verify that there is at least a four inch clearance between the highest point on the mass subassembly and the underside of the brace between the two columns that surround the cylinders that raise and lower the load plate. If the clearance is too small, reposition the target for the fourth drop height to achieve the required clearance. This should assure that there will be adequate clearance when the reference load cell is in position under the load plate.

Before beginning any calibration work, and throughout the entire calibration period, it is necessary that there be no data filters in operation in the FWD. Verify that the "peak smoothing" processor has been turned off. This feature is accessed from the Dynatest Main Menu by selecting "Road Options" (item #3, followed by item #12), where "Peak Readings" should show "direct" and not "smooth".

General Procedure

The FWD load cell should be calibrated at least twice. Multiple calibration tests are performed on the load cell, and the results are averaged, since it is not possible to perform relative calibration on the load cell. Acceptance criteria based upon the repeatability of the calibration factor are identified in the load cell calibration procedure. If the results persist in failing the acceptance criteria, then the cause of the erratic results should be identified and corrected.

Each deflection sensor shall be calibrated once. Spare deflection sensors do not have to be calibrated until they are in active use. After all load and deflection sensors have been calibrated, the interim calibration factors shall be entered into the FWD computer before proceeding with relative calibration.

A sample reference calibration setup screen for the Dynatest FWD with version 10 or version 20 software is given in Figure 1. The information in Figure 1 can also be used as the basis for setup of Dynatest FWDs running version 25 and higher software.

A complete summary of the data to be recorded is given in Table 1. Before beginning to perform the calibrations, FWD-specific information should be recorded via printouts from the FWD data acquisition program screens (e.g., showing the deflection sensor serial numbers and calibration factors, load cell serial number, calibration factor, and sensitivity, and voltage screens from the Dynatest software), which have been annotated with the date and FWD identification information (i.e., FWD model and serial number).

Locate the calibration data acquisition system as close as possible to the FWD computer so that the two systems operators will be able to converse easily. Load the reference calibration software **FWDREFCL** into the reference system computer. Directions for performing reference calibration using this software are provided in the FWDREFCL User's Guide.

Before doing any calibrations, verify that the computers for the FWD and the reference data

```
    Reference Calibration
 1. Test UNITS...: lbf.mil.inch     (kPa.mu.mm)
 2. Temperature..: Fahrenheit       (Centigrade)
 3. Stn.Request..: OFF              (ON)
 4. Test Checks..: NONE             (Decreasing defls, Roll-Off, RollOFF+Decr)
 5. Reject prompt: OFF              (ON)
 6. Stationing...: [Doesn't matter]
 7. Temp.Request.: OFF              (ON)
 8. Cond.Request.: OFF              (ON)
 9. Variation : Load NOT Checked !  Deflections NOT Checked !
10. Diameter of Plate: 11.8
11. Deflector distances: [Doesn't matter.  Keep what you have.]
                                 1                   2
12. Drop No.   : 123P4P5P6P7P8P9P0P1P2P3P4P5P6P7P8P9P0P1P2P3P4P5P6P7S...........
13. Heights    : CCCP1P1P1P1P1P1P2P2P2P2P2P2P3P3P3P3P3P3P4P4P4P4P4P41111111111
14. Test Plots: ...............................................................
15. Save Peaks: ....*.*.*.*.*.*.*.*.*.*.*.*.*.*.*.*.*.*.*.*.*.*.*.*...........
16. Load His. : ...............................................................
17. Whole His.: ............*...........*...........*...........*..............

18. Load another TEST SETUP.
19. Store the CURRENT TEST SETUP.
```

Figure 1: Reference Calibration Test Setup for the Dynatest FWD

acquisition system are registering the correct date and time. If either is set incorrectly, correct it before proceeding.

Equipment

As described in Appendix A.

FWD Load Cell Calibration Procedure

1. If the reference load cell has not been calibrated within the last 12 months, then it should be recalibrated in accordance with the procedure given in Appendix D.

2. Initialize the computer data acquisition program. This will include entry of operator names, FWD serial number, FWD load cell serial number, and its current calibration factor.

3. Position the FWD so that the load plate is near the center of the calibration test pad, or on any other stiff, smooth surface. Verify that there is no sand or other loose debris

Table 1 - FWD Calibration Data Reporting Requirements

Data Item	Mode of Entry	Source[1]
FWD Operator Name	Manual	Operator
Calibration System Operator Name	Manual	Operator
Date and Time of Calibration	Automatic	Computer Clock
FWD Serial/ID Number	Manual	Operator
FWD Manufacturer	Manual	Operator
FWD Owner	Manual	Operator
FWD Load Cell Serial Number	Manual	Transducer Setup and Gain Printout
FWD Deflection Sensor Serial Numbers	Manual	Transducer Setup and Gain Printout
Reference Load Cell Serial Number	Automatic	Configuration File[2]
Reference LVDT Serial Number	Automatic	Configuration File[2]
FWD Calibration Center Location	Automatic	Configuration File[2]
Current Calibration Factor for FWD Load Cell	Manual	Transducer Setup and Gain Printout
Current Cal. Factors for FWD Deflection Sensors	Manual	Transducer Setup and Gain Printout
Ref. Load Cell Calibration Constants	Automatic	Configuration File[2]
Ref. Load Cell Calibration Date	Automatic	Configuration File[2]
Ref. LVDT Calibration Constants	Computed	**FWDREFCL** Software
Ref. LVDT Calibration Date	Automatic	**FWDREFCL** Software
FWD Load Cell Readings (20 total)	Manual	FWD Computer
Ref. Load Cell Readings (20 total)	Automatic	Calibration Data Acquisition System
FWD Deflection Readings (20 per sensor)	Manual	FWD Computer
Ref. LVDT Readings (20 per sensor)	Automatic	Calibration Data Acquisition System
Interim Cal. Factors from Reference Calibration	Computed	**FWDREFCL** Software
FWD Relative Calibration Data	Automatic	Relative Calibration Data Files
Calibration Factors from Relative Calibration	Computed	**FWDCAL2** Software
Final Calibration Factors	Manual	Final Gain Worksheet

[1]For SHRP FWDs. Source may be different for FWDs from other manufacturers.

[2]Reference calibration configuration file (**FWDREFCL.CNF**).

under the reference load cell.

4. Attach the cable from the signal conditioner/data acquisition system to the reference load cell. Position the reference load cell beneath the FWD load plate, making sure that the three guides are aligned around the plate. Zero the signal conditioner with the load plate high, so that there is no external load on the reference load cell.

   Note: For accurate results it is critically important that the reference load cell be zeroed with the FWD load plate in the raised position. Also, the signal conditioner excitation and gain must be set exactly to the levels at which the reference load cell was calibrated.

5. Complete the following sequence of drops, as shown in Figure 1, for a single test:

   3 seating drops at height 3 (data not recorded), followed by a pause

   5 drops at height 1, with a pause after each drop

   5 drops at height 2, with a pause after each drop

   5 drops at height 3, with a pause after each drop

   5 drops at height 4, with a pause after each drop except the last

   Stop after the last drop (plate remains down)

   As shown in Figure 1, it is useful to program six drops at each height, rather than five, so that one can be considered a "spare" in case a drop is missed by the reference system instrumentation. If the first five drops are successfully recorded, then the data for the sixth drop can be discarded.

   The plate should not be raised at any time during the sequence. Data from both the FWD load cell and the reference system should be recorded for all drops except the three seating drops.

6. Perform the load cell reference calibration twice. If the two calibration factors agree within 0.003, then the results of the two tests shall be averaged. If they are outside this limit, then a third calibration of the load cell shall be performed. If the standard deviation of the three results is less than ±0.003 (based on n - 1 degrees of freedom), then the three results shall be averaged. If the standard deviation exceeds ±0.003, then all three calibration factors shall be discarded and the load cell calibration procedure should be repeated.

7. Upon completion of the calibration testing, raise the FWD load plate and remove the reference load cell.

The presence of any one or more of the following conditions invalidates the load cell calibration test results.

- Excessive noise messages for drop heights 2, 3, or 4. (For the low drop height (e.g., the 6000-pound load level) there is seldom enough free-fall time for the vibration caused by the release of the mass to attenuate before the mass strikes the plate. Thus excess noise messages at the low drop height may, in general, be disregarded.) The noise, due either to electrical noise or mechanical vibrations, is of concern only if it results in an erroneous zero value or an erroneous peak reading. The time history graphs provided by the **FWDREFCL** software should be viewed to determine if the noise is of concern before rejecting the calibration.

- Standard deviations for the five readings at any drop height that differ by more than a factor of three between the reference system data set and the FWD data set.

- Standard error of the adjustment factor (see Reference Calibration Data Analysis) in excess of ± 0.0020.

- Failure to satisfy the repeatability criteria for multiple calibration tests.

Should any of these conditions occur, the load cell calibration test procedure must be repeated after identifying the source of the problem and correcting it.

FWD Deflection Sensor Calibration Procedure

1. Initialize the computer data acquisition program. This would include entry of the operator names, FWD serial number, FWD deflection sensor serial number, and its current calibration factor.

2. Clean the spring-loaded tip of the LVDT. Use a non-lubricating contact cleaner in a pressurized can to spray cleaner into the bearing sleeve until the tip goes in and out without noticeable friction. Check by working the tip in and out. The stroke should be smooth, without "bumps." If the LVDT cannot be made to operate smoothly do not continue with the calibration.

3. Use the micrometer calibrator to calibrate the LVDT. To do this, the LVDT should first be positioned in the calibrator and set to the null point (zero voltage output), with the

micrometer set to 5 mm. The micrometer should then be advanced slightly beyond 7 mm, and returned to the 7 mm mark. Verify that the MetraByte board reads within ±30 bits of -2000 bits. If necessary, adjust the Gain knob on the 2310 signal conditioner in increments of 0.1 (for instance, from a setting of 1.50 x1 to a setting of 1.40 x1) to achieve the required reading. The LVDT voltage output and the micrometer reading (7 mm) should be recorded.

The micrometer should be moved in 0.5 mm increments to a final reading of 3.0 mm, with the micrometer reading and LVDT voltage output recorded at each 0.5 mm step. Turn the barrel of the micrometer in one direction only, to avoid errors due to backlash.

Analyze the resulting data using a linear regression to determine the coefficient m in the equation $Y = m X + b$, where Y is the position of the LVDT tip in microns, as measured by the micrometer, and X is the corresponding voltage output in bits, as read by the computer data acquisition board. (The **FWDREFCL** software provides prompts for this entire process, reads and records the requisite data, and performs the computations.)

The slope m will be approximately -1.00 microns per bit. The standard error of the slope should be less than ±0.0010. If a larger standard error is obtained, the LVDT calibration should be repeated.

4. Enter the LVDT calibration results into the computer data acquisition system. (This is handled automatically by the **FWDREFCL** software.) After the calibration results are entered, the signal conditioner gain must not be changed.

5. Secure the LVDT in its holder on the reference system aluminum beam, so that it is near the null point (eg., zero voltage output). Verify with a spirit level that the LVDT is vertical in its holder. If it is not vertical, adjust the position of the aluminum beam to attain verticality. This may require shimming the beam where it is bolted to the concrete block.

6. Position the FWD trailer so that the load plate is as close as possible to the deflection sensor holder. It is important, however, that the FWD should not come in contact with the beam or any other part of the reference system during the testing.

7. Remove the deflection sensors from their holders on the FWD beam, and verify that they are free of dirt and grime which would adversely affect their seating in the reference system deflection sensor holder. Run the magnetic base over a piece of fine-grained emery paper that is placed on a firm, flat surface (such as the upper flange of the aluminum beam), to assure that it is clean.

8. Place one deflection sensor in the sensor holder, and position the LVDT holder so that the LVDT and the FWD sensor are aligned.

9. Place a second deflection sensor on top of the LVDT holder, so that it will measure the movement of the end of the beam (and hence, of the LVDT housing).

10. Complete the following sequence of drops, as shown in Figure 1, for a single test:

    3 seating drops at height 3 (data not recorded), followed by a pause

    5 drops at height 1, with a pause after each drop

    5 drops at height 2, with a pause after each drop

    5 drops at height 3, with a pause after each drop

    5 drops at height 4, with a pause after each drop except the last

    Stop after the last drop (plate remains down)

    As shown in Figure 1, it is useful to program six drops at each height, rather than five, so that one can be considered a "spare" in case a drop is missed by the reference system instrumentation. If the first five drops are successfully recorded, then the data for the sixth drop can be discarded.

    The plate should not be raised at any time after the seating drops. One complete FWD time history plot should be studied for the fifth drop at each drop height, to verify that the calibration beam does not move during the test period.

The presence of any of the following conditions invalidates the calibration data.

- Movement of the calibration beam, as measured by the deflection sensor resting on the top of the beam, prior to, or simultaneous with, the peak deflection reading from the device under test. It is entirely possible that there will ultimately be some movement of the beam, as the deflection wave passes under the concrete inertial block. The important criterion is whether the beam moved prior to the time that the deflection sensor on the ground registered its peak reading. Beam movement can be determined by inspection of the FWD time history data files. At the moment when the sensor being calibrated shows its peak reading the sensor on the reference beam should show no more than ± 0.08 mils (± 2 microns) of displacement.

- Excessive noise messages for drop heights 2, 3, or 4. (For the low drop height (eg., the 6000-pound load level) there is seldom enough free-fall time for the vibration caused by the release of the mass to attenuate before the mass strikes the plate. Thus excess noise messages at the low drop height may, in general, be disregarded.) The noise, due either to electrical noise or mechanical vibrations, is of concern only if it results in an erroneous zero value or an erroneous peak reading. The time history graphs, provided by the **FWDREFCL** software, should be viewed to determine if the noise is of concern before rejecting the calibration.

- Standard deviations for the five readings at any drop height that differ by more than a factor of three between the reference system data set and the FWD data set.

- Standard error of the adjustment factor (see Reference Calibration Data Analysis) in excess of ±0.0020.

Should any of these conditions occur, the calibration test for the deflection sensor must be repeated after identifying the source of the problem and correcting it.

Reference Calibration Data Analysis

1. Analyze the data as follows (calculations are done automatically by the **FWDREFCL** software):

   A. Perform a least squares regression forced through zero for all of the data for each measurement device (i.e., 20 pairs of data per test -- 5 replicates at each of 4 load levels). The result of this regression will be the coefficient for an equation of the form Y = m X, where Y represents the response of the reference system, X represents the response of the FWD measurement device, and m is the slope of the regression line. Both X and Y should be measured in the same system of units.

   B. The coefficient, m, determined in step A, represents the adjustment factor for the calibration factor in the FWD Field Program. The new calibration factor is computed by multiplying the former calibration factor by the coefficient m from step A. This is listed as the new calibration factor on the **FWDREFCL** report.

   C. The standard error of the adjustment factor should be less than ±0.0020. If a larger standard error is obtained for any sensor, the reference calibration for that sensor should be repeated.

2. Enter the new calibration factors for all sensors (load and deflection transducers) in the

FWD Field Program before continuing with the relative calibration. The new calibration factor for the FWD load cell is a "final" calibration factor, while the new calibration factors for the deflection sensors are "interim" factors, which will be further refined by doing relative calibration.

RELATIVE CALIBRATION PROCEDURE

General Background

Relative calibration of the FWD deflection sensors is used to ensure that all sensors on a given FWD are in calibration with respect to each other. As such, it serves as the final step in the overall FWD calibration process, and as a quick means to periodically verify that the sensors are functioning properly and consistently.

Relative calibration uses the relative calibration stand supplied by the FWD manufacturer. The sensors are stacked vertically in the stand, one above another, so that all sensors are subjected to the same pavement deflection. Relative calibration assumes that the overall mean deflection, as determined from simultaneous measurements by the full set of deflection sensors, yields an accurate estimate of the true deflection. This assumption requires that the deflection sensors must have first been subjected to the reference calibration procedure.

Some FWDs have fewer than or more than seven active deflection sensors. If they do, these procedures should be modified to calibrate the actual number of active sensors in use on the FWD.

Equipment

FWD relative calibration stand with as many positions as the number of active deflection sensors. For purpose of illustration a seven-position stand is assumed herein.

FWD relative calibration software (**FWDCAL2**) and documentation.

General Procedure

The process involves rotation of the seven deflection sensors through the seven positions in the calibration stand. Each combination of sensors and levels is considered a "set," and thus there are seven sets of data. The test point is "conditioned" before beginning the calibration procedure to reduce the possibility that set will be significant in the data analysis. The required order of movement of the sensors is shown in Table 2. Spare deflection sensors do not have to be calibrated until they are in active use.

Table 2 - Relative Calibration Sensor Positions by Set

Level in Sensor Stand	Deflection Sensor Number in the Stand						
Set:	1	2	3	4	5	6	7
(Top)							
A	1	2	3	4	5	6	7
B	2	3	4	5	6	7	1
C	3	4	5	6	7	1	2
D	4	5	6	7	1	2	3
E	5	6	7	1	2	3	4
F	6	7	1	2	3	4	5
G	7	1	2	3	4	5	6
(Bottom)							

Note: The rotation must be done as prescribed above in order for the software (FWDCAL2) to work properly. For instance, for Set 2, move Sensor 2 to the position formerly occupied by Sensor 1, etc.

When done in conjunction with reference calibration, the relative calibration procedure shall be repeated twice. Acceptance criteria based upon the repeatability of the calibration factor are identified in the relative calibration procedure. If the results persist in failing the acceptance criteria, then the cause of the erratic results should be identified and corrected.

After the relative calibration is completed, the final calibration factors shall be entered into the FWD computer.

A sample relative calibration setup screen for the Dynatest FWD with version 10 or version 20 software is given in Figure 2. The information in Figure 2 can also be used as the basis for setup of Dynatest FWDs running version 25 and higher software.

```
    Relative Calibration
 1. Test UNITS...: lbf.mil.inch      (kPa.mu.mm)
 2. Temperature..: Fahrenheit        (Centigrade)
 3. Stn.Request..: OFF               (ON)
 4. Test Checks..: NONE              (Decreasing defls, Roll-Off, RollOFF+Decr)
 5. Reject prompt: OFF               (ON)
 6. Stationing...: [doesn't matter]
 7. Temp.Request.: OFF               (ON)
 8. Cond.Request.: OFF               (ON)
 9. Variation : Load NOT Checked !  Deflections NOT Checked !
10. Diameter of Plate: 11.8
11. Deflector distances: [doesn't matter - keep what you have]
                                1         2         3         4
12. Drop No.  : 1234567P8901234P5678901P2345678P9012345P6789012P3456789S.......
13. Heights+  : CC44444PCC44444PCC44444PCC44444PCC44444PCC44444PCC44444S1111111
14. Test Plots: ...............................................................
15. Save Peaks: ..*****...*****...*****...*****...*****...*****...*****.......
16. Load His. : ...............................................................
17. Whole His.: ...............................................................

18. Load another TEST SETUP.
19. Store the CURRENT TEST SETUP.

+Note: Drop height should be adjusted to attain deflections within the specified
range.
```

Figure 2: Relative Calibration Test Setup for the Dynatest FWD

Relative Calibration of the Deflection Sensors

1. Remove all of the deflection sensors from their holders on the FWD. Make sure that the sensors are labeled (e.g., from 1 to 7, or 0 to 6) with respect to their normal position on the FWD. The center sensor is in position number "1" on the Dynatest FWD and in position number "0" on the KUAB FWD.

2. Label the seven levels on the sensor stand from "A" to "G." The top level is usually labeled "A."

3. Position the seven deflection sensors in the stand for the first of the seven sets.

4. Support the sensor stand in a vertical position. Mark the location where the stand rests so that it can be relocated precisely on the same spot. This may be done by gluing a washer to the pavement, or by making a small divot in the pavement with a chisel.

5. Select the FWD drop height and the distance from the loading plate to the sensor stand to yield deflections on the order of 400 to 600 microns (16 to 24 mils). If deflections in

this range cannot be achieved, then it may be necessary to relocate the FWD to a different pavement. In general, a concrete pavement on a relatively weak subgrade will yield the required deflection. In most cases the reference calibration test pad should be usable for relative calibration.

6. Warm up the FWD rubber buffers and condition the test point by repeating a sequence of ten drops until the loads and deflections that are registered are nearly uniform. The deflections in a sequence of ten drops should not be showing a steadily increasing or decreasing trend. If liquefaction or compaction is indicated by the warm-up data, relocate the FWD to another pavement.

7. Lower the FWD loading plate. DO NOT raise the loading plate or move the FWD during the relative calibration testing. This will assure a constant distance between the center of the load plate and the base of the sensor stand.

8. For each set make two seating drops (no data recorded) followed by five replicate drops (for which data is recorded) while holding the stand in a vertical position. With seven sets and 5 replicate drops, data for a total of 35 drops is required (see Figure 2).

Relative Calibration Data Analysis

A three-way analysis of variance should be used to evaluate the data. This will partition the variance into four sources: (1) that due to sensor number, (2) that due to position in the calibration stand, (3) that due to set, and (4) that due to random error of measurement. This analysis is performed by the **FWDCAL2** software. In this analysis, deflection is the dependent variable, and sensor number, position and set are the three main factors. The three hypotheses that may be tested are:

H_0: Sensor number is a significant source of error

H_0: Data set number is a significant source of error

H_0: Position in the stand is a significant source of error

Through the use of hypothesis testing it is possible to determine whether random error due to sensor number, due to position in the calibration stand, and due to set number are statistically significant. The only factor that should result in a change in the deflection sensor calibration factors is sensor number.

If the random error due to sensor number is found to be statistically significant, then the calculated adjustments in the calibration factors for each sensor should be made. If a change is made in the calibration factor for one sensor, then the calibration factors for all sensors should be changed in accordance with the calculations.

If position in the stand is statistically significant, it is likely that the stand was not held vertical throughout all of the sets during the test. Or a connection in the stand may have been loose. The problem should be corrected, and the test should be repeated.

If set is statistically significant, there may have been a systematic change in the properties of the pavement materials, for instance due to compaction or liquefaction. The test should be repeated after the testing site has been further "conditioned" according to the procedure. If the deflection readings do not become relatively constant during the conditioning, then another site should be selected for the testing.

The mere fact that either position or set, or both, are significant does not necessarily invalidate the relative calibration. Judgement must be used to assess whether or not these factors may be of sufficient physical significance (as opposed to statistical significance) to require that the relative calibration should be repeated or that a new test site should be selected.

The standard error of measurement (e.g., the square root of the mean square error due to error) should be on the order of ± 0.08 mils (± 2 microns) or less if the system is working properly and the calibration test was conducted carefully.

The analysis of the data obtained from the relative calibration procedure and the method used to determine revised calibration factors is as follows (calculations are done automatically within the **FWDCAL2** software):

1. Compute the mean deflection measurement, x_i, for each sensor (average for the seven sets) and the overall mean, x_o, for all of the sensors averaged together.

2. Compute the adjustment ratio, R_i, of the overall mean to the sensor mean for each sensor.

$$R_i = \frac{x_o}{x_i}$$

Adjustment of Calibration Factors

When relative calibration is conducted in conjunction with reference calibration, the procedure is repeated two times. If the two sets of calibration factors agree within 0.003 for each deflection sensor, then the results of the two tests shall be averaged. If they are outside the limit, then a third relative calibration shall be performed. If the standard deviation of the three results (based on n - 1 degrees of freedom) is less than ±0.003, then the three results shall be averaged. If the standard deviation exceeds ±0.003, the relative calibration procedure should be repeated.

An example of the calculations following this procedure is shown in Appendix C. The average final calibration factors should be computed, and the factor for each deflection sensor should be entered into the FWD computer software (e.g., the "FWD Field Program").

When relative calibration is done alone, typically on a monthly basis, then adjustment of the calibration factors in the FWD Field Program should be made only when those changes are both significant, and verified to be necessary. The following guidelines are to be used to evaluate the need for adjustment to the calibration factors.

1. Computed sensor adjustment ratios, R_i, between 0.997 and 1.003 inclusive are considered to be equivalent to a ratio of 1.000. In other words the required adjustments are trivial and need <u>not</u> be made.

2. Where the adjustment ratios for one or more sensors fall outside of the range 0.997 to 1.003, the calibration process should be repeated. If both sets of data agree within 0.003, the gains should be adjusted for <u>all</u> sensors.

3. The final calibration factor is calculated by multiplying the current calibration factor for a given sensor, i, by its adjustment ratio, R_i.

   According to the recommendations of the FWD manufacturers, a final calibration factor less than 0.98 or greater than 1.02 is possibly indicative of a damaged sensor, which should be repaired by the manufacturer, or replaced. Final calibration factors that are within this range should be entered into the FWD data collection software.

4. If any calibration factors are changed, the relative calibration process must be repeated to verify the accuracy of the final values. The resulting adjustment ratios should be within the range 0.997 to 1.003 for all sensors. If they are not, the test procedure should be repeated.

Reports

The full FWD calibration report shall consist of the following:

- Printouts of the following Dynatest FWD Field Program screens (or equivalent for non-Dynatest FWDs).
  - Transducer Setup and Calibration Factors
  - Voltages
  - Load Cell Calibration

  Each of the above printouts is to be annotated with the FWD unit identification (e.g., manufacturer's serial number or agency ID), and the calibration date.

- All printouts from the **FWDREFCL** software

- The final printouts from the **FWDCAL2** software for all relative calibration trials.

- The Final Calibration Computation worksheet (see Appendix C)

Distribution of this report shall be as follows:

- Original retained by FWD operator for submission to his agency (LTPP Regional Engineer for LTPP FWDs).

- One copy transmitted to LTPP Division Office within one week of calibration.

- One copy retained on file by calibration center for a period of at least three years.

The diskettes on which the reference and relative calibration data are stored should be kept in the FWD. It is recommended that labeled backup copies be kept on file with the calibration report at the office out of which the FWD is operated. For the LTPP FWDs, additional backup copies of the calibration diskettes are to be kept on file at the LTPP Regional Office.

When relative calibration is done alone (e.g., as a monthly calibration check), the relative calibration report will consist of all printouts from the **FWDCAL2** software, annotated as necessary to explain any problems which might have been encountered.

APPENDIX A: REFERENCE CALIBRATION EQUIPMENT AND FACILITIES

I. Facilities

Indoor space with:

- easy access for FWD and towing vehicle
- level floor large enough so that both the FWD trailer <u>and</u> the towing vehicle can sit level during the test and be enclosed indoors
- reasonably constant temperature (between 50 and 100 F) and humidity (40-90 percent), heated, but not necessarily air conditioned
- good security for calibration equipment

Test pad:

- 15 feet by 15 feet, with an 8-foot wide clear zone around perimeter (for maneuvering FWDs and the reference data acquisition system)
- smooth, crack-free portland cement concrete surface. A modest amount of hairline cracking is permissible. Should the test pad develop cracks which are visibly open (1/16 inch or more), it should be replaced.
- isolated (by impregnated felt bond breaker, or sawed and caulked joint) from the area where the concrete inertial block supporting the aluminum reference beam will rest
- slab deflection of at least 16 mils due to 16,000 lb load at the position of the deflection sensor holder when the FWD is in the specified position for calibration. The sensor holder should be located not closer than two feet from the edge of the test pad, but it is not required, nor is it possible, that the test pad should deflect uniformly across the entire area of the pad. Because the inertial block supporting the aluminum reference beam must be placed adjacent to, but not on the calibration test pad, the maximum possible distance from the sensor holder to the edge of the test pad will be about five feet.

Note: Fatigue calculations indicate that acceptable fatigue life can be achieved with a 5-inch-thick portland cement concrete slab resting on an 8-inch open-graded crushed stone base. A layer of filter fabric should be placed below the base to protect it from intrusion of subgrade fines. To achieve adequate deflections, the subgrade modulus should be less than 12,000 psi (80 MPa) with bedrock deeper than 25-30 feet. Where bedrock exists at depths of 15 to 25 feet, a subgrade modulus of 7,500 psi (50 Mpa) or less will be needed. Test pads located where bedrock is less than 15 feet deep are likely to be very sensitive to minor variations in subgrade moisture, and hence are not advisable.

II. Equipment

- concrete inertial block (4,000 lbs.)
- 5-foot aluminum reference beam
- Air-Cel low frequency rubber isolation pads for support of the concrete block
- LVDT mounting hardware
- deflection sensor holder assembly
- magnetic tip for LVDT
- Schaevitz Model GCD-121-125, 0.125-inch stroke DC LVDT with Cannon connector
- Schaevitz metric LVDT calibrator C-41M
- Measurements Group, Inc. Vishay Model 2310 signal conditioner, with factory modification for +15 VDC and -15 VDC excitation
- Keithley-MetraByte Model DAS-16G A/D data acquisition board, with STA-16 screw terminal board and C-1800 ribbon cable. The G2 version of the data acquisition board is recommended for IBM PC-XT and PC-AT computers, and compatibles; the G1 version is acceptable. A Model μDAS-16G board should be used with IBM PS/2 (microchannel bus) computers.
- connecting cables, Vishay to LVDT and Vishay to MetraByte
- FWD reference calibration software (FWDREFCL) and documentation
- custom built reference load cell (300 mm diameter, 40,000 lbs. capacity)
- connecting cable, Vishay to load cell

Note: Drawings of each of the special items of equipment, and cabling diagrams, are available from the Long-Term Pavement Performance (LTPP) Division at the Federal Highway Administration, Turner-Fairbank Highway Research Center, McLean, Virginia.

IBM PC-XT or PC-AT, or compatible, computer recommended; IBM PS/2 computer acceptable. Configuration:

- 80386 processor or higher
- 25 MHz or faster processor speed
- co-processor, if applicable
- 1 megabyte or more RAM
- 100 megabyte or more hard drive
- an 8-bit expansion slot for the MetraByte board

Monitor:

- Color monitor; monochrome not recommended
- VGA recommended; EGA acceptable

Graphics Printer:

- Laser printer recommended; dot matrix acceptable, but very slow

(Where both "recommended" and "acceptable" options are given in the above specifications, an effort has been made in the software development to accommodate both alternatives. However, since most of the testing has been done on computer hardware meeting the "recommended" specifications, installation of the calibration station will go more smoothly if those specifications are met. A demonstration version of the **FWDREFCL** software is available from the LTPP Division in the Federal Highway Administration (located at the Turner-Fairbank Highway Research Center, McLean, VA) which can be used to determine if the computer and peripherals will work satisfactorily with the program.)

APPENDIX B: SPECIAL PROCEDURES FOR TESTING THE KUAB FWD

Reference calibration of the KUAB FWD can be carried out in a manner very similar to the procedure outlined for the Dynatest FWD. However, because the KUAB has its load plate forward of the deflection sensor beam (i.e., toward the towing vehicle), it will be necessary to place the trailer on an angle with respect to the test pad, so that the load plate can be positioned as close as possible to the LVDT and the deflection sensor holder. The end of the aluminum beam holding the LVDT should be just behind the trailer wheels, near the place where the "foot" of the KUAB A-frame rests on the floor.

KUAB FWDs must have operational program SFWD version 4.0 or higher to perform reference calibrations. This version can be obtained from the manufacturer.

Before the reference calibration procedure is performed, the FWD Operator should first conduct a static calibration of the deflection sensors. The KUAB software will automatically file the static calibration factors. The manufacturer recommends that the dynamic calibration factors be entered as 1.05 for all sensors. These values should not be changed during or after the reference calibration.

Due to the larger distance between the center of the load plate and the seismometer holder it may not be possible to achieve the specified deflection of 16 mils at 16,000 pounds. The deflection should be as large as possible.

To achieve the specified load levels the manufacturer recommends using Load Mode 3 (9+9 small buffers, 2 stack weights). Adjust the drop height endswitches as necessary to be within the load tolerances.

In general the KUAB will be tested with the 17-millisecond rubber buffers installed. The reference data acquisition system and the **FWDREFCL** software allow for calibration using the 25-millisecond buffers, but the movement of the aluminum beam should be checked carefully to assure that there is no motion before the ground deflection peaked out.

The **FWDREFCL** software contains an number of special features to accommodate the KUAB, and thus in initializing the software, the FWD type should be set for "KUAB." The deflection sensor that is mounted through the load plate (i.e., the center sensor) is called sensor number zero on the KUAB, and it is in position number 0 as far as **FWDREFCL** is concerned.

KUAB FWDs with version 4.0 software are able to pause during the drop sequence, prior to releasing the mass. This is achieved by entering the letter "P" after the drop height position code during programming of the drop sequence. For example, the required reference calibration drop sequence would be entered as follows (drop height, number of drops):

333(1P,6)(2P,6)(3P,6)(4P,6)

The pause occurs with the mass elevated, ready to drop. The mass will not be released until the FWD operator strikes a key.

To repeat the drop sequence without raising the load plate from the ground, strike the ESC key twice immediately following the final drop. This will interrupt the initial drop sequence, allowing a second drop sequence to be started without raising the plate.

Because the top of the reference load cell is 300 millimeters in diameter, it will only be possible to calibrate the small (300 mm) load plate on the KUAB. If the KUAB is outfitted with the large (450 mm) load plate, it should be replaced with the 300 millimeter load plate in order to attain accurate results.

A special holder is provided for mounting the KUAB seismometer under the LVDT. The Dynatest geophone holder should be removed and the KUAB holder bolted down in its place. The LVDT mounting plate that attaches to the end of the aluminum beam should be removed from its position under the beam and reinstalled on top of the beam. The KUAB deflection sensors will be slid upward off the two rods that hold them in position on the sensor beam in the trailer. Remove the tripod foot by loosening its holding screw, and then slip the deflection sensor over the peg on the holder under the LVDT. Tighten the holding screw firmly.

Conducting load plate calibration is particularly difficult on the KUAB, because it is hard to detect when the FWD mass has been released. To make this easier, a double layer (or thicker) of "duct tape" should be wrapped around the guide post (down which the runners under the falling mass roll), located an inch or two above the bottom of the stroke. The proper position for the tape can be found when the mass is at its lowest drop height. Adjust the KUAB load sensitivity in the reference system computer to a value of 5 to 10 bits. Remove the tape after completion of the reference calibration.

Enter the new calibration factors for the deflection sensors as the "SHRP Calibration Factors" under the Calibrate menu in the KUAB operational program. The calibration factor for the 300 mm load plate is entered in the same manner. The calibration factor for the large (450 mm) load plate should remain unchanged.

Most KUAB FWDs do not have a calibration stand for performing relative calibration. Thus it will not be possible to perform the relative calibration procedure as described herein.

Limited experience in the calibration of KUAB FWDs has shown that the combination of static calibration and dynamic calibration may be adequate to yield a satisfactory calibration and accurate final calibration factors. However, relative calibration further refines the reference calibration factors, and it allows a monthly check of the accuracy of the deflection sensors. Thus it is highly recommended that a means of performing relative calibration with the KUAB FWD be developed.

APPENDIX C: SAMPLE COMPUTATION OF FINAL CALIBRATION FACTORS

Sensor	Final Calibration Factors From Relative Calibration Trial 1	Trial 2	Trial 3	Average Final Calibration Factors	Standard Deviation
1	1.014	1.011	1.015	1.013	0.0035
2	1.010	1.007	1.012	1.010	0.0035
3	1.012	1.010	1.013	1.011	0.0035
4	1.016	1.020*	1.012	1.016	0.0035
5	1.017	1.018	1.018	1.018	0.0035
6	1.008	1.012*	1.011	1.010	0.0035
7	1.012	1.012	1.009	1.011	0.0035

Notes:

1. If the results from the first two trials agree within 0.003 for each deflection sensor, then it is not necessary to perform a third test. Average the results of the first two trials, and enter the average final calibration factors in the FWD computer. In the example above, after Trial 2 the data marked (*) did not meet this criterion.

2. If three trials are performed, compute the mean and the standard deviation of the three results for each deflection sensor. If the standard deviations (based on n - 1 degrees of freedom) are all less than ±0.003, enter the average final calibration factors in the FWD computer. If any of the standard deviations exceed ±0.003, repeat the entire relative calibration test.

APPENDIX D: REFERENCE LOAD CELL CALIBRATION PROCEDURE

INTRODUCTION

The reference load cell is a precision instrument, capable of measuring loads within ±0.3 percent or better. Such a high degree of precision can be attained, however, only if this calibration procedure is followed exactly. It is essential that the reference load cell be calibrated using a universal testing machine that is properly maintained and accurately calibrated.

FREQUENCY OF CALIBRATION

Calibration of the reference load cell should be performed at least once per year. It should also be performed immediately after any of the six Allen head screws that attach the load measurement links to the upper or lower plates of the reference load cell are loosened. Calibration would also be necessary if the load cell fails to pass the unbalanced zero test (within ±5 percent) as detected by the **FWDREFCL** program.

EQUIPMENT

- Universal testing machine. A static testing machine, hydraulic or screw-powered, with a load capacity of 120,000 pounds or more should be used for the reference load cell calibration. Although the reference load cell will only be calibrated to a capacity of 20,000 pounds, the higher capacity of the testing machine assures that the test frame will be adequately rigid. The testing machine should have several load ranges, among them a 0 - 20,000 pound range (slightly higher ranges, such as 0 - 24,000 pounds, etc., would be acceptable). Care must be taken to avoid overloading the reference load cell during its calibration.

  Note: Do <u>not</u> use a servo-controlled, closed-loop testing system such as a MTS machine for this purpose. In general such equipment does not provide the high degree of accuracy that is required for this calibration.

- Bearing blocks: special wood/aluminum bearing blocks.

- Measurements Group, Inc. Model 2310 Signal Conditioner. This should be the <u>same</u> signal conditioner that will be used in the reference calibration procedure.

- Keithley-MetraByte DAS-16G data acquisition board, installed in the same computer that is used for reference calibration.

- Push-button trigger for activating the data acquisition system.

The reference load cell and its cable, and the associated signal conditioner, data acquisition board and computer should be considered a system of instruments, which should be calibrated together and used together.

CALIBRATION OF EQUIPMENT

The universal testing machine should be calibrated according to ASTM procedure E-74 within twelve months prior to conducting this procedure. The device(s) used to calibrate the universal testing machine should be certified to be traceable to the National Institute for Science and Technology (NIST - formerly the National Bureau of Standards) calibration(s). The certificate of calibration provided for the universal testing machine should be used to develop an adjustment algorithm which will correct the indicated load on the universal testing machine to the NIST load. It is highly recommended that the reference load cell be calibrated soon after the universal testing machine is calibrated.

The MetraByte board should be calibrated according to the procedure described in the manufacturer's instruction manual. Its accuracy should be verified using a reference voltage source such as a 1.350 volt mercury cell (eg., camera battery in new condition).

The 2310 signal conditioner amplifier should be balanced according to the procedure described in the manufacturer's instruction manual. With the signal input terminals shorted together, at gain 100 the ac noise on the ±10 volt output terminals should be 1 millivolt or less.

EQUIPMENT PREPARATION

Inspect the reference load cell carefully before calibration. Verify that the cable and the Amphenol connectors are making proper contact in their sockets (eg., fitting and locking tightly). Make a continuity check to verify that there are no breaks in the wires. Verify that the Allen screws on the load cell are tight.

Note: The six Allen screws on the top and the bottom of the load cell were torqued to 100 lb.-in. and set with Locktite during assembly. These screws should not be loosened unless it is absolutely necessary. If any of the screws are loosened, they should be removed one at a time and their threads cleaned. Locktite should be reapplied to their threads, and they should be torqued to precisely 100 lb.-in.

Verify that the three steel pads on the bottom of the reference load cell are in good condition. Verify that one of the wood/aluminum bearing blocks has a ribbed rubber pad cemented to it. If the edges of the rubber pad are loose, use rubber cement to reattach it.

Install a spherically-seated bearing block in the cross head of the universal testing machine.

Make the following settings on the front panel of the 2310 signal conditioner:

- Excitation Voltage set to 10 volts
- Filter set to 1000 Hz
- AC IN button fully extended (eg., out)
- Gain set to 5.5 x100
- Auto Balance switch OFF

Verify that the Tape Playback switch on the rear panel of the signal conditioner is OFF. Position the signal conditioner and the computer several feet apart near the testing machine and attach them to ac line power.

COMPUTER PREPARATION

Use the same computer system for reference load cell calibration that is used for FWD calibration. A graphics printer must be available.

Load the software **LDCELCAL** into the reference system computer. This program should be located in the same subdirectory with **FWDREFCL.EXE** and **FWDREFCL.CNF.** A disk with the files **REFLCCAL.WK1** and **REFLCCAL.FMT** on it should be inserted in drive A. The computer must be running under **DOS** and not under **WINDOWS** during the calibration.

The computer program **LDCELCAL** is designed to interact with a Lotus 1-2-3, version 2.3, spreadsheet to accomplish the data analysis. The subdirectory containing the 1-2-3 program must be on the PATH in order for the two programs to work together successfully. The **WYSIWYG** add-in utility should be installed according to the Lotus directions. Defaults in

Lotus 1-2-3 should be set as follows.

- Default directory: A:\
- Auto-execute macros: on
- Auto-attach add-in #1: C:\LOTUS\WYSIWYG

See the Lotus User's Manual for instructions regarding setting the defaults. If the program is correctly installed and set up, the data analysis will be run, a listing of the data will be produced, and graphical output will be printed automatically. A demonstration version of **LDCELCAL** is available to use with Lotus 1-2-3 to verify that your computer system can interact properly with the program.

CALIBRATION PROCEDURE

1. Attach the cable from the signal conditioner to the reference load cell, turn on the signal conditioner, and allow the system to warm up for at least 15 minutes. Attach the cables connecting the signal conditioner to the computer. Attach the push-button trigger in the blue terminal box of the MetraByte data acquisition system. Turn on the computer and the printer. If an hydraulic universal testing machine is used, turn the pump on and allow it to warm up for 15 minutes.

2. Place a wood/aluminum bearing block with no rubber pad in the center of the testing machine platen.

3. Place the reference load cell on top of the bearing block with the three steel pads down (i.e., in contact with the top surface of the lower bearing block).

4. Place the second bearing block on top of the load cell with the cemented rubber pad down (i.e., in contact with the top surface of the load cell).

5. Carefully align the edges of the load cell and the two bearing blocks, and center the system under the upper loading block of the universal testing machine.

6. Set the testing machine on a range equal to or slightly larger than 20,000 pounds. Apply a nominal load of 20,000 pounds to the reference load cell three times. Apply the load at a rate in the range of 5,000 to 20,000 pounds per minute.

7. Temporarily remove the upper wood/aluminum bearing block. Set the Auto Balance

switch on the 2310 signal conditioner to OFF. Read and record the unbalanced zero voltage. If this voltage is in excess of ±5 volts the load cell has been damaged by yielding and it should be returned to the manufacturer for repair.

8. Push down the Auto Balance switch on the signal conditioner to the RESET position and release it to the ON position. Adjust the Trim knob until the MetraByte board reads 0 bits.

9. Replace and align the upper bearing block, rubber pad down. Verify that the three guide fingers do not come in contact with the upper bearing block.

10. Apply a load of 20,000 pounds, and while it is held relatively constant verify that the MetraByte board reads within ±30 bits of -2000 bits. If necessary, adjust the Gain knob on the 2310 signal conditioner in 0.1 increments (for example, from a setting of 5.50 x100 to 5.40 x100) to achieve the required reading. Release the load. Record the gain setting.

    Note: When the load is released the MetraByte board will not read exactly zero because it was zeroed without the upper bearing block in place. Do <u>not</u> rezero the signal conditioner at this point.

11. Apply load at a rate no faster than 1,000 pounds per minute. Record the MetraByte board readings at 1,000 pound intervals up to a maximum load of 20,000 pounds. While releasing the load, record a reading at 10,000 pounds and at zero load.

12. Remove the upper bearing block and, if necessary, adjust the Trim knob on the signal conditioner until the MetraByte board reads 0 bits. Push and hold the Cal switch in the +B position and record the reading. Repeat for the -B position. Set the Auto Balance switch to OFF and again record the unbalanced zero voltage. This reading should be within three bits of the earlier reading. If it is not, repeat the calibration procedure from step 4 (be sure that the load cell is centered in the testing machine, and be sure to repeat the 20,000-pound preloading procedure in step 6).

DATA ANALYSIS

Using a spreadsheet utility program such as Lotus 1-2-3, enter the results of the calibration. In column A enter the nominal loads registered by the universal testing machine (i.e., 0, 1000, 2000, etc.). In column B correct these loads to the NIST traceable loads, based on the certificate of calibration for the testing machine. In column C subtract the tare weight of the upper bearing block from the loads in column B. In column D enter the MetraByte board readings in bits. Note that the readings are negative. In columns E, F, G and H calculate V^2, V^3, V^4, and V^5, respectively (where V represents the readings in column D).

Use the spreadsheet regression utility to calculate a linear regression of corrected load (as the Y-variable) versus bits (as the X-variable). The regression should be forced through zero, yielding an equation of the form $Y = m V$, where Y is the corrected load (column C), V is the voltage (column D), and m is the slope of the line of best fit. The coefficient m should be approximately -10 pounds per bit.

Use the regression utility to calculate a fifth degree polynomial regression of the form:

$$Y = A_1 V + A_2 V^2 + A_3 V^3 + A_4 V^4 + A_5 V^5$$

where the coefficients A_i are determined by the regression. Evaluate the polynomial solution according to the following criteria.

1. The standard error of the Y estimate should be less than ±50 pounds.

2. The standard error of each of the coefficients should be small with respect to the coefficient. Generally speaking the coefficient should be at least a factor of ten larger than its standard error. For instance, if the coefficient A_2 is -0.15, its standard error should be ±0.015 or smaller. If this is not the case, the regression coefficient is not significant.

If the standard error any of the coefficients is too large (eg., not significant), repeat the regression using a fourth degree polynomial of the form:

$$Y = A_1 V + A_2 V^2 + A_3 V^3 + A_4 V^4$$

Again evaluate the polynomial according to the criteria in 1 and 2 above. When the evaluation criteria are satisfied, and <u>all</u> of the coefficients are significant (usually this will happen with either a fourth degree polynomial or a third degree polynomial), record the regression coefficients.

ENTER THE REGRESSION COEFFICIENTS IN FWDREFCL

The regression coefficients should be entered in the data acquisition program **FWDREFCL**. Instructions for doing this can be found in the Load Cell Setup section of the **FWDREFCL** User's Guide. Any of the unused higher order terms should have their coefficients entered as 0.0.

When the regression coefficients are entered in **FWDREFCL**, the unbalanced zero, the +B and -B calibration factors, the load cell signal conditioner gain factor, and the date of calibration should also be entered.

Appendix B

FWDCAL 2.0 Program Listing

```
DECLARE SUB GainAdjustMsg ()
DECLARE SUB ReplaceSensor ()
DECLARE SUB LatinPage1 ()
DECLARE SUB GainsPage1 ()
DECLARE SUB FileToScreen ()
DECLARE SUB AvgGainToFile ()
DECLARE SUB AvgGainToScreen ()
DECLARE SUB StartAnalysis ()
DECLARE SUB OutputToFile ()
DECLARE SUB LatinSqDesign ()
DECLARE SUB SelectAnalysis ()
DECLARE SUB GetSensorNum ()
DECLARE SUB AssignPosition (Index%, Posit%())
DECLARE SUB BadFile ()
DECLARE SUB Quit ()
DECLARE SUB DisplayCopyright ()
DECLARE SUB CheckHeader (InitNumPeaks%, InitNumWHBlocks%, ExitCode%)
DECLARE SUB ReadPeaks ()
DECLARE SUB ReadNextLine (DataType%, LineLength%)
DECLARE SUB GetFileName (FPath$, file$, Ext$)
'$INCLUDE: 'declare.inc'
'$INCLUDE: 'cmnblank.inc'

COMMON SHARED /cal01/ LineCounter&, LineData$, English%, Edition%, ADFlag%, ADFlag1%, FWDSN$, FileDate$,
NumDeflectors%
COMMON SHARED /cal02/ InitNumPeaks%, Operator$, Posit%(), Analysis$, OExt$, SumTotal#, Ti#(), SetCount%, TOL$(),
RAN$()
COMMON SHARED /cal03/ StdDevDef!(), StdDevPos!(), MeanBySet!(), MeanLoad!(), MeanSet#(), MeanPos#(), MeanDef#(),
NumDrops%
COMMON SHARED /cal04/ MeanAllLoad!, StdDevAllLoad!, CVAllLoad!, CVPos!(), CVDef!(), MeanAllDef#, StdDevAllDef!,
CVAllDef!
COMMON SHARED /cal05/ SSLT#, SSLPos#, SSLSet#, SSLSens#, SSLE#, FLPos#, FLSet#, FLSens#
COMMON SHARED /cal06/ DegFreeLPos%, DegFreeLSet%, DegFreeLSens%, DegFreeLE%, DegFreeLT%
COMMON SHARED /cal07/ MSLPos#, MSLSet#, MSLSens#, MSLE#, SerialNum%(), RelGain#(), MeansRat#(), NewGain#()
COMMON SHARED /cal08/ DefData!(), LoadData!(), OutDef!(), DataSet$(), AvgMeansRat#(), AvgNewGain#()
COMMON SHARED /cal09/ repm1$, repm2$, RepSens%, BigDef!, G!, ProblemExist%, SC%, Jnum1%, Jnum2%, LSAM$

'The determination of significance is based on a hard coded F-Statistic
'for a given set of degrees of freedom and confidence level.
'To modify the determination of significance, the user must change the value
'for -FStatistic- in this code.
CONST True% = -1, False = 0, CritFLPos! = 2.14, CritFLset! = 2.14, CritFLSens! = 2.14
CONST NumSensors% = 7, NumPositions% = 7, NumSets% = 7, NumReps% = 5, Galph! = .2326

DIM DefData!(7, 7, 7, 5), LoadData!(35), OutDef!(35, 7), DataSet$(3, 35)
DIM Posit%(7), MeanSet#(7), MeanPos#(7), MeanDef#(7), MeanLoad!(7)
DIM CVPos!(7), CVDef!(7), StdDevDef!(7), StdDevPos!(7), MeanBySet!(7, 7)
DIM Ti#(7), RelGain#(10), NewGain#(3, 10), MeansRat#(3, 7), SerialNum%(10)
DIM AvgNewGain#(7), AvgMeansRat#(7), TOL$(7), RAN$(7)

GP.Monitor% = Monitor%
CALL DisplayCopyright
FPath$ = ""

Start:
SCREEN 0: WIDTH 80, 25: CLS
RepSens% = 0
NumStations% = 0
SetCount% = 0

CLOSE

CALL SelectAnalysis
CALL GetFileName(FPath$, file$, Ext$)
Source$ = FPath$ + file$ + Ext$
OPEN Source$ FOR INPUT AS #1
CLS : CALL NormalColor: LOCATE 13, 20: PRINT "Reading Input Data from: "; file$ + Ext$
LineCounter& = 0
DO
```

```
    IF LineCounter& < 37 THEN
      CALL CheckHeader(InitNumPeaks%, InitNumWHBlocks%, ExitCode%)
    ELSE
      CALL ReadNextLine(DataType%, LineLength%)
      SELECT CASE DataType%
        CASE 1
          CALL ReadPeaks          'peak deflection data block
        CASE ELSE
          EXIT DO
      END SELECT
    END IF
  LOOP
  IF DropCount% <> CritNumDrops% THEN
     CALL BadFile
  END IF
  CLS : CALL NormalColor
  IF (SetCount% > 1) AND (Analysis$ = "S") THEN
       SM1$ = "Input data file has" + STR$(SetCount%) + " data sets": SM1 = LEN(SM1$):
  LOCATE 12, 40 - SM1 / 2: PRINT SM1$
       SM2$ = "Analysis will be performed sequentially on each set": SM2 = LEN(SM2$):
  LOCATE 13, 40 - SM2 / 2: PRINT SM2$;
       SLEEP 4
  ELSEIF (SetCount% > 1) AND (Analysis$ = "G") THEN
       SM1$ = "Input data file has" + STR$(SetCount%) + " data sets": SM1 = LEN(SM1$):
  LOCATE 12, 40 - SM1 / 2: PRINT SM1$
       SM2$ = "Analysis will be performed sequentially on each set": SM2 = LEN(SM2$):
  LOCATE 13, 40 - SM2 / 2: PRINT SM2$;
       SLEEP 4
  ELSEIF (SetCount% < 3) AND (Analysis$ = "R") THEN
       SM1$ = "Not enough data sets to run Reference-Relative Calibration Analysis": SM1 = LEN(SM1$): LOCATE 12,
  40 - SM1 / 2: PRINT SM1$
       SM2$ = "Please select correct analysis type from the menu": SM2 = LEN(SM2$):
  LOCATE 13, 40 - SM2 / 2: PRINT SM2$
       SLEEP 4
       GOTO Start
  END IF

  OExt$ = ".C" + Analysis$ + RIGHT$(Ext$, 1)
  Output$ = FPath$ + file$ + OExt$
  OPEN Output$ FOR OUTPUT AS #2
  IF Analysis$ = "G" OR Analysis$ = "g" THEN
       CALL GetSensorNum
  END IF
  CALL StartAnalysis
  IF SetCount% = 3 AND Analysis$ = "R" THEN
     CALL AvgGainToFile
     CALL AvgGainToScreen
  END IF
  IF Jnum1% > 0 AND Analysis$ <> "R" THEN
       CALL GainAdjustMsg
  END IF
  CLOSE
  GOTO Start
  CALL Quit
```

```
SUB AssignPosition (Index%, Posit%()) STATIC
  Count = 0
  FOR i = Index% TO NumSensors%
      Posit%(i) = i - Index% + 1
  NEXT i
  FOR i = Index% - 1 TO 1 STEP -1
      Count = Count + 1
      Posit%(Count) = NumSensors% - i + 1
  NEXT i
END SUB
```

```
SUB AvgGainToFile
FOR i% = 1 TO NumSensors%
AvgNewGain#(i%) = (NewGain#(1, i%) + NewGain#(2, i%) + NewGain#(3, i%)) / 3
NEXT i%
' ********************************* Page 1 ******************************
Year$ = MID$(FileDate$, 1, 2)
Month$ = MID$(FileDate$, 3, 2)
Day$ = MID$(FileDate$, 5, 2)
MDY$ = Month$ + "-" + Day$ + "-" + Year$
'********************** Geophone Calibration Sensor ******************
PRINT #2, SPC(14); "SHRP FWD Relative Calibration - Average Gains Table"
PRINT #2, "FWD SN: "; FWDSN$; SPC(38); "Calibration Date: "; MDY$
PRINT #2, "Data File Name : "; file$ + Ext$; SPC(12); "Average Means and Gains for 3 data Sets"
PRINT #2, "Operator : "; Operator$
PRINT #2,
PRINT #2, "                  Sensor     Existing          New Relative Gain        "
PRINT #2, "        Sensor #   S/N      Gain Factor   Set 1   Set 2   Set 3   Average"
PRINT #2, "        --------  ------    -----------   -----   -----   -----   -------"
t8$ = "            #       ####        #.###       #.###   #.###   #.###    #.###"
FOR S% = 1 TO NumSensors%
    PRINT #2, USING t8$; S%; SerialNum%(S%); RelGain#(S%); NewGain#(1, S%); NewGain#(2, S%); NewGain#(3, S%);
AvgNewGain#(S%)
NEXT S%
END SUB
```

```
SUB AvgGainToScreen
CLS : CALL NormalColor
FOR i% = 1 TO NumSensors%
AvgNewGain#(i%) = (NewGain#(1, i%) + NewGain#(2, i%) + NewGain#(3, i%)) / 3
NEXT i%
' ******************************** Page 1 ******************************
Year$ = MID$(FileDate$, 1, 2)
Month$ = MID$(FileDate$, 3, 2)
Day$ = MID$(FileDate$, 5, 2)
MDY$ = Month$ + "-" + Day$ + "-" + Year$
'*********************** Geophone Calibration Sensor ******************
PRINT SPC(14); "SHRP FWD Relative Calibration - Average Gains Table"
PRINT "FWD SN: "; FWDSN$; SPC(38); "Calibration Date: "; MDY$
PRINT "Data File Name : "; file$ + Ext$; SPC(12); "Average Means and Gains for 3 data Sets"
PRINT "Operator : "; Operator$
PRINT
PRINT "                 Sensor     Existing          New Relative Gain       "
PRINT "       Sensor #   S/N      Gain Factor   Set 1   Set 2   Set 3   Average"
PRINT "       --------  ------    -----------   -----   -----   -----   -------"
t8$ = "           #      ####        #.###      #.###   #.###   #.###    #.###"
FOR S% = 1 TO NumSensors%
    PRINT USING t8$; S%; SerialNum%(S%); RelGain#(S%); NewGain#(1, S%); NewGain#(2, S%); NewGain#(3, S%);
AvgNewGain#(S%)
NEXT S%
LOCATE 25, 25: PRINT "Press any key to continue";
WHILE INKEY$ = "": WEND
END SUB
```

```
SUB BadFile STATIC
  CLOSE
  COLOR 7, 0, 0
  CLS
  PRINT : PRINT
  PRINT "*                      EXECUTION HALTED"
  PRINT "*    The data file selected does not match the structure specified "
  PRINT "*    for relative calibration in FWD Operational Field Guidelines"
  PRINT "*                    Version 1.00, TABLE 6"
  PRINT
  IF Edition% <> 10 AND Edition% <> 20 THEN
    PRINT "* Version 10 or 20 of Dynatest Field Program Not Used"
  ELSEIF NumDeflectors% <> NumSensors% THEN
    PRINT "* Not Using 7 Deflectors"
  ELSEIF ActiveDrops% < 46 THEN
     PRINT "* Less Than 46 Active Drops in Sequence"
  ELSEIF InitNumPeaks% MOD NumDrops% > 0 THEN
    PRINT "* Not Using 5 Repeat Drops"
  END IF
  PRINT
  PRINT
  END
END SUB
```

```
SUB CheckHeader (InitNumPeaks%, InitNumWHBlocks%, ExitCode%) STATIC
  CALL ReadNextLine(DataType%, LineLength%)
  SELECT CASE LineCounter&
    CASE 1
      FileWidth% = VAL(MID$(LineData$, 2, 4))
      IF FileWidth% = 32 THEN
     English% = False%
      ELSE
     English% = True%
      END IF
      FileDate$ = MID$(LineData$, 14, 6)        'Data collected on FileDate$
      Edition% = VAL(MID$(LineData$, 31, 2))
      IF Edition% <> 10 AND Edition% <> 20 THEN CALL BadFile
    CASE 2
      NumDeflectors% = VAL(LEFT$(LineData$, 1))
      IF NumDeflectors% <> NumSensors% THEN CALL BadFile
      FWDSN$ = MID$(LineData$, 9, 8)
    CASE 3 TO 10, 22 TO 29, 31, 32, 34 TO 36
    CASE 11 TO 20                          'deflector 1 to 10
      SensorNumber% = VAL(MID$(LineData$, 2, 2))
      SerialNum%(LineCounter& - 10) = VAL(MID$(LineData$, 4, 5))
      RelGain#(LineCounter& - 10) = VAL(MID$(LineData$, 10, 5))
    CASE 21                                'operator
      Operator$ = LTRIM$(RTRIM$(LineData$))
    CASE 30                                'active sequence drops
      Posit% = INSTR(LineData$, ".")
      ActiveDrops% = Posit% - 1
      IF ActiveDrops% < 46 THEN CALL BadFile
     CASE 33                                'peaks stored
      CheckText$ = LEFT$(LineData$, ActiveDrops%)
      InitNumPeaks% = InCount2%(CheckText$, "*")
      NumDrops% = InitNumPeaks% \ NumSets%
      IF InitNumPeaks% MOD NumDrops% > 0 THEN CALL BadFile
  END SELECT
END SUB
```

```
SUB Cochran
'Cochran's test to determine significance of variance between sensors
'set up Vdef (Mean, Sensor) for sorting
DIM Temp(1, 2), Vdef(7, 2)
     FOR S% = 1 TO 7
       Vdef(S%, 1) = StdDevDef!(S%) ^ 2
       Vdef(S%, 2) = S%
     NEXT S%
     'SORT
       FOR Iter% = 1 TO 7
       FOR S% = 1 TO 6
            IF Vdef(S% + 1, 1) > Vdef(S%, 1) THEN
              Temp(1, 1) = Vdef(S% + 1, 1)
              Temp(1, 2) = Vdef(S% + 1, 2)
              Vdef(S% + 1, 1) = Vdef(S%, 1)
              Vdef(S% + 1, 2) = Vdef(S%, 2)
              Vdef(S%, 1) = Temp(1, 1)
              Vdef(S%, 2) = Temp(1, 2)
            END IF
       NEXT S%
     NEXT Iter%
     BigVarDev! = Vdef(1, 1)
     BigDef! = Vdef(1, 2)
'Sum all Means
     FOR M% = 1 TO 7
       SumVarDev! = SumVarDev! + StdDevDef!(M%) ^ 2
     NEXT M%
     G! = BigVarDev! / SumVarDev!
     IF G! > Galph! THEN ProblemExist% = 1
END SUB
```

```
SUB DisplayCopyright STATIC
  SCREEN 0: WIDTH 80: CLS
  PRINT
  PRINT "
  PRINT "
  PRINT "
  PRINT "
  PRINT "
```

```
  LOCATE 10, 20: PRINT "FWD Relative Calibration Analysis Software"
  LOCATE 12, 35: PRINT "Version 2.0"
  LOCATE 15, 20: PRINT "Strategic Highway Research Program  (SHRP)"
  LOCATE 20, 10: PRINT "Support material Copyright (c) 1989   PCS/Law Engineering Inc."
  LOCATE 21, 12: PRINT "Additional material Copyright (c) 1988   Crescent Software"
  LOCATE 23, 13: PRINT "Enhancements by Nichols Consulting Engineers, Chtd. 1992."
  SLEEP 4
  CALL NormalColor
  CALL ClearBuf
END SUB
```

```
SUB FileToScreen STATIC
  FTS$ = "Y"
  WindowType% = 1: CLS
  WFile$ = file$ + OExt$
  CALL NormalColor
  LOCATE 7, 7: PRINT "Output Path and File Name: "
  LOCATE 7, 37: PRINT FPath$; WFile$
  LOCATE 13, 7: PRINT "Display calibration results on screen: "
  CALL HiliteColor
  LOCATE 13, 50: PRINT FTS$
  CALL NormalColor
DO
    OldFTS$ = FTS$
    CALL GetString(13, 50, 1, FTS$, "L", 0, 0, "", "", ExitCode%)
    FTS$ = UCASE$(FTS$)
SELECT CASE FTS$
    CASE "Y"
     CALL NormalColor: CLS
     CALL GainsPage1
          Img$ = "PgDn to ANOVA Table           Esc to exit results screens": Img = LEN(Img$): LOCATE 25, 40
- Img / 2: PRINT Img$;
DO
  DO
     a$ = INKEY$: LOOP WHILE a$ = ""
     IF LEN(a$) = 2 THEN
          a$ = RIGHT$(a$, 1)
     END IF
SELECT CASE a$
     CASE CHR$(73) ' page up
          CALL GainsPage1
          Img$ = "PgDn to ANOVA Table           Esc to exit results screens": Img = LEN(Img$): LOCATE 25, 40
- Img / 2: PRINT Img$;
     CASE CHR$(81) ' page down
          CALL LatinPage1
          Img$ = "PgUp to Gains Table           Esc to exit results screens": Img = LEN(Img$): LOCATE 25, 40
- Img / 2: PRINT Img$;
     CASE CHR$(27)
          EXIT DO
END SELECT
LOOP
          EXIT DO
     CASE "N"
          EXIT DO
     CASE ELSE
          REDIM PUText$(1)
          PUText$(1) = "Please enter a Y or N only..."
          CALL PopupError
          FTS$ = OldFTS$
END SELECT
LOOP
CLS
END SUB
```

```
SUB GainAdjustMsg
SCREEN 0: WIDTH 80, 25: CLS : CALL NormalColor
Year$ = MID$(FileDate$, 1, 2)
Month$ = MID$(FileDate$, 3, 2)
Day$ = MID$(FileDate$, 5, 2)
MDY$ = Month$ + "-" + Day$ + "-" + Year$
'************************** Geophone Gain Adjustments ******************
PRINT
PRINT SPC(15); "SHRP FWD Relative Calibration -  Gain adjustments"
PRINT
PRINT "FWD SN: "; FWDSN$; SPC(38); "Calibration Date: "; MDY$
PRINT "Data File Name : "; file$ + Ext$
PRINT "Operator : "; Operator$
PRINT
PRINT
PRINT "Results of this test indicate the possible need to adjust then gains."
PRINT "This should be confirmed with a repeat test."

PRINT
PRINT "Gain adjustment should be performed when the new gain factors from two"
PRINT "independent calibrations are within "; CHR$(241); "0.002 of each other."

PRINT
PRINT "Gain adjustments should be made ONLY to the out of range geophone(s)."

PRINT
PRINT "After adjusting any gain setting, the relative calibration test must be"
PRINT "repeated to confirm that all sensors are within tolerance."

bm$ = "Press any key to continue": bml = LEN(bm$): LOCATE 25, 40 - bml / 2: PRINT bm$;
WHILE INKEY$ = "": WEND
END SUB
```

```
SUB GainsPage1
SCREEN 0: WIDTH 80, 25: CLS
Year$ = MID$(FileDate$, 1, 2)
Month$ = MID$(FileDate$, 3, 2)
Day$ = MID$(FileDate$, 5, 2)
MDY$ = Month$ + "-" + Day$ + "-" + Year$
'************************** Geophone Calibration ******************
PRINT SPC(18); "SHRP FWD Relative Calibration - Gains Table"
PRINT "FWD SN: "; FWDSN$; SPC(37); "Calibration Date: "; MDY$
PRINT "Data File Name : "; file$ + Ext$; SPC(32); "Data Set "; SC%; " of "; SetCount%
PRINT "Operator : "; Operator$
PRINT
PRINT "              Sensor   Existing    Means       New          Out of Limit"
PRINT "  Sensor #    S/N    Gain Factor   Ratio   Relative Gain   Tolerance   2% Range"
PRINT "  --------   ------  -----------   ------  -------------   ---------   --------"
t8$ = "     #        ####      #.###     #.####       #.###         \  \        \  \"
FOR S% = 1 TO NumSensors%
    PRINT USING t8$; S%; SerialNum%(S%); RelGain#(S%); MeansRat#(SC%, S%); NewGain#(SC%, S%); TOL$(S%); RAN$(S%)
NEXT S%
PRINT
    IF Jnum1% > 0 THEN
     PRINT "* Warning: At least one sensor is outside the tolerance limit."
     PRINT "  Verify these results with an additional test!"
     END IF
    IF Jnum2% > 0 THEN
     PRINT "* Warning: At least one sensor is outside the 2% range limit."
     PRINT "  Notify Supervising Engineer after verifying with additional tests!"
     END IF
    IF Jnum1% > 0 THEN
     PRINT "* RESULTS INDICATE THAT THE SENSOR GAINS SHOULD BE RESET."
     END IF
    IF RepSens% > 0 THEN
       PRINT repm1$
       PRINT repm2$; USING "#.###"; NewGain#(SC%, RepSens%)
    END IF
END SUB
```

```
SUB GetFileName (FPath$, file$, Ext$) STATIC
  STATIC ZP$
  WindowType% = 1: CLS
  IF ZP$ = "" THEN ZP$ = "N"
  WFile$ = file$
  IF Ext$ <> "" THEN
    WFile$ = WFile$ + Ext$
  END IF
  CALL ScreenBorder
  CALL TitleColor
  Title$ = "  FWD Data File Selection  "
  TL% = LEN(Title$)
  Col% = ((80 - TL%) / 2) + 1
  LOCATE 2, Col%: PRINT Title$
  CALL NormalColor
  LOCATE 7, 7: PRINT "Directory path for data file: ";
  LOCATE 10, 7: PRINT "Do you want a list of data files for this path (Y/N) "
  LOCATE 13, 7: PRINT "Deflection Data File Name: "
  CALL HiliteColor
  LOCATE 7, 37: PRINT FPath$
  LOCATE 10, 60: PRINT ZP$
  LOCATE 13, 34: PRINT WFile$
  CALL NormalColor
  LOCATE 25, 4
  PRINT "         F10:Continue  "; CHR$(24); CHR$(25);
  PRINT "   Home  End     F7:Quit";
  Item% = 1
  MaxItem% = 3
  DO
    SELECT CASE Item%
      CASE 1
     OldPath$ = FPath$
     CALL GetString(7, 37, 32, FPath$, "L", 0, 0, "", "", ExitCode%)
     FPath$ = LTRIM$(RTRIM$(UCASE$(FPath$)))
     CurrDrive$ = CHR$(GetDrive%)
     CurrDir$ = GetDir$(CurrDrive$)
     CurrPath$ = CurrDrive$ + ":" + CurrDir$
     IF FPath$ <> "" THEN
       IF MID$(FPath$, 2, 1) = ":" THEN
         ChkDrive$ = LEFT$(FPath$, 1)
         IF NOT GoodDrive%(ChkDrive$) THEN       'check if valid drive
           REDIM PUText$(1)
           PUText$(1) = "Drive " + ChkDrive$ + " is not a valid choice... Please try another path."
           CALL PopupError
           ExitCode% = 0
           FPath$ = OldPath$
         ELSE                                    'drive OK, check dir
           IF RIGHT$(FPath$, 1) = "\" THEN
          FPath$ = LEFT$(FPath$, LEN(FPath$) - 1)
           END IF
           IF RIGHT$(FPath$, 1) = ":" THEN
          FPath$ = FPath$ + "\"
           END IF
           CALL CDir(FPath$, ErrFlag%)
           IF NOT ErrFlag% THEN                  'path OK
          CALL CDir(CurrPath$, ErrFlag%)      '  switch back to curr dir
           ELSE                                  'path not OK
          REDIM PUText$(2)
          PUText$(1) = "Error occurred switching to " + FPath$
          PUText$(2) = "May not be a valid path... Please try again."
          CALL PopupError
          ExitCode% = 0
          FPath$ = OldPath$
           END IF
         END IF
       ELSE                            'no drive letter in specified path
         IF RIGHT$(FPath$, 1) = "\" THEN
           FPath$ = LEFT$(FPath$, LEN(FPath$) - 1)
         END IF
```

```
    CALL CDir(FPath$, ErrFlag%)
    IF NOT ErrFlag% THEN                'path OK
      CALL CDir(CurrPath$, ErrFlag%)    '  switch back to curr dir
    ELSE                                'path not OK
      REDIM PUText$(2)
      PUText$(1) = "Error occurred switching to " + FPath$
      PUText$(2) = "May not be a valid path... Please try again."
      CALL PopupError
      ExitCode% = 0
      FPath$ = OldPath$
    END IF
  END IF
END IF
IF FPath$ <> "" AND RIGHT$(FPath$, 1) <> "\" THEN FPath$ = FPath$ + "\"
LOCATE 7, 37: PRINT FPath$
 CASE 2
DO
  OldZP$ = ZP$
  CALL GetString(10, 60, 1, ZP$, "L", 0, 0, "", "", ExitCode%)
  ZP$ = UCASE$(ZP$)
  SELECT CASE ZP$
    CASE "Y"
      ShowFiles$ = FPath$ + "*.*"
      NumMatchs% = FCount%(ShowFiles$)
      IF NumMatchs% > 0 THEN
     CALL DisplayFileNames(NumMatchs%, ShowFiles$, FPath$, file$, Ext$, ExitCode%, 0)
     WFile$ = file$ + Ext$
      ELSE
     REDIM PUText$(1)
     PUText$(1) = "No files found matching " + ShowFiles$
     CALL PopupError
     ZP$ = "N"
      END IF
    CASE "N"
      'go on
    CASE ELSE
      REDIM PUText$(1)
      PUText$(1) = "Please choose a Y or N only... try again!"
      CALL PopupError
      ExitCode% = 0
  END SELECT
  IF ExitCode% <> 0 THEN EXIT DO
LOOP
 CASE 3
DO
  OldWFile$ = WFile$
  CALL GetString(13, 34, 12, WFile$, "L", 0, 0, "", "", ExitCode%)
  WFile$ = LTRIM$(RTRIM$(UCASE$(WFile$)))
  LF = LEN(WFile$)
  FOR VV = 1 TO LF
    chk = ASC(MID$(WFile$, VV, 1))
    IF chk = 32 THEN
      REDIM PUText$(1)
      PUText$(1) = "SPACES ARE NOT ALLOWED IN FILE NAMES"
      CALL PopupError
      WFile$ = OldWFile$
      ExitCode% = 0
      EXIT FOR
    END IF
  NEXT VV
  IF ExitCode% <> 0 THEN
    SP% = INSTR(WFile$, ".")
    IF SP% <> 0 THEN
      file$ = LEFT$(WFile$, SP% - 1)
      Ext$ = LTRIM$(RTRIM$(RIGHT$(WFile$, LEN(WFile$) - (SP% - 1))))
    ELSE
      file$ = LTRIM$(RTRIM$(LEFT$(WFile$, 8)))
      Ext$ = ""
    END IF
```

```
         EXIT DO
       END IF
     LOOP
    END SELECT
    SELECT CASE ExitCode%                        'determine next action
      CASE 71            'home
     Item% = 1
      CASE 79            'end
     Item% = MaxItem%
      CASE 15, 75, 72       'Shift-Tab, left arrow, up arrow
     Item% = Item% - 1
      CASE 9, 13, 77, 80   'Tab, CR, right arrow, down arrow
     Item% = Item% + 1
      CASE 68            'F10:Continue
     IF file$ = "" THEN
       REDIM PUText$(1)
       PUText$(1) = "A file name must be entered... please try again!"
       CALL PopupError
       Item% = 3
     ELSE
       ChkName$ = FPath$ + file$ + Ext$
       IF NOT Exist%(ChkName$) THEN
         REDIM PUText$(1)
         PUText$(1) = "File not found...  Please try again."
         CALL PopupError
         file$ = ""
         Ext$ = ""
         ExitCode% = 0
         Item% = 3
       ELSE
         ExitCode% = 1
         EXIT SUB
       END IF
     END IF
      CASE 65            'F7: quit
     CLS
     PRINT : PRINT : PRINT "Program Execution Terminated by User"
     END
      CASE ELSE
      ' do nothing
    END SELECT
    IF Item% < 1 THEN Item% = 1
    IF Item% > MaxItem% THEN Item% = MaxItem%
  LOOP
END SUB
```

```
SUB GetSensorNum
CLS
Choice% = 1
DO
 REDIM Item$(NumSensors% + 2)
 Title$ = " Select Geophone Replaced "
 FOR i% = 1 TO NumSensors%
     Item$(i%) = "Sensor No." + STR$(SerialNum%(i%))
 NEXT i%
     Item$(8) = "No Replacement"
     Item$(9) = "Quit Program"
     CALL BarMenu(Title$, Item$(), Choice%, 0)
SELECT CASE Choice%
     CASE 1
          EXIT DO
     CASE 2
          EXIT DO
     CASE 3
          EXIT DO
     CASE 4
          EXIT DO
     CASE 5
          EXIT DO
     CASE 6
          EXIT DO
     CASE 7
          EXIT DO
     CASE 8
          EXIT DO
     CASE 9
          SCREEN 0: WIDTH 80, 25: CLS
          CLOSE : CALL NormalColor
          PRINT
          PRINT "Program terminated by the user"
          END
     CASE ELSE
          REDIM PUText$(1)
          PUText$(1) = "Please Select Sensors 1 through 7 only..."
          CALL PopupError
     END SELECT
LOOP
IF Choice% = 8 THEN
     RepSens% = 0
ELSE
     RepSens% = Choice%
END IF
CLS
CALL NormalColor
END SUB
```

```
SUB LatinPage1
SCREEN 0: WIDTH 80, 25: CLS
Year$ = MID$(FileDate$, 1, 2)
Month$ = MID$(FileDate$, 3, 2)
Day$ = MID$(FileDate$, 5, 2)
MDY$ = Month$ + "-" + Day$ + "-" + Year$

PRINT SPC(12); "SHRP FWD Relative Calibration - Latin Square ANOVA Table"
PRINT "FWD SN: "; FWDSN$; SPC(37); "Calibration Date: "; MDY$
PRINT "Data File Name : "; file$ + Ext$; SPC(32); "Data Set "; SC%; " of "; SetCount%
PRINT "Operator : "; Operator$
PRINT
'******************* Latin Square Design Analysis Output *****************
PRINT "     Variation      Sum of      Degrees of    Mean        Computed    Critical"
PRINT "     Source         Squares       Freedom     Square          f           f"
PRINT "     -----------    ---------   ----------    ---------   --------    --------"
Data$ = "     \         \    ##.##^^^^       ###       ##.##^^^^    ####.##      ##.##"
IF FLPos# > 1000 OR FLSet# > 1000 OR FLSens# > 1000 THEN
   Data$ = "     \         \    ##.##^^^^       ###       ##.##^^^^   ##.##^^^^     ##.##"
END IF
PRINT USING Data$; "Position"; CSNG(SSLPos#); DegFreeLPos%; CSNG(MSLPos#); CSNG(FLPos#); CritFLPos!
PRINT USING Data$; "Set"; CSNG(SSLSet#); DegFreeLSet%; CSNG(MSLSet#); CSNG(FLSet#); CritFLset!
PRINT USING Data$; "Sensor"; CSNG(SSLSens#); DegFreeLSens%; CSNG(MSLSens#); CSNG(FLSens#); CritFLSens!
PRINT USING Data$; "Error"; CSNG(SSLE#); DegFreeLE%; CSNG(MSLE#)
PRINT USING Data$; "TOTAL"; CSNG(SSLT#); DegFreeLT%
PRINT

IF Jnum1% > 0 THEN
 SELECT CASE LSAM$
  CASE "YNN"
PRINT "Gain adjustments are indicated and drop set is statistically significant at "
PRINT "the 5% level. 'Set' significance may be due to warming of the buffers or "
PRINT "consolidation of pavement materials during the test. A repeat calibration, "
PRINT "after conditioning the FWD buffers with 50 drops from height 3, is required"
PRINT "to confirm the need for gain adjustments. If the deflections from the last 10"
PRINT "drops vary by more than 1 mil (25.4 microns), repeat the calibration at a "
PRINT "new location."

CASE "YYN"
PRINT "Gain adjustments are indicated. Sensor and drop set are statistically "
PRINT "significant at the 5% level. A repeat calibration, after conditioning the FWD "
PRINT "buffers with 50 drops at height 3, is required to confirm the need for gain  "
PRINT "adjustments. If deflections for the last 10 drops vary by more than 1 mil     "
PRINT "(25.4 microns) repeat the calibration at a new location."

CASE "YNY"
PRINT "Gain adjustments are indicated. Set and stand position are statistically "
PRINT "significant at the 5% level. A repeat calibration, after conditioning the FWD"
PRINT "buffers with 50 drops at height 3, is required to confirm the need for gain  "
PRINT "adjustments. When doing the calibration, extra care should be taken to seat  "
PRINT "the geophones properly, and hold the stand vertically, with a moderate level "
PRINT "of downward pressure. If deflections for the last 10 drops vary by more than "
PRINT "1 mil (25.4 microns) repeat the calibration at a new location."

CASE "YYY"
PRINT "Gain adjustments are indicated. Set, sensor, and stand position are      "
PRINT "statistically significant at the 5% level. A repeat calibration is required  "
PRINT "after conditioning the FWD buffers with 50 drops at height 3 for adjustments."
PRINT "When doing the calibration, extra care should be taken to properly seat the  "
PRINT "geophones, and hold the stand vertically, with a moderate level of downward  "
PRINT "pressure. If deflections for the last 10 drops vary by more than 1  "
PRINT "mil (25.4 microns) repeat the calibration at a new location."

CASE "NNN"
PRINT "Nothing is significant. Gain adjustments are indicated. A repeat calibration"
PRINT "is required to confirm the need for adjustments."

CASE "NYN"
PRINT "The gain ratios and the statistical results indicate that gain adjustments"
```

```
PRINT "are needed. A repeat calibration is required to confirm the need for gain"
PRINT "adjustments."

CASE "NNY"
PRINT "Gain adjustments are indicated. Stand position is statistically          "
PRINT "significant at the 5% level. A repeat calibration is required to confirm    "
PRINT "the need for gain adjustments. Care should be taken to ensure that the       "
PRINT "geophone bases are clean, firmly seated, and that the stand is held      "
PRINT "vertically with moderate downward pressure."

CASE "NYY"
PRINT "Gain adjustments are indicated. Sensor and Stand position are statistically"
PRINT "significant at the 5% level. A repeat calibration is required to confirm    "
PRINT "the need for gain adjustments. Care should be taken to ensure that the       "
PRINT "geophone bases are clean, firmly seated, and that the stand is held      "
PRINT "vertically with moderate downward pressure."

CASE ELSE
END SELECT
ELSE
SELECT CASE LSAM$

CASE "YNN"
PRINT "No gain adjustments are indicated, but drop set is statistically significant"
PRINT "at the 5% level. This can be due to warming of the buffers or consolidation "
PRINT "of pavement materials during the test. Review the data carefully. If anything"
PRINT "appears suspect, repeat the calibration after conditioning the FWD buffers with"
PRINT "50 drops from height 3. If the deflections from the last 10 drops vary by more"
PRINT "than 1 mil (25.4 microns), repeat the calibration at a new location."

CASE "YYN"
PRINT "Sensor and drop set are statistically significant at the 5% level, but"
PRINT "gain adjustments are not indicated. Review the data carefully. If anything  "
PRINT "appears suspect, repeat the calibration after conditioning the FWD buffers with"
PRINT "50 drops from height 3. If the deflections from the last 10 drops vary by more"
PRINT "than 1 mil (25.4 microns), repeat the calibration at a new location."

CASE "YNY"
PRINT "Set and stand position are statistically significant at the 5% level, but    "
PRINT "gain adjustments are not indicated. Examine the data carefully. If anything"
PRINT "appears suspect, repeat the calibration after conditioning the FWD buffers with"
PRINT "50 drops from height 3. When doing the calibration, extra care should be taken to"
PRINT "properly seat the geophones and hold the stand vertically with moderate downward"
PRINT "pressure. If deflections for the last 10 drops vary by more than 1 mil"
PRINT "(25.4 microns) repeat the calibration at a new location."

CASE "YYY"
PRINT "Set, sensor, and stand position are statistically significant at the 5% level."
PRINT "Although gain changes are not indicated, these results are suspect. A repeat "
PRINT "calibration is required after conditioning with 50 drops at height 3."
PRINT "Extra care should be taken to properly seat the geophones and hold the stand"
PRINT "vertically with moderate downward pressure. If deflections for the last 10 drops"
PRINT "If vary by more than 1 mil (25.4  microns) repeat the calibration at a new"
PRINT "location. If this message appears in subsequent tests, contact your supervising"
PRINT "engineer for further instructions. "

CASE "NNN"
PRINT "Results indicate that no gain adjustments are needed."

CASE "NYN"
PRINT "Sensor is statistically significant at the 5% level, but gain adjustments are"
PRINT "not indicated. Test results should be carefully reviewed. If anything appears"
PRINT "suspect, repeat the calibration. Otherwise, these results are acceptable."

CASE "NNY"
PRINT "Gains do not needed to be adjusted, but stand position is statistically      "
PRINT "significant at the 5% level. This may be caused by failure to keep the stand "
PRINT "vertical, or improper seating of the geophones. In the future, care should be"
PRINT "taken to ensure that the geophone bases are clean and well seated, and the   "
```

```
PRINT "stand is kept vertical with moderate downward pressure."

CASE "NYY"
PRINT "Sensor and stand position are statistically significant at the 5% level, but "
PRINT "gain adjustments are not indicated. Review calibration results carefully.    "
PRINT "If anything appears suspect, repeat the calibration, taking care to ensure "
PRINT "that geophone bases are clean and properly seated, and the stand is kept"
PRINT "vertical with moderate downward pressure."

CASE ELSE
END SELECT
END IF
'******************* Cochran test results *************************
IF ProblemExist% = 1 THEN
   PRINT "** Cochran test variance between geophones indicates variance for Sensor No. "; BigDef!
   PRINT "   is significantly larger than the other sensors. Please consult the output file."
END IF
END SUB
```

```
SUB LatinSqDesign
'***********************************************************************
'             Subprogram for Latin Square Design analysis
'***********************************************************************
DIM Tj#(7), Tk#(7), Tij#(7, 7), Tik#(7, 7), Tjk#(7, 7), Tijk#(7, 7, 7)
DIM SSumTi#(7), SSumTj#(7), SSumTk#(7), SetSum(7), TotalLoad(35)
'**************** Initialize Variables to Zero ***************
SumTotal# = 0
TotalSS# = 0
FOR i% = 1 TO NumSensors%
   Ti#(i%) = 0
   MeanDef#(i%) = 0
   MeanPos#(i%) = 0
   MeanSet#(i%) = 0
FOR J% = 1 TO NumSets%
   MeanBySet!(i%, J%) = 0
NEXT J%
NEXT i%
'**************** Compute main statistics for the analysis ***************
FOR i% = 1 TO NumSensors%
    FOR J% = 1 TO NumPositions%
        FOR K% = 1 TO NumSets%
            FOR L% = 1 TO NumReps%
          SumTotal# = SumTotal# + DefData!(i%, J%, K%, L%)
          TotalSS# = TotalSS# + (DefData!(i%, J%, K%, L%)) ^ 2
          Ti#(i%) = Ti#(i%) + DefData!(i%, J%, K%, L%)
          SSumTi#(i%) = SSumTi#(i%) + (DefData!(i%, J%, K%, L%)) ^ 2
          Tj#(J%) = Tj#(J%) + DefData!(i%, J%, K%, L%)
          SSumTj#(J%) = SSumTj#(J%) + (DefData!(i%, J%, K%, L%)) ^ 2
          Tk#(K%) = Tk#(K%) + DefData!(i%, J%, K%, L%)
          Tij#(i%, J%) = Tij#(i%, J%) + DefData!(i%, J%, K%, L%)
          Tik#(i%, K%) = Tik#(i%, K%) + DefData!(i%, J%, K%, L%)
          Tjk#(J%, K%) = Tjk#(J%, K%) + DefData!(i%, J%, K%, L%)
          Tijk#(i%, J%, K%) = Tijk#(i%, J%, K%) + DefData!(i%, J%, K%, L%)
         NEXT L%
     NEXT K%
   NEXT J%
NEXT i%
SumTi# = 0
SumTj# = 0
SumTk# = 0
SumTij# = 0
SumTik# = 0
SumTjk# = 0
FOR i% = 1 TO NumSensors%
    SumTi# = SumTi# + Ti#(i%) ^ 2
    SumTj# = SumTj# + Tj#(i%) ^ 2
    SumTk# = SumTk# + Tk#(i%) ^ 2
    FOR J% = 1 TO NumPositions%
     SumTij# = SumTij# + Tij#(i%, J%) ^ 2
     SumTik# = SumTik# + Tik#(i%, J%) ^ 2
     SumTjk# = SumTjk# + Tjk#(i%, J%) ^ 2
    NEXT J%
NEXT i%
'**************** Compute Std. Dev. for the data set ****************
FOR i% = 1 TO NumSensors%
    FOR K% = 1 TO NumSets%
     MeanBySet!(i%, K%) = Tik#(i%, K%) / NumReps%
    NEXT K%
     MeanDef#(i%) = Ti#(i%) / (NumSensors% * NumReps%)
     MeanPos#(i%) = Tj#(i%) / (NumPositions% * NumReps%)
     MeanSet#(i%) = Tk#(i%) / (NumSets% * NumReps%)
NEXT i%

SSumLoad# = 0
TotalAllLoad# = 0
Set% = 1
FOR D% = 1 TO NumSets% * NumReps%
    SSumLoad# = SSumLoad# + LoadData!(D%) ^ 2
```

```
        TotalAllLoad# = TotalAllLoad# + LoadData!(D%)
        TotalLoad(Set%) = TotalLoad(Set%) + LoadData!(D%)
        IF D% MOD 5 = 0 THEN Set% = Set% + 1: MeanLoad!(Set% - 1) = TotalLoad(Set% - 1) / 5
    NEXT D%

         MeanAllLoad! = TotalAllLoad# / (NumSets% * NumReps%)
         StdDevAllLoad! = SQR((SSumLoad# - ((NumSets% * NumReps%) * (MeanAllLoad!) ^ 2)) / (NumSets% * NumReps% -
    1))
         CVAllLoad! = (StdDevAllLoad! / MeanAllLoad!) * 100
         MeanAllDef# = SumTotal# / (NumSensors% * NumSets% * NumReps%)
         StdDevAllDef! = SQR((TotalSS# - (NumPositions% * NumSets% * NumReps%) * ((SumTotal# / (NumPositions% *
    NumSets% * NumReps%)) ^ 2)) / (NumPositions% * NumSets% * NumReps% - 1))
         CVAllDef! = (StdDevAllDef! / MeanAllDef#) * 100

    FOR i% = 1 TO NumSensors%
        StdDevDef!(i%) = SQR((SSumTi#(i%) - ((NumSensors% * NumReps%) * (Ti#(i%) / (NumSensors% * NumReps%)) ^ 2))
    / (NumSensors% * NumReps% - 1))
        StdDevPos!(i%) = SQR((SSumTj#(i%) - ((NumPositions% * NumReps%) * (MeanPos#(i%)) ^ 2)) / (NumPositions% *
    NumReps% - 1))
        CVDef!(i%) = (StdDevDef!(i%) / MeanDef#(i%)) * 100
        CVPos!(i%) = (StdDevPos!(i%) / MeanPos#(i%)) * 100
        MeansRat#(SC%, i%) = MeanAllDef# / MeanDef#(i%)
        NewGain#(SC%, i%) = MeansRat#(SC%, i%) * RelGain#(i%)
    NEXT i%

    '*************** Compute final LATIN-SQARE statistics *****************

         NegTerm# = (SumTotal# ^ 2) / (NumPositions% * NumSets% * NumReps%)
         SSLT# = TotalSS# - NegTerm#
         SSLPos# = SumTj# / (NumPositions% * NumReps%) - NegTerm#
         SSLSet# = SumTk# / (NumSets% * NumReps%) - NegTerm#
         SSLSens# = SumTi# / (NumSensors% * NumReps%) - NegTerm#
         SSLE# = SSLT# - SSLPos# - SSLSet# - SSLSens#
         DegFreeLPos% = NumPositions% - 1
         DegFreeLSet% = NumSets% - 1
         DegFreeLSens% = NumSensors% - 1
         DegFreeLT% = (NumPositions% * NumSets% * NumReps%) - 1
         DegFreeLE% = DegFreeLT% - DegFreeLPos% - DegFreeLSet% - DegFreeLSens%

         MSLPos# = SSLPos# / DegFreeLPos%
         MSLSet# = SSLSet# / DegFreeLSet%
         MSLSens# = SSLSens# / DegFreeLSens%
         MSLE# = SSLE# / DegFreeLE%
         FLPos# = MSLPos# / MSLE#
         FLSet# = MSLSet# / MSLE#
         FLSens# = MSLSens# / MSLE#
    END SUB
```

```
SUB OutputToFile
DIM Avg$(7)
Year$ = MID$(FileDate$, 1, 2)
Month$ = MID$(FileDate$, 3, 2)
Day$ = MID$(FileDate$, 5, 2)
MDY$ = Month$ + "-" + Day$ + "-" + Year$
Jnum1% = 0
Jnum2% = 0
FOR i% = 1 TO NumSensors%
    IF ABS(1 - MeansRat#(SC%, i%)) > .003 THEN
          TOL$(i%) = "YES"
          Jnum1% = Jnum1% + 1
     ELSE
          TOL$(i%) = " NO"
    END IF
    IF ABS(1 - NewGain#(SC%, i%)) > .02 THEN
          RAN$(i%) = "YES"
          Jnum2% = Jnum2% + 1
     ELSE
          RAN$(i%) = " NO"
    END IF
NEXT i%
'************************** Geophone Calibration ******************
PRINT #2, SPC(18); "SHRP FWD Relative Calibration - Gains Table"
PRINT #2, "FWD SN: "; FWDSN$; SPC(37); "Calibration Date: "; MDY$
PRINT #2, "Data File Name : "; file$ + Ext$; SPC(32); "Data Set "; SC%; " of "; SetCount%
PRINT #2, "Operator : "; Operator$
PRINT #2,
PRINT #2, "             Sensor    Existing     Means        New          Out of Limit"
PRINT #2, "  Sensor #    S/N     Gain Factor   Ratio   Relative Gain   Tolerance   2% Range"
PRINT #2, "  --------   ------   -----------   ------  -------------   ---------   --------"
t8$ = "     #       ####       #.###       #.####       #.###          \   \      \   \"
FOR S% = 1 TO NumSensors%
    PRINT #2, USING t8$; S%; SerialNum%(S%); RelGain#(S%); MeansRat#(SC%, S%); NewGain#(SC%, S%); TOL$(S%);
RAN$(S%)
NEXT S%
PRINT #2,
    IF Jnum1% > 0 THEN
     PRINT #2, "* Warning: At least one sensor is outside the tolerance limit."
     PRINT #2, "  Verify these results with additional tests!"
     END IF
    IF Jnum2% > 0 THEN
     PRINT #2, "* Warning: At least one sensor is outside the 2% range limit."
     PRINT #2, "  Notify Supervising Engineer after verifying with additional tests!"
     END IF
    IF Jnum1% > 0 THEN
       PRINT #2,
       PRINT #2, "* RESULTS INDICATE THAT THE SENSOR GAINS SHOULD BE RESET."
     END IF
    IF RepSens% > 0 THEN
       PRINT #2,
       PRINT #2, repm1$
       PRINT #2, repm2$; USING "#.###"; NewGain#(SC%, RepSens%)
    END IF
PRINT #2,
PRINT #2,
IF Jnum1% > 0 THEN
     '************************** Geophone Gain Adjustments ******************
     PRINT #2, SPC(16); "SHRP FWD Relative Calibration - Gain adjustments"
     PRINT #2,
     PRINT #2, "Results of this test indicate the possible need to adjust the gains."
     PRINT #2, "This should be confirmed with a repeat test."
     PRINT #2,
     PRINT #2, "Gain adjustment should be performed when the New Gain Factors for two"
     PRINT #2, "independent calibrations are within +/- 0.002 of each other."
     PRINT #2,
     PRINT #2, "Gain adjustments should be made ONLY to the out of range geophone(s)."
     PRINT #2,
     PRINT #2, "After adjusting any gain setting, the relative calibration test must be"
```

```
            PRINT #2, "repeated to confirm that all sensors are within tolerance."
        END IF
        PRINT #2,
        PRINT #2,
        PRINT #2, CHR$(12)
        '******************** Latin Square Design Analysis Output *****************
        PRINT #2, SPC(12); "SHRP FWD Relative Calibration - Latin Square ANOVA Table"
        PRINT #2, "FWD SN: "; FWDSN$; SPC(37); "Calibration Date: "; MDY$
        PRINT #2, "Data File Name : "; file$ + Ext$; SPC(32); "Data Set "; SC%; " of "; SetCount%
        PRINT #2, "Operator : "; Operator$
        PRINT #2,
        PRINT #2, "     Variation       Sum of       Degrees of    Mean         Computed    Critical"
        PRINT #2, "     Source          Squares        Freedom     Square           f           f"
        PRINT #2, "     -----------     ---------    ----------    ---------    --------    --------"
        Data$ = "     \          \     ##.##^^^^       ###       ##.##^^^^     ####.##      ##.##"
        IF FLPos# > 1000 OR FLSet# > 1000 OR FLSens# > 1000 THEN
           Data$ = "     \          \     ##.##^^^^       ###       ##.##^^^^    ##.##^^^^    ##.##"
        END IF
        PRINT #2, USING Data$; "Position"; CSNG(SSLPos#); DegFreeLPos%; CSNG(MSLPos#); CSNG(FLPos#); CritFLPos!
        PRINT #2, USING Data$; "Set"; CSNG(SSLSet#); DegFreeLSet%; CSNG(MSLSet#); CSNG(FLSet#); CritFLset!
        PRINT #2, USING Data$; "Sensor"; CSNG(SSLSens#); DegFreeLSens%; CSNG(MSLSens#); CSNG(FLSens#); CritFLSens!
        PRINT #2, USING Data$; "Error"; CSNG(SSLE#); DegFreeLE%; CSNG(MSLE#)
        PRINT #2, USING Data$; "TOTAL"; CSNG(SSLT#); DegFreeLT%
        PRINT #2,

        IF FLSet# - CritFLset! > 0 THEN
             IF (FLSens# - CritFLSens! > 0) THEN
                  IF FLPos# - CritFLPos! > 0 THEN
                       LSAM$ = "YYY"
                  ELSE
                       LSAM$ = "YYN"
                  END IF
             ELSE
                  IF FLPos# - CritFLPos! > 0 THEN
                       LSAM$ = "YNY"
                  ELSE
                       LSAM$ = "YNN"
                  END IF
             END IF
        ELSE
             IF (FLSens# - CritFLSens! > 0) THEN
                  IF FLPos# - CritFLPos! > 0 THEN
                       LSAM$ = "NYY"
                  ELSE
                       LSAM$ = "NYN"
                  END IF
             ELSE
                  IF FLPos# - CritFLPos! > 0 THEN
                       LSAM$ = "NNY"
                  ELSE
                       LSAM$ = "NNN"
                  END IF
             END IF
        END IF
        IF FLSens# - CritFLSens! < 0 AND FLPos# - CritFLPos < 0 AND FLSet# - CritFLset < 0 THEN
           LSAM$ = "NNN"
        END IF

        IF Jnum1% > 0 THEN
         SELECT CASE LSAM$
          CASE "YNN"
        PRINT #2, "Gain adjustments are indicated, and drop set is statistically significant at "
        PRINT #2, "the 5% level. 'Set' significance may be due to warming of the buffers or     "
        PRINT #2, "consolidation of pavement materials during the test. A repeat calibration,   "
        PRINT #2, "after conditioning the FWD buffers with 50 drops from height 3, is required  "
        PRINT #2, "to confirm the need for gain adjustments. If the deflections from the last 10"
        PRINT #2, "drops vary by more than 1 mil (25.4 microns), repeat the calibration at a    "
        PRINT #2, "new location."
```

```
CASE "YYN"
PRINT #2, "Gain adjustments are indicated, and sensor and drop set are statistically   "
PRINT #2, "significant at the 5% level. A repeat calibration, after conditioning the FWD "
PRINT #2, "buffers with 50 drops at height 3, is required to confirm the need for gain  "
PRINT #2, "adjustments. If deflections for the last 10 drops vary by more than 1 mil     "
PRINT #2, "(25.4 microns) repeat the calibration at a new location."

CASE "YNY"
PRINT #2, "Gain adjustments are indicated, and set and stand position are statistically "
PRINT #2, "significant at the 5% level. A repeat calibration, after conditioning the FWD"
PRINT #2, "buffers with 50 drops at height 3, is required to confirm the need for gain  "
PRINT #2, "adjustments. When doing the calibration, extra care should be taken to seat  "
PRINT #2, "the geophones properly, and hold the stand vertically, with a moderate level "
PRINT #2, "of downward pressure. If deflections for the last 10 drops vary by more than "
PRINT #2, "1 mil (25.4 microns) repeat the calibration at a new location."

CASE "YYY"
PRINT #2, "Gain adjustments are indicated, and set, sensor, and stand position are      "
PRINT #2, "statistically significant at the 5% level. A repeat calibration is required  "
PRINT #2, "after conditioning the FWD buffers with 50 drops at height 3 for adjustments."
PRINT #2, "When doing the calibration, extra care should be taken to properly seat the  "
PRINT #2, "geophones, and hold the stand vertically, with a moderate level of downward  "
PRINT #2, "pressure. If deflections for the last 10 drops vary by more than 1  "
PRINT #2, "mil (25.4 microns) repeat the calibration at a new location."

CASE "NNN"
PRINT #2, "Nothing is significant. Gain adjustments are indicated. A repeat calibration   "
PRINT #2, "is required to confirm the need for adjustments."

CASE "NYN"
PRINT #2, "Both the ratios and the statistical results indicate the gain adjustments   "
PRINT #2, "are needed. A repeat calibration is required to confirm  the need for gain   "
PRINT #2, "adjustments."

CASE "NNY"
PRINT #2, "Gain adjustments are indicated, and stand position is statistically          "
PRINT #2, "significant at the 5% level. A repeat calibration is required to confirm     "
PRINT #2, "the need for gain adjustments. Care should be taken to ensure that the       "
PRINT #2, "geophone bases are clean, and firmly seated, and that the stand is held      "
PRINT #2, "vertically with moderate downward pressure."

CASE "NYY"
PRINT #2, "Gain adjustments are indicated, and sensor and stand position is statistically"
PRINT #2, "significant at the 5% level. A repeat calibration is required to confirm     "
PRINT #2, "the need for gain adjustments. Care should be taken to ensure that the       "
PRINT #2, "geophone bases are clean, and firmly seated, and that the stand is held      "
PRINT #2, "vertically with moderate downward pressure."

CASE ELSE
END SELECT
ELSE
SELECT CASE LSAM$

CASE "YNN"
PRINT #2, "No gain adjustments are indicated, but drop set is statistically significant "
PRINT #2, "at the 5% level. This can be due to warming of the buffers or consolidation  "
PRINT #2, "of pavement materials during the test. Review the data carefully. If anything"
PRINT #2, "is suspect, repeat the calibration after conditioning the FWD buffers with 50"
PRINT #2, "drops from height 3. If the deflections from the last 10 drops vary by more  "
PRINT #2, "than 1 mil (25.4 microns), repeat the calibration at a new location."

CASE "YYN"
PRINT #2, "Sensor and drop set are statistically significant at the 5% level, but"
PRINT #2, "gain adjustments are not indicated. Review the data carefully. If anything   "
PRINT #2, "is suspect, repeat the calibration after conditioning the FWD buffers with 50"
PRINT #2, "drops from height 3. If the deflections from the last 10 drops vary by more  "
PRINT #2, "than 1 mil (25.4 microns), repeat the calibration at a new location."

CASE "YNY"
```

```
PRINT #2, "Set and stand position are statistically significant at the 5% level, but gain"
PRINT #2, "adjustments are not indicated. Examine the data carefully. If anything appears"
PRINT #2, "suspect, repeat the calibration after conditioning the FWD buffers with 50"
PRINT #2, "drops from height 3. When doing the calibration, extra care should be taken to"
PRINT #2, "properly seat the geophones, and hold the stand vertically, with a moderate  "
PRINT #2, "level of pressure. If deflections for the last 10 drops vary by more than 1  "
PRINT #2, "1 mil (25.4 microns) repeat the calibration at a new location."

CASE "YYY"
PRINT #2, "Set, sensor, and stand position are statistically significant at the 5% level."
PRINT #2, "Although gain changes are not indicated, these results are suspect. A repeat "
PRINT #2, "calibration is required after conditioning with 50 drops at height 3. When   "
PRINT #2, "doing the calibration, extra care should be taken to properly seat the       "
PRINT #2, "geophones, and hold the stand vertically, with a moderate level of pressure. "
PRINT #2, "If deflections for the last 10 drops vary by more than 1 mil (25.4  microns) "
PRINT #2, "repeat the calibration at a new location. If this message appears  in the  "
PRINT #2, "subsequent tests, contact the supervising engineer for further instructions. "

CASE "NNN"
PRINT #2, "Results indicate that no gain adjustments are needed."

CASE "NYN"
PRINT #2, "Sensor is statistically significant at the 5% level, but gain do not needed  "
PRINT #2, "to be adjusted. Test results should be reviewed carefully. If anything is      "
PRINT #2, "suspect, repeat the calibration. Otherwise, these results are acceptable."

CASE "NNY"
PRINT #2, "Gains do not needed to be adjusted, but stand position is statistically      "
PRINT #2, "significant at the 5% level. This may be caused by failure to keep the stand "
PRINT #2, "vertical, or improper seating of the geophones. In the future, care should be"
PRINT #2, "taken to ensure that the geophone bases are clean and well seated, and the   "
PRINT #2, "stand is kept vertical, with a moderate downward pressure."

CASE "NYY"
PRINT #2, "Sensor and stand position are statistically significant at the 5% level, but "
PRINT #2, "gain adjustments are not indicated. Review calibration results carefully.    "
PRINT #2, "If anything is suspect, repeat the calibration, taking care to ensure that   "
PRINT #2, "geophone bases are clean, and properly seated, and the stand is kept vertical"
PRINT #2, "with moderate downward force applied."

CASE ELSE
END SELECT
END IF
'******************** Cochran test results *************************
IF ProblemExist% = 1 THEN
   PRINT #2, "* Results of Cochran Test on Significance of Variance Between Geophones"
   PRINT #2,
   PRINT #2, "  The variance for Sensor No. "; BigDef!; " is significantly larger than"
   PRINT #2, "  the other sensors. This could be a result of incorrect seating of the"
   PRINT #2, "  sensor in the stand OR an indication that this sensor is bad and needs"
   PRINT #2, "  to be replaced. Please confirm with additional tests."
END IF
PRINT #2, CHR$(12)
' ****************************** Data Replay ******************************
PRINT #2, SPC(23); "Relative Calibration - Input Data"
PRINT #2, "FWD SN: "; FWDSN$; SPC(37); "Calibration Date: "; MDY$
PRINT #2, "Data File Name : "; file$ + Ext$; SPC(32); "Data Set "; SC%; " of "; SetCount%
PRINT #2, "Operator : "; Operator$
PRINT #2,
PRINT #2, "      Set  Drop   Load          Deflections, 0.001 inches [mils]"
PRINT #2, "       #     #     lbf     Df1    Df2    Df3    Df4    Df5    Df6    Df7"
PRINT #2, "      ---  ----  ------   -----  -----  -----  -----  -----  -----  -----"
t0$ = "       #     #   ##,###   ##.##  ##.##  ##.##  ##.##  ##.##  ##.##  ##.##"
Lin% = 1
Set% = 1
FOR W% = 1 TO NumSets * NumReps%
    drop% = (W% - (Set% - 1) * 5)
    PRINT #2, USING t0$; Set%; drop%; LoadData!(W%); OutDef!(W%, 1); OutDef!(W%, 2); OutDef!(W%, 3); OutDef!(W%,
4); OutDef!(W%, 5); OutDef!(W%, 6); OutDef!(W%, 7)
```

```
        IF W% MOD 5 = 0 THEN
           Set% = Set% + 1
           PRINT #2,
        END IF
     NEXT W%
     PRINT #2,
     PRINT #2, CHR$(12)
     ' ************************** Summary Statistics ****************************
     ' ******************************** Page 4 **********************************
     PRINT #2, SPC(24); "Relative Calibration - Summary Statistics"
     PRINT #2, "FWD SN: "; FWDSN$; SPC(37); "Calibration Date: "; MDY$
     PRINT #2, "Data File Name : "; file$ + Ext$; SPC(32); "Data Set "; SC%; " of "; SetCount%
     PRINT #2, "Operator : "; Operator$
     PRINT #2,
     PRINT #2, "            Load      Df1     Df2     Df3     Df4     Df5     Df6     Df7    Df1-7"
     PRINT #2, "            ------   -----   -----   -----   -----   -----   -----   -----   -----"
     t1$ = "  \        \  ##,###  ##.##  ##.##  ##.##  ##.##  ##.##  ##.##  ##.##   ##.##"
     t2$ = "  \        \  ##,###  ##.##  ##.##  ##.##  ##.##  ##.##  ##.##  ##.##   ##.##"
     t3$ = "  \         \  #,###  ##.##  ##.##  ##.##  ##.##  ##.##  ##.##  ##.##   #.###"
     t4$ = "  \         \  ##.##  ##.##  ##.##  ##.##  ##.##  ##.##  ##.##  ##.##   ##.##"
     t5$ = "  \       \  ##.##  ##.##  ##.##  ##.##  ##.##  ##.##  ##.##"
     t6$ = "  \       \   #.##   #.##   #.##   #.##   #.##   #.##   #.##"
     t7$ = "  \       \  ##.##  ##.##  ##.##  ##.##  ##.##  ##.##  ##.##"
     FOR N% = 1 TO 7
        Avg$(N%) = "Set" + STR$(N%) + " Avg"
        PRINT #2, USING t1$; Avg$(N%); MeanLoad!(N%); MeanBySet!(1, N%); MeanBySet!(2, N%); MeanBySet!(3, N%);
     MeanBySet!(4, N%); MeanBySet!(5, N%); MeanBySet!(6, N%); MeanBySet!(7, N%); MeanSet#(N%)
     NEXT N%
     PRINT #2,
     PRINT #2,
     PRINT #2, "                              Overall Statistics"
     PRINT #2,
     PRINT #2, "             Load     Df1     Df2     Df3     Df4     Df5     Df6     Df7     Df1-7"
     PRINT #2, "             ------   -----   -----   -----   -----   -----   -----   -----   -----"
     PRINT #2, USING t2$; "Average"; MeanAllLoad!; MeanDef#(1); MeanDef#(2); MeanDef#(3); MeanDef#(4); MeanDef#(5);
     MeanDef#(6); MeanDef#(7); MeanAllDef#
     PRINT #2, USING t3$; "Std Dev"; StdDevAllLoad!; StdDevDef!(1); StdDevDef!(2); StdDevDef!(3); StdDevDef!(4);
     StdDevDef!(5); StdDevDef!(6); StdDevDef!(7); StdDevAllDef!
     PRINT #2, USING t4$; "COV, %"; CVAllLoad!; CVDef!(1); CVDef!(2); CVDef!(3); CVDef!(4); CVDef!(5); CVDef!(6);
     CVDef!(7); CVAllDe
     PRINT #2,
     PRINT #2,
     PRINT #2, "                         Position in Stand"
     PRINT #2, "             1       2       3       4       5       6       7"
     PRINT #2, "           -----   -----   -----   -----   -----   -----   -----"
     PRINT #2, USING t5$; "Avg Df "; MeanPos#(1); MeanPos#(2); MeanPos#(3); MeanPos#(4); MeanPos#(5); MeanPos#(6);
     MeanPos#(7)
     PRINT #2, USING t6$; "Std Dev"; StdDevPos!(1); StdDevPos!(2); StdDevPos!(3); StdDevPos!(4); StdDevPos!(5);
     StdDevPos!(6); StdDevPos!(7)
     PRINT #2, USING t7$; "COV, % "; CVPos!(1); CVPos!(2); CVPos!(3); CVPos!(4); CVPos!(5); CVPos!(6); CVPos!(7)
     PRINT #2,
     PRINT #2, CHR$(12)
     END SUB
```

```
SUB Quit STATIC
  CLOSE
  COLOR 7, 0, 0
  CLS
  PRINT : PRINT
  IF file$ <> "" THEN PRINT "          Output results are contained in file: "; FPath$ + file$ + OExt$
  PRINT
  END
END SUB
```

```
SUB ReadNextLine (DataType%, LineLength%) STATIC
  STATIC OldDataType%
  IF NOT EOF(1) THEN
    LINE INPUT #1, LineData$
    DataType$ = LEFT$(LineData$, 1)
    DataType% = INSTR("SB'E*- 1234567890", DataType$)
    OldDataType% = DataType%
    LineCounter& = LineCounter& + 1
    IF DataType% = 4 THEN
      IF UCASE$(LEFT$(LineData$, 3)) = "EOF" THEN
     DataType% = -1
      END IF
    END IF
  ELSE
    DataType% = -1                      'end of file occurred
  END IF
END SUB
```

```
SUB ReadPeaks
    SetCount% = SetCount% + 1
    FOR K% = 1 TO InitNumPeaks%
    CALL ReadNextLine(DataType%, LineLength%)
    SELECT CASE DataType%
      CASE -1                           'end of file encountered
     EXIT FOR
      CASE 0, 4                         'unknown data in line #xxxx
     EXIT FOR
      CASE 1
     CALL ReadPeaks
     EXIT SUB
      CASE 2                            'start of history block
     EXIT SUB
      CASE 3                            'found a comment
     EXIT FOR
      CASE 5                            'found subsection id
     EXIT FOR
      CASE ELSE                         'normal processing
          DataSet$(SetCount%, K%) = LineData$
    END SELECT
  NEXT K%
END SUB
```

```
SUB ReplaceSensor
     IF RepSens% < 1 OR RepSens% > 7 THEN
          EXIT SUB
     END IF
     MeanRepDef# = (SumTotal# - Ti#(RepSens%)) / ((NumSensors% - 1) * NumSensors% * NumReps%)
     FOR S% = 1 TO NumSensors%
          MeansRat#(SC%, S%) = MeanRepDef# / MeanDef#(S%)
          NewGain#(SC%, S%) = MeansRat#(SC%, S%) * RelGain#(S%)
     NEXT S%
     IF ABS(1 - MeansRat#(SC%, RepSens%)) > .003 THEN
        repm1$ = "* Means Ratio for REPLACED Sensor No." + STR$(SerialNum%(RepSens%)) + " is outside the
tolerance range."
        repm2$ = "* New Relative Gain for REPLACED Sensor No." + STR$(SerialNum%(RepSens%)) + " is "
     ELSE
        repm1$ = "* Means Ratio for REPLACED Sensor No." + STR$(SerialNum%(RepSens%)) + " is within the
tolerance range."
        repm2$ = "* New Relative Gain for REPLACED Sensor No." + STR$(SerialNum%(RepSens%)) + " is "
     END IF
END SUB
```

```
SUB SelectAnalysis
CLS
Choice% = 1
IF SetCount% > 1 THEN
   Choice% = 3
END IF
DO
     REDIM Item$(4)
     Title$ = " Select Analysis Type "
     Item$(1) = "Standard Analysis "
     Item$(2) = "Replace a Geophone "
     Item$(3) = "Reference-Relative Calibration (3 data sets in file)"
     Item$(4) = "Quit Program        "
     CALL BarMenu(Title$, Item$(), Choice%, 0)
     SELECT CASE Choice%
          CASE 1
               Analysis$ = "S"
               EXIT DO
          CASE 2
               Analysis$ = "G"
               EXIT DO
          CASE 3
               Analysis$ = "R"
               EXIT DO
          CASE 4
               SCREEN 0: WIDTH 80, 25: CLS
               CLOSE : CALL NormalColor
               PRINT
               PRINT "Program terminated by the user"
               END
          CASE ELSE
               REDIM PUText$(1)
               PUText$(1) = "Please Select an Option"
               CALL PopupError
     END SELECT
LOOP
END SUB
```

```
SUB StartAnalysis
FOR Sets% = 1 TO SetCount%
SCREEN 0: WIDTH 80, 25: CLS : CALL NormalColor
IF Analysis$ = "S" THEN
     anat1$ = "Standard relative calibration analysis being performed"
     anat2$ = "on data set " + STR$(Sets%) + " in file " + file$ + Ext$
     anat1 = LEN(anat1$): LOCATE 12, 40 - anat1 / 2: PRINT anat1$
     anat2 = LEN(anat2$): LOCATE 13, 40 - anat2 / 2: PRINT anat2$
END IF
IF Analysis$ = "G" OR Analysis$ = "g" THEN
     anat1$ = "Replacement geophone relative calibration analysis being performed"
     anat2$ = "on data set " + STR$(Sets%) + " in file " + file$ + Ext$
     anat1 = LEN(anat1$): LOCATE 12, 40 - anat1 / 2: PRINT anat1$
     anat2 = LEN(anat2$): LOCATE 13, 40 - anat2 / 2: PRINT anat2$
END IF
IF Analysis$ = "R" OR Analysis$ = "r" THEN
     anat1$ = "Relative calibration analysis as part of reference calibration procedure"
     anat2$ = "is being performed on data set " + STR$(Sets%) + " in file " + file$ + Ext$
     anat1 = LEN(anat1$): LOCATE 12, 40 - anat1 / 2: PRINT anat1$
     anat2 = LEN(anat2$): LOCATE 13, 40 - anat2 / 2: PRINT anat2$
END IF

     SC% = Sets%
     K% = 1: RCount% = 0
     CALL AssignPosition(K%, Posit%())
     FOR M% = 1 TO InitNumPeaks%
          RCount% = RCount% + 1
          IF NOT English% THEN
               FOR i% = 1 TO NumSensors%
                    Positn% = i% * 4 + 1
                    J% = Posit%(i%)
                    DefData!(i%, J%, K%, RCount%) = VAL(MID$(DataSet$(Sets%, M%), Positn%, 4))
                    OutDef!(M%, i%) = VAL(MID$(DataSet$(Sets%, M%), Positn%, 4))
               NEXT i%
               LoadData!(M%) = VAL(MID$(DataSet$(Sets%, M%), 1, 4))
          ELSE
               FOR i% = 1 TO NumSensors%
                    Positn% = i% * 6 + 33
                    J% = Posit%(i%)
                    DefData!(i%, J%, K%, RCount%) = VAL(MID$(DataSet$(Sets%, M%), Positn%, 6))
                    OutDef!(M%, i%) = VAL(MID$(DataSet$(Sets%, M%), Positn%, 6))
               NEXT i%
               LoadData!(M%) = VAL(MID$(DataSet$(Sets%, M%), 34, 5))
          END IF
          IF RCount% MOD NumReps% = 0 THEN
               RCount% = 0
               K% = K% + 1
               CALL AssignPosition(K%, Posit%())
          END IF
     NEXT M%
     CALL LatinSqDesign
     IF Analysis$ = "G" AND RepSens% > 0 THEN
          CALL ReplaceSensor
     END IF
     CALL OutputToFile
     IF Analysis$ <> "R" THEN
          CALL FileToScreen
     END IF
NEXT Sets%
END SUB
```

Appendix C

Latin Square Analysis of Variance (ANOVA)

Latin Square ANOVA

The Latin Square experiment design layout for the relative calibration test is shown in Table 1. In this design, the sensor number S_i represents the treatment for each combination of drop set and stand position. Drop set represents the 5 drop sequence used to test each combination of sensor and stand position. For purposes of classification, within each cell in the experiment design the measured deflections are designated as δ_{ijkl} where *i* represents the sensor number, *j* represents the position in the stand, *k* represents the drop set, and *l* represents the repeat drops in each drop set. An equivalent and more convenient designation for the deflection values is δ_{ikl} where the subscripts are the same as above. This is because position in the stand is dependent on sensor number and drop set. All combinations of *i, j, k,* and *l* do not exist in the data set.

Table 1. 7x7 Latin square design for relative calibration analysis.

Position in Stand	Drop Set						
	1	2	3	4	5	6	7
1	S_1	S_7	S_6	S_5	S_4	S_3	S_2
2	S_2	S_1	S_7	S_6	S_5	S_4	S_3
3	S_3	S_2	S_1	S_7	S_6	S_5	S_4
4	S_4	S_3	S_2	S_1	S_7	S_6	S_5
5	S_5	S_4	S_3	S_2	S_1	S_7	S_6
6	S_6	S_5	S_4	S_3	S_2	S_1	S_7
7	S_7	S_6	S_5	S_4	S_3	S_2	S_1

The response model for the relative Latin square experiment Design is:

$$\delta_{ijkl} = \mu + \alpha_j + \beta_k + \tau_i + \varepsilon_{ijkl} \tag{1}$$

where,

δ_{ijkl}	=	Observed deflection response for sensor *i*, in position *j*, for drop set *k*, and repeat drop number *l*.
α_j	=	Effect of stand position *j*.
β_k	=	Effect of drop set *k*.
τ_i	=	Effect of sensor *i*.
ε_{ijkl}	=	random error.

The following restriction are imposed on the effects as follows:

$$\sum_{j=1}^{NumPos} \alpha_j = \sum_{k=1}^{NumSets} \beta_k = \sum_{i=1}^{NumSens} \tau_i = 0 \tag{2}$$

where,

NumPos	=	Number of positions in the stand.

The δ_{ijkl} are assumed to have a normal distribution with means

$$\mu_{ijk} = \mu + \alpha_j + \beta_k + \tau_i \tag{3}$$

and with a common variance σ^2.

The following three hypothesis are tested with the Latin Square ANOVA:

1. H'_0: $\alpha_1 = \alpha_2 = \cdots = \alpha_{\text{NumPos}} = 0$
   H'_1: At least one α_j is not equal to zero, i.e. position is significant.

2. H''_0: $\beta_1 = \beta_2 = \cdots = \beta_{\text{NumSet}} = 0$
   H''_1: At least one β_k is not equal to zero, i.e. set is significant.

3. H'''_0: $\tau_1 = \tau_2 = \cdots = \tau_{\text{NumSens}} = 0$
   H'''_1: At least one τ_i is not equal to zero, i.e. sensor is significant.

The sum of squares identity can be written as

$$SST = SSp + SSd + SSs + SSE \tag{4}$$

where,

SST	=	Total sum of squares
SSp	=	Position sum of squares
SSd	=	Drop Set sum of squares
SSs	=	Sensor sum of squares
SSE	=	Error sum of squares

Since the position subscript j is dependent upon the sensor number subscript i and drop set subscript k, it is convenient to show the computing formulas for the sum of squares using the following notation:

$T_{i\bullet\bullet}$	=	Sum of all deflections for sensor i.
$T_{\bullet j\bullet}$	=	Sum of all deflections for position j.
$T_{\bullet\bullet k\bullet}$	=	Sum of all deflections for drop set k.
$T_{\bullet\bullet\bullet}$	=	Sum of all deflection measurements.

The computational formulas for the sum of squares can be written as follows.

$$SST = \sum_{i=1}^{NumSens} \sum_{k=1}^{NumSets} \sum_{l=1}^{NumReps} \delta_{ikl}^2 - \frac{T_{\bullet\bullet\bullet\bullet}^2}{(NumPos \times NumSets \times NumReps)} \tag{5}$$

$$SSp = \frac{\sum_{j=1}^{NumPos} T_{\bullet j\bullet\bullet}^2}{(NumPos \times NumReps)} - \frac{T_{\bullet\bullet\bullet\bullet}^2}{(NumPos \times NumSets \times NumReps)} \tag{6}$$

$$SSd = \frac{\sum_{k=1}^{NumSets} T_{\bullet\bullet k\bullet}^2}{(NumSets \times NumReps)} - \frac{T_{\bullet\bullet\bullet\bullet}^2}{(NumPos \times NumSets \times NumReps)} \tag{7}$$

$$SSs = \frac{\sum_{i=1}^{NumSens} T^2_{i\bullet\bullet\bullet}}{(NumSens \times NumReps)} - \frac{T^2_{\circ\bullet\bullet\bullet}}{(NumPos \times NumSets \times NumReps)} \tag{8}$$

$$SSE = SST - SSp - SSd - SSs \tag{9}$$

The mean square error estimates are computed as follows.

$$S^2_{Position} = \frac{SSp}{(NumPos - 1)} \tag{10}$$

$$S^2_{Set} = \frac{SSd}{(NumSets - 1)} \tag{11}$$

$$S^2_{Sensor} = \frac{SSs}{(NumSens - 1)} \tag{12}$$

$$S^2 = \frac{SSE}{[(NumReps \times NumPos \times NumSets) - 3(NumPos) + 2]} \tag{13}$$

The computed F values are

$$F_{Position} = \frac{S^2_{Position}}{S^2} \qquad F_{Set} = \frac{S^2_{Set}}{S^2} \qquad F_{Sensor} = \frac{S^2_{Sensor}}{S^2} \tag{14}$$

For the SHRP relative calibration test, each main effect being tested has 6 degrees of freedom and the error term has 226 degrees of freedom. The critical F statistic at the 5% confidence level is 2.14. The computed F values are compared to the critical F statistic. If a computed F values is less than the critical F statistic, then the corresponding H_0 hypothesis is accepted and the effect is judged not to be statistically significant at the 5% level. If the computed F value is greater than the critical F statistic, then the corresponding H_0 hypothesis is rejected and the effect is indicated as being statistically significant.

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