STATE OF FLORIDA

ASSESSING THE PRECISION OF FALLING WEIGHT DEFLECTOMETERS FOR FIELD MEASUREMENTS

Research Report
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STATE MATERIALS OFFICE

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EXECUTIVE SUMMARY

Deflection based techniques are being widely used to evaluate the structural integrity and for estimating the elastic moduli of in-service pavements. These deflections can be non-destructively induced and measured using various commercially available devices. In recent years, the Falling Weight Deflectometer (FWD) has gained worldwide acceptance among most highway agencies due to its versatility and ease of use. However, as with any testing using subject-driven, instrumented devices, the major concerns of the end usefulness of the resulting data are accuracy and precision. Although a level of uncertainty is always inherent to any measurement process, it must also be appropriately quantified or assessed. Therefore, the Florida Department of Transportation (FDOT) initiated the present field study to assess the level of precision of FWD measurements on flexible pavements. Deflection data was acquired using three FWD units concurrently on four asphalt pavement sections. The precision was then addressed in terms of testing repeatability and reproducibility. In addition, the effects of buffer designs on deflection measurements were also evaluated.

This report presents a description of the testing program, data collection efforts, and subsequent analyses and findings.

BACKGROUND

Due to their speed and ease of operation, deflection-based techniques are being widely used in the evaluation of the structural integrity and for estimating the elastic moduli of in-place pavement systems. The deflections can be non-destructively induced and measured using various commercially available devices. These devices are designed based on a variety of loading modes and measuring sensors. The loading modes include static, steady-state vibratory, and impulse loading, while the resulting responses are measured with sensors that include geophones, accelerometers, and linear voltage differential transducers (LVDT).

The Florida Department of Transportation (FDOT) implemented the use of the Falling Weight Deflectometer (FWD) in the early 1980s. It has, however, until recently specified the use of a vibratory-type device (Dynaflect) for pavement design purposes. This design practice was a result of comprehensive empirical correlations between Dynaflect and 12-inch plate load test data developed in an earlier study (*1*).

In 1993, the American Association of State Highway and Transportation Officials (AASHTO) incorporated the use of FWD testing for pavement design and rehabilitation purposes in its Pavement Design Guide (*2*). In recent years, the FWD has gained further acceptance among highway agencies because of its versatility, reliability, and ease of use. A 2001 FDOT survey of current state practices of using FWDs indicated that 97 percent of the respondents own FWD units, based on a 71 percent response rate (*3*). In addition, FWD loading is believed to better simulate the effects of traffic on pavement structures. Therefore, FDOT has recently implemented the use of FWD for all pavement-related evaluations, including design activities. It has also developed a practical approach for such an implementation (*4*).

This field study was initiated to assess the precision of FWD for field measurements. Deflection data were acquired using three FWD units concurrently on four asphalt pavement sections. These sections were randomly selected to include different structural designs and layer thicknesses. The precision of FWD data was addressed in terms of repeatability and reproducibility. In addition, the effects of different buffer designs on deflection measurements were also evaluated.

SUMMARY OF CURRENT STATE PRACTICES

In May of 2001, FDOT conducted a survey to assess the current practices of using FWD by highway agencies. Following are general findings on the current state practices in two FWD program areas, based on a 71 percent response rate:

FWD Program Management

- 70 percent of the respondents own and operate Dynatest units, while 11 percent own and operate JILS units, 8 percent own and operate KUAB units, and the remaining 8 percent own and operate a combination of Dynatest, KUAB, and/or JILS units.
- The average use of the FWD with respect to program areas is 63 percent for structural capacity evaluation, 18 percent for research, 15 percent for pavement investigation, and 4 percent for other pavement evaluation activities.
- 78 percent of the respondents use FWD at the project level, while 19 percent use it at both project and network levels.
- 61 percent of the respondents test less than 500 roadway lane miles annually.
- The average annual FWD operating budget varies among agencies depending on the number of projects, project length, and individual costs involved.

- In addition to testing State highways, 39 percent of the respondents use FWD to test city streets, 11 percent test airport runways, and 17 percent test some other type of facilities.

FWD Operation

- 72 percent of responding agencies have a Quality Control/Quality Assurance plan in effect.
- 57 percent typically use one crewmember per FWD unit.
- 72 percent perform an annual reference calibration on their FWD unit(s).
- Over 69 percent perform a monthly relative calibration on their FWD unit(s).
- Over 31 percent use in-service pavements to perform a relative calibration.
- 64 percent use a seven-sensor set up when testing for a typical pavement rehabilitation project.
- Nearly 70 percent of the FWD units owned by these agencies operate under the DOS environment.
- Only 28 percent of the transportation agencies use a seasonal and/or temperature adjustment factor(s) for determining the effective subgrade modulus for design purposes.

OBJECTIVE

As with any testing using instrumented devices, the major concerns of the end usefulness of the resulting data are accuracy and precision. Although a level of uncertainty is always inherent to any measurement process, and, thus, must be accepted, it must also be appropriately quantified or assessed. Therefore, the primary objective of this study was to develop precision statements for FWD field measurements on flexible pavements. Data was acquired from three FWD units operating concurrently on a large number of asphalt pavement sections. The precision was addressed in terms of testing repeatability and reproducibility. In addition, the effects of different types of buffer system on the measured deflections were also evaluated.

EXPERIMENTAL PROGRAM AND DATA COLLECTION

Falling Weight Deflectometer (FWD) Devices

The FWD consists of a trailer mounted, falling weight system capable of loading a pavement in a manner that simulates actual wheel loads in both magnitude and duration. An impulse load is generated by dropping a mass from a specified height. The mass is raised hydraulically, then released by an electrical signal and dropped with a buffer system on a 12-inch (300-mm) diameter rigid steel plate. A set of springs between the falling mass and hit bracket mounted above the load cell buffers the impact by decelerating the mass. A thin, neoprene pad rests between the plate and the pavement surface to allow for an even load distribution. When a weight is dropped, an impulse load enters the pavement system creating body and surface waves. The resulting vertical velocity of the pavement surface is picked up through a series of sensors located along the centerline of the trailer. These signals are then used to obtain the maximum deflection from each geophone through analog integrations. A single analog integration of a signal generates the deflection-time trace. The deflection measurements are recorded by the data acquisition system typically located in the tow vehicle.

Data Collection

In the present investigation, deflection measurements were acquired using three FDOT-owned FWD units. A 9000-lb (40 kN) load level was adopted, and the resulting deflections were monitored using a 7-sensor configuration to conform to the Strategic Highway Research Program (SHRP) recommendation for flexible pavement testing. Figure 1 shows a schematic of the sensor configuration used in this study. Deflection measurements were acquired on four flexible pavement projects, representing typical highway pavement structures in Florida. Within each project, the testing was performed at ten predefined test sites of the travel lane. At each site, the tests were conducted using the three FWD units, with each unit making three 'replicate runs' in random sequence. Four consecutive load drops were used for each test. However, only the deflection data resulting from the last three load drops were considered for analysis to ensure adequate characterization of the pavement system. Deflection data produced under the first impact load is generally believed not to be always representative of the true pavement reaction (*5*). Thus, the first load was mainly used for loading-plate 'seating' purposes. The resulting deflections from the other three drops were averaged for each sensor and were further used for the purpose of this study. In order to minimize the effect of temperature on the measured deflections, testing was conducted in a randomized sequence. One has to note that, for practicality, each of the FWD units was randomly assigned one operator. Therefore, any potential operator effects become intrinsic to the FWD testing/measurements.

Effect of Buffer Systems

An FWD load is induced when the falling mass is decelerated by a set of rubber buffers situated between the mass and the hit bracket mounted above the load cell. The mass, the drop height, and the buffer stiffness control the magnitude of load applied to a pavement system. Different buffer designs are currently available depending on the shape of the contact surface at buffer bottoms. This part of the study considered the effects of both fully and semi-rounded buffers on deflection measurements. For such a purpose, two random FWD units were alternatively fitted with both types of buffer systems and the corresponding deflections were measured on 10 different sites.

DATA ANALYSIS

Precision Level of FWD Measurements

Two of the most important criteria of the usefulness of any testing device are accuracy and precision. As such, every ASTM test method is required to include a precision and bias statement for that particular test. For FWD testing, the pertinent test method, ASTM D 4694, *Standard Test Method for Deflections With a Falling-Weight-Type Impulse Load Device (6),* does not presently provide precision or bias statements. The present study was therefore initiated with a primary objective of developing precision statements for FWD field measurements on flexible pavements. Since the present study is concerned only with deflection measurements on in-service pavement systems, providing references with which the respective deflection results could be compared to in order to determine the bias in the measurements would not have been realistic and/or practical. Consequently, the accuracy of the FWD data could not be appropriately assessed. In addition, pavement surface deflections are affected by many variables such as environmental conditions, testing time, site condition, etc., and measured values are only valid until one of these conditions significantly changes. The precision was, however, addressed in terms of the level of testing repeatability and reproducibility. Within each site, four deflection basins (as described above, only the last three were considered in the analysis) were collected using each of the FWD units along predetermined paths. Therefore, within each project, 120 tests were conducted representing a total of 840 deflection data points of which 630 were analyzed for the purpose of this study. All the projects were selected to include different layer thicknesses and structures, as given in Table 1. These test sections were essentially surface-on-grade flexible pavement sections in good condition. All test sites, pavement structures, operator, testing sequences, and times were randomly selected (assigned in the case of operators) in an effort to achieve unbiased testing and test site distribution.

Deflection data from all three FWD units was first analyzed in statistical terms of range, standard deviation and coefficient of variation. The range serves herein as a convenient measure of data dispersion, while the standard deviation and coefficient of variation provide, respectively, a convenient measure of deviation around the mean and a normalized way of expressing data variability. Given the large amount of data recorded by the seven sensors on a total of forty test sites (four projects, ten test sites per project), only those data related to sensors 1 and 6 are provided for illustrative purposes herein and are summarized in Table 2. In general, the measured deflections exhibit relatively little dispersion in data. For any given sensor, the maximum range measured within a given unit was 2.42 mils, while the maximum range between units was 3.81 mils. These measurements correspond to a maximum difference of 15 and 25 percent for repeatability and reproducibility, respectively. As would be expected, these maximum ranges were measured at the sensor directly under the applied load (sensor number 1).

The standard deviation, or deviation around the mean was also found to be relatively small, with a maximum value of 1.5 mils, measured at the sensor directly under the applied load, for individual FWD units and 1.27 mils when assessing the reproducibility of the test (between units). For all practical purposes, the magnitude of these values is not significant. Here again, the deviation around the mean was observed to be lower for the other sensors. The coefficients of variation also indicate that the variability in the data is relatively small. It should be noted that the range, standard deviation, and coefficient of variation all increase slightly when assessing the variability between FWD units as opposed to within a single unit. This is generally expected due to increased variability associated with the reproducibility of test data. In addition, an alternate approach, known as the AREA basin shape factor, was also used wherein the respective basin deflections as measured on any individual test were converted into a single equivalent number as described below.

AREA Basin Shape Factor

As described previously, this study resulted in the collection of a large amount of deflection data. Thus, an alternate approach, known as the AREA basin shape factor, was also used wherein the respective basin deflections as measured on any individual test were converted into a single equivalent number. Hence, in order to analyze and compare respective sensor data from the three FWD units within any test site, the measured deflections were converted to an equivalent AREA basin shape factor (henceforth referred as the AREA factor). The AREA factor is essentially the result of numerically integrating a normalized deflection basin and is a convenient way of examining the effects of multiple sensors at the same time (*7*). It relates to the ratio of pavement stiffness to that of the subgrade. The pavement stiffness characteristic is dependent upon both the thickness of the pavement structure and the stiffness of the materials that make up the pavement structure.

When the AREA factor was initially developed, four sensors were typically used in a test setup at 12-inch intervals. The AREA factor is calculated by using the sensors at 0, 12, 24, and 36-inch offsets as shown in Figure 2. The AREA function depends then upon the spacing between the adjacent individual sensors and is equal to the sum of the three areas as shown in Figure 2. The corresponding numeric expression is as follows:

$$AREA = 12 * \frac{\left(\frac{D_1}{D_1} + \frac{D_2}{D_1}\right)}{2} + 12 * \frac{\left(\frac{D_2}{D_1} + \frac{D_3}{D_1}\right)}{2} + 12 * \frac{\left(\frac{D_3}{D_1} + \frac{D_4}{D_1}\right)}{2} \quad (1)$$

Where D_1, D_2, D_3, and D_4 are deflections measured at sensors 1, 2, 3, and 4, respectively.

This methodology can be applied to any test setup and Equation 1 can be modified accordingly. The FWD units used in this study had seven sensors each, with longitudinal spacing as shown previously in Figure 1. Therefore, the corresponding deflections in this case can be expressed in terms of AREA factor as follows:

$$\begin{aligned} AREA = {} & 4*\left(1+\frac{D_2}{D_1}\right)+2*\left(\frac{D_2}{D_1}+\frac{D_3}{D_1}\right)+3*\left(\frac{D_3}{D_1}+\frac{D_4}{D_1}\right)+3*\left(\frac{D_4}{D_1}+\frac{D_5}{D_1}\right) \\ & +6*\left(\frac{D_5}{D_1}+\frac{D_6}{D_1}\right)+12*\left(\frac{D_6}{D_1}+\frac{D_7}{D_1}\right) \end{aligned} \qquad (2)$$

Where D_1 through D_7 represent the deflections measured at sensors 1 through 7, respectively.

Repeatability of FWD Measurements in Terms of AREA Factors

Repeatability can be defined as the variation in observed values within a single FWD unit, or simply put, the ability of an individual unit to produce consistent (or comparable) measurements, under similar testing conditions. If these multiple sets of data are statistically similar to each other, it can then be concluded that each unit collected repeatable data. Each unit collected three sets (runs) of data at every test site for a given project. Even though the ten sites within each project have a similar pavement structure, measured deflection data can be statistically different because of the inherent variability in layer thickness and local site conditions. For analysis purposes, data would have to be compared for every individual test site, leading to a large number of statistical tests. However, if the variance of a set of data resulting from one run of a FWD unit is statistically similar to the variance resulting from a second run, then the unit can be said to measure statistically similar data. To compare the resulting variance values, a statistical test known as Levene’s test, a test for equality of variances, was performed on the individual runs of each FWD unit for every project considering all the test sites in that project. This test is a modified form of the common F-test, wherein variances from 3 or more populations can be compared. It evaluates whether or not the respective mean of the absolute deviation values from a treatment median are equal for all treatments. If the mean deviations are equal, then the variances of the observations in all treatments will be the same. The test statistic is the usual F-Statistic for testing equality of means applied to the absolute deviation (*8*). Table 3 summarizes the results of this analysis and shows that, at the 95% confidence level, the FWD units measured repeatable data, in terms of AREA factors, except for Project-1, where units 2 and 3 generated statistically different results between runs.

Reproducibility of Deflection Measurements in Terms of AREA Factors

Reproducibility can be defined as the variation in observed values as generated using two or more FWD units when testing under similar conditions. Deflections from individual sensors were first plotted for the three units for each of the four projects. Figure 3 presents a comparison of the deflections measured by sensors 1 and 6 respectively, at each of the 10 test sites in a project. A test for equality of variances was also performed between the three units, the results of which are presented in Table 3. The results show that the variances in the calculated AREA factor are the same for the three units. Figure 4 also presents a comparison of the variance in the AREA factor for each of the units (plotted on the primary y-axis), with the overall average AREA factor for each project plotted on the secondary y-axis for comparison purposes. This figure shows that the variances do not differ significantly between units.

Precision Estimates

The main objective of this study was to develop precision statements for deflection data measured by FWD units. The pooled-statistics considered all the deflection measurements obtained on the 40 test sites using 3 FWD units and a 9000 lb (40 kN) load level. Therefore, within this test range, the precision statements were developed respectively for the repeatability and reproducibility of the field deflection data at a 95 percent confidence level. These pooled statistics were calculated using individual deflection measurements from the seven sensors. ASTM C-670, *Standard Practice for Preparing Precision and Bias Statements for Test Methods for Construction Materials (9)*, states that the acceptable difference between two test results or the 'difference-two-sigma (d2s)' can be selected as the appropriate index of precision in precision statements. This index indicates a maximum acceptable difference between two test results obtained on test portions of the same material under the same test conditions (*9*). The (d2s) index can be calculated by multiplying the appropriate standard deviation by the factor $2\sqrt{2}$. Table 4 summarizes all these results. For illustration purposes, the precision statements for deflections measured at sensor number 6, located a radial distance of 36 inches from the load are as follows:

Repeatability (Within FWD Unit Precision)

The deflections measured at a radial distance of 36 inches during two properly performed tests using the same FWD unit and a 9-kip load on the same test site should not differ by more than 0.29 mils at a 95 percent confidence level.

Reproducibility (Between FWD Units Precision)

The deflections measured at a radial distance of 36 inches during two properly performed tests using two FWD units and a 9-kip load on the same test site should not differ by more than 0.40 mils at a 95 percent confidence level.

Effect of Buffer Designs on Deflection Measurements

As described previously, this study also considered the effects of both fully and semi-rounded buffers on deflection measurements. Past studies have shown that varying the shape of the buffer pads has a significant effect on the measured deflections *(1)*. To study this effect, testing was conducted on ten sites using two FWD units alternatively fitted with both types of buffer systems. These FWD units were used concurrently to minimize any temperature-induced variability in the collected data. The resulting deflections from all seven sensors were expressed in terms of AREA factors using Equation 2.

The illustrative comparison, in terms of AREA factor values, of all the data collected using both buffer systems is shown in Figure 5. The comparison considered a total of 20 paired-data points. This figure indicates that there is a good correlation between the two buffer systems as reflected by the R-square value of 0.92. In addition, all the measurements fall near a straight regression line with relatively little dispersion about the regression line. Within this range, the regression line is higher but still closer to the equality line. This implies that, within the same test site, a cylindrical buffer would generally result in a relatively, but not necessarily significantly, higher AREA factor than a round buffer. The percent differences in the calculated AREA shape factor are presented in Table 5. In general, as illustrated in Figure 6, when using the cylindrical buffer system, higher deflections were recorded for all the sensors, but with lower average standard deviations. A two-way analysis of variance performed on the collected data showed that the AREA factor is significantly different at the 95% confidence level, the results of which are presented in Table 6. Although these statistical analysis results show the two buffer systems to be significantly different, the average difference between measured responses is below 3.5 percent, which is typically not a significant difference when measuring FWD deflections. Further analysis on individual deflections from each sensor showed that the differences in deflection measurements averaged from 1.30 mils for sensor number 1 to 0.16 mils for sensor number 7 located 60 inches away. Thus, for all practical purposes, the type of buffer system does not appear to be a significant factor in the repeatability or reproducibility of deflection measurements. Consistency in buffer selection should, however, be attempted in order to minimize potential variability in test results.

SUMMARY OF FINDINGS

FDOT has recently implemented the use of FWD for all pavement-related evaluation, including design activities. In support of this implementation, a study was initiated with the primary objective of assessing the accuracy and precision of FWD field measurements. Specifically, FWD testing repeatability and reproducibility were evaluated. The effects of different buffer designs on deflection measurements were also assessed. Precision statements for repeatability and reproducibility of field measurements were developed and are summarized herein.

In general, the measured deflections exhibited relatively little dispersion in data. As expected, maximum deflections were measured directly under the applied load (sensor number 1), and therefore larger ranges in measured deflections were observed at this sensor as compared to other sensors farther away from the load plate. The coefficients of variation also indicated that the variability in the data is relatively small. It should be noted that the range, standard deviation, and coefficient of variation increased slightly when between-unit variability was considered as opposed to within-unit variability.

This study also considered the effects of both fully and semi-rounded contact surfaces on deflection measurements (cylindrical versus round buffers). In general, the cylindrical buffer shape consistently resulted in higher deflection measurements than the round buffer shape. These differences in deflection measurements averaged from 1.30 mils at sensor number 1 to 0.16 mils at sensor number 7 located 60 inches away from the center of the load plate. It should be noted that this is still less than the magnitude of the repeatability and reproducibility precision statements. Thus, buffer type selection does not appear to be a significant factor in the repeatability of deflection measurements with the FWD.

CONCLUSIONS

The analysis of all the deflection data as collected during the course of this study indicated, within the test range, the following:

- In general, the measured deflections exhibit relatively little dispersion in data. For any given sensor, the maximum range measured within a given FWD unit was 2.42 mils, while the maximum range between any two given units was 3.81 mils.
- A high level of repeatability and reproducibility of the deflection measurements was obtained. For instance, pooled standard deviation values of the deflections measured at the sensor directly under the applied load were 1.5 and 1.27 for repeatability and reproducibility, respectively. For all practical purposes, the magnitude of these values is not significant. Further analysis of the deflection data, in terms of AREA basin shape factor, also indicated that the respective variance values do not differ significantly between units.
- A comparison, in terms of AREA factors, of all the data collected using both buffer systems indicated that, for all practical purposes, the type of buffer system does not appear to be a significant factor in the repeatability or reproducibility of deflection measurements.

- In terms of repeatability and reproducibility statements, for two properly performed tests using a 9-kip load on the same test site the deflections measured at a radial distance of 36 inches, for instance, should not differ by more than 0.29 mils when using the same FWD unit or should not differ by more than 0.40 mils when using two FWD units at a 95 percent confidence level.

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REFERENCES

1. Godwin, H. F., W. G. Miley, and G. C. Page. *Soil Support Values as Determined by the Dynaflect.* Study 81-2, Florida Department of Transportation, Gainesville, August 1981.
2. *AASHTO Guide for the Design of Pavement Structures.* American Association of State Highway and Transportation Officials, Washington, D. C., March 1993.
3. Nazef A., and B. Choubane. *Survey of Current Practices of Using Falling Weight Deflectometers.* Research Report FL/DOT/SMO/01-452, Florida Department of Transportation, Gainesville, September 2001.
4. Choubane B., and R. L. McNamara. *A Practical Approach to Predicting Subgrade Moduli Using Falling Weight Deflectometer (FWD) Data.* Research Report FL/DOT/SMO/00-442, Florida Department of Transportation, Gainesville, June 2000.
5. Bentsen, R. A., S. Nazarian, and J. A. Harrison. *Reliability Testing of Seven Nondestructive Testing Devices*. Nondestructive Testing of Pavements and Backcalculation Moduli, ASTM STP 1026, A. J. Bush, III and G. Y. Baladi, Eds., American Society for Testing and Materials, Philadelphia, 1989.
6. ASTM D 4694 – 96, *Standard Test Method for Deflections with a Falling-Weight-Type Impulse Device.* American Society for Testing and Materials, 1999, Section 4, Volume 4.03.
7. Hoffman M. S., and M. R. Thompson. *Mechanistic Interpretation of Nondestructive Pavement Testing Deflections.* Transportation Engineering Series No. 32, Illinois Cooperative Highway and Transportation Research Series No. 190, University of Illinois at Urbana-Champaign, 1981.
8. Montgomery D. C. *Design and Analysis of Experiments, 5th Edition.* John Wiley and Sons Inc, pp-81-82.
9. ASTM C-670. *Standard Practice for Preparing Precision and Bias Statements for Test Methods for Construction Materials.* American Society for Testing and Materials, 2002.

TABLE 1 Description Summary of Pavement Structures

Pavement Layer	Project 1	Project 2	Project 3	Project 4
Asphalt Layer Thickness, inches	2.1	12.0	3.8	1.5
Limerock Base Thickness, inches	10.0	8.5	8.0	8.0
Stabilized Subgrade Thickness, inches	12.0	12.0	12.0	8.0
Embankment Type	A-2-4	A-2-4	A-2-4	A-2-4

TABLE 2 Sample Summary of Repeatability and Reproducibility Statistics in Terms of Range, Standard Deviation, and Coefficient of Variation

Repeatability (Within Unit)											Reproducibility (Between Units)											
Project 1																						
	Site	Unit 1			Unit 2			Unit 3			Project-1			Project-2			Project-3			Project-4		
		Range	Std. Dev	COV	Range	Std. Dev	COV	Range	Std. Dev	COV	Range	Std. Dev	COV	Range	Std Dev	COV	Range	Std. Dev	COV	Range	Std. Dev	COV
Sensor 1	1	0.72	0.37	2.95	0.50	0.25	1.85	0.95	0.48	3.40	2.51	0.92	6.77	1.59	0.54	12.19	0.97	0.31	2.07	0.97	0.31	2.07
	2	0.90	0.46	3.35	1.48	0.74	5.10	0.81	0.41	2.63	2.57	0.96	6.48	1.23	0.45	10.63	0.66	0.22	1.42	0.66	0.22	1.42
	3	1.38	0.69	5.22	1.34	0.77	5.55	2.30	1.23	8.39	3.54	1.19	8.40	1.29	0.47	11.64	0.52	0.19	1.24	0.52	0.19	1.24
	4	0.79	0.40	3.34	0.59	0.33	2.61	1.00	0.50	3.76	2.16	0.79	6.10	0.82	0.32	8.87	1.05	0.33	2.13	1.05	0.33	2.13
	5	1.49	0.84	7.19	1.58	0.87	6.95	2.11	1.12	8.66	3.00	1.08	8.63	1.12	0.41	9.90	1.10	0.35	2.24	1.10	0.35	2.24
	6	1.74	0.88	6.56	1.89	0.99	6.97	2.42	1.25	8.35	3.81	1.27	8.81	1.33	0.48	11.52	0.79	0.26	1.71	0.79	0.26	1.71
	7	0.50	0.27	2.16	0.86	0.45	3.53	0.63	0.34	2.54	1.74	0.64	4.85	1.16	0.40	10.14	1.65	0.61	4.12	1.65	0.61	4.12
	8	0.47	0.24	1.86	0.45	0.23	1.67	0.68	0.35	2.48	1.85	0.73	5.27	1.01	0.41	10.03	1.20	0.39	2.65	1.20	0.39	2.65
	9	1.49	0.77	5.37	0.97	0.51	3.39	1.22	0.63	3.92	3.07	1.03	6.61	1.02	0.33	9.68	1.45	0.50	3.35	1.45	0.50	3.35
	10	1.52	0.79	6.62	1.31	0.67	5.26	1.40	0.79	5.97	2.94	0.97	7.61	0.89	0.32	8.78	1.01	0.35	2.22	1.01	0.35	2.22
Sensor 6	1	0.13	0.07	6.81	0.18	0.09	8.83	0.11	0.06	4.99	0.30	0.10	9.01	0.35	0.12	6.72	0.43	0.13	5.60	0.38	0.13	6.17
	2	0.15	0.08	7.51	0.16	0.09	8.26	0.19	0.10	7.89	0.37	0.12	10.47	0.33	0.12	7.19	0.48	0.17	7.22	0.62	0.21	9.28
	3	0.02	0.01	1.10	0.06	0.03	2.91	0.07	0.03	2.92	0.19	0.06	5.87	0.32	0.12	7.04	0.42	0.14	5.91	0.50	0.16	8.06
	4	0.07	0.04	4.31	0.14	0.07	7.25	0.11	0.06	5.32	0.25	0.10	9.79	0.35	0.11	7.08	0.29	0.10	4.07	0.56	0.19	8.97
	5	0.13	0.07	8.14	0.12	0.06	7.01	0.09	0.05	4.28	0.24	0.09	9.42	0.33	0.12	6.70	0.35	0.11	4.42	0.42	0.13	6.73
	6	0.10	0.06	5.64	0.10	0.06	5.16	0.03	0.02	1.21	0.29	0.11	10.22	0.45	0.15	8.18	0.41	0.12	4.49	0.35	0.13	7.06
	7	0.04	0.03	2.75	0.04	0.02	2.31	0.10	0.05	4.96	0.25	0.08	8.60	0.53	0.19	9.52	0.25	0.09	3.66	0.55	0.19	11.42
	8	0.08	0.04	4.50	0.09	0.05	4.36	0.12	0.06	5.04	0.34	0.12	10.91	0.56	0.20	9.87	0.51	0.16	6.06	0.70	0.26	15.80
	9	0.20	0.11	9.39	0.14	0.07	6.24	0.11	0.06	4.62	0.26	0.09	7.29	0.38	0.13	7.56	0.35	0.12	4.80	0.61	0.22	12.43
	10	0.10	0.05	5.38	0.08	0.04	4.48	0.07	0.04	3.55	0.26	0.10	10.07	0.32	0.12	6.98	0.35	0.13	5.17	0.32	0.13	6.89

TABLE 3 Results of the Test For Equal Variances (Levene's Test)

Project	Repeatability (Within Unit)			Reproducibility (Between Units)	
	FWD Unit	F-value	P-value	F-value	P-value
Project-1	Unit-1 Unit-2 Unit-3	1.166 7.234 4.359	0.327 0.003 0.023	0.368	0.693
Project-2	Unit-1 Unit-2 Unit-3	0.378 0.987 0.362	0.689 0.386 0.700	0.589	0.745
Project-3	Unit-1 Unit-2 Unit-3	0.169 0.300 0.700	0.845 0.743 0.505	0.072	0.930
Project-4	Unit-1 Unit-2 Unit-3	0.505 0.317 2.795	0.609 0.731 0.079	0.013	0.987

TABLE 4 Summary of Pooled Statistics For Precision Analysis

Sensor	Variance		Standard Deviation, mils		Precision (d2s), mils	
	Repeatability	Reproducibility	Repeatability	Reproducibility	Repeatability	Reproducibility
1	0.276	0.351	0.53	0.59	1.49	1.68
2	0.114	0.188	0.34	0.43	0.95	1.23
3	0.058	0.108	0.24	0.33	0.68	0.93
4	0.028	0.057	0.17	0.24	0.47	0.67
5	0.019	0.036	0.14	0.19	0.39	0.54
6	0.011	0.020	0.10	0.14	0.29	0.40
7	0.004	0.007	0.07	0.09	0.19	0.24

TABLE 5 Percent Difference in Respective AREA Factor Values as Determined Using Round and Cylindrical Buffer Systems

Site	Area Factor				Difference, %			
	Unit 1		Unit 2		Within Unit		Between Units	
	Round Buffer	Cylind. Buffer	Round Buffer	Cylind. Buffer	Unit 1	Unit 2	Round Buffer	Cylind. Buffer
1	17.98	18.63	17.55	17.89	3.61	1.93	2.39	3.97
2	18.14	17.99	17.15	17.43	0.84	1.61	5.45	3.12
3	17.16	17.77	17.00	16.89	3.51	0.66	0.94	4.93
4	17.24	17.41	16.82	17.01	1.02	1.12	2.40	2.30
5	16.61	16.91	16.4	16.25	1.81	0.88	1.27	3.87
6	15.91	16.84	15.52	16.07	5.87	3.52	2.42	4.58
7	14.62	15.11	14.20	14.75	3.36	3.89	2.86	2.36
8	14.74	15.96	14.64	15.20	8.27	3.81	0.67	4.77
9	15.44	15.90	14.79	15.47	2.99	4.56	4.18	2.72
10	16.53	16.59	16.16	16.39	0.38	1.43	2.24	1.21
Average	16.44	16.91	16.02	16.34	3.17	2.34	2.48	3.38
St. Dev.	1.25	1.07	1.07	1.00	2.43	1.45	1.46	1.24

TABLE 6 Results of the Analysis of Variance (ANOVA) on the Effects of Buffer System on Deflection Measurements in Terms of AREA Factor

Source of Variation	Deg. of Freedom	Sum of Squares	Mean Squares	F-value	*P-value*
			Unit 1		
Buffer Type	1	1.12	1.12	13.5	0.005
Site	9	23.57	2.62	31.5	0
Error	9	0.75	0.08	--	--
Total	19	25.45	--	--	--
			Unit 2		
Buffer Type	1	0.49	0.49	12.1	0.007
Site	9	21.01	2.33	57.9	0
Error	9	0.36	0.04	--	--
Total	19	21.86	--	--	--

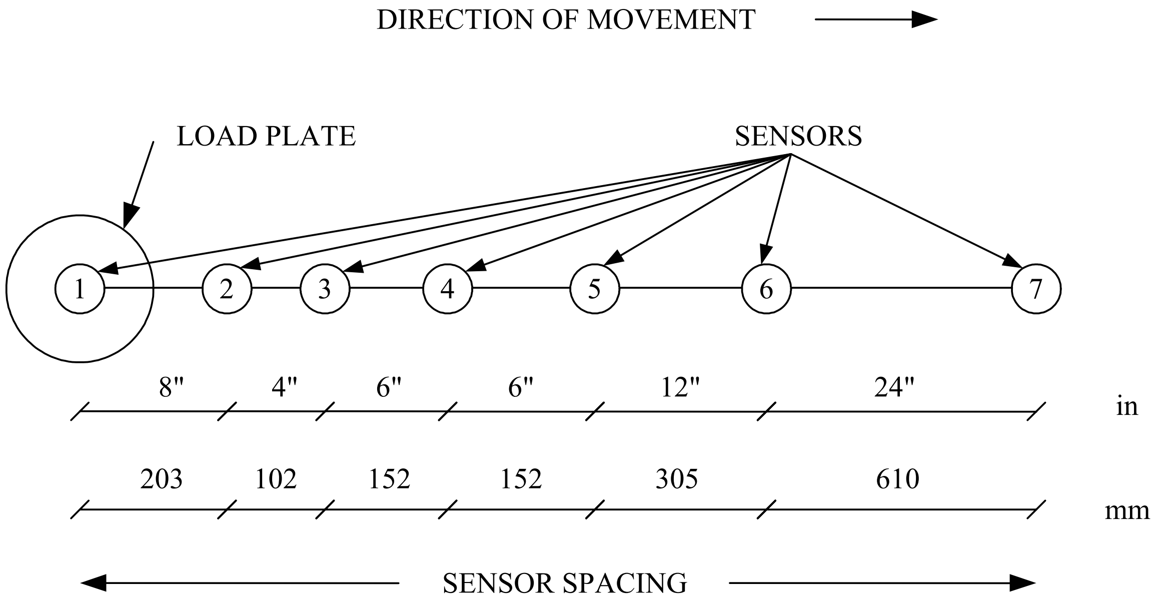


FIGURE 1 Schematic Illustration of Sensor Configuration Used in This Study.

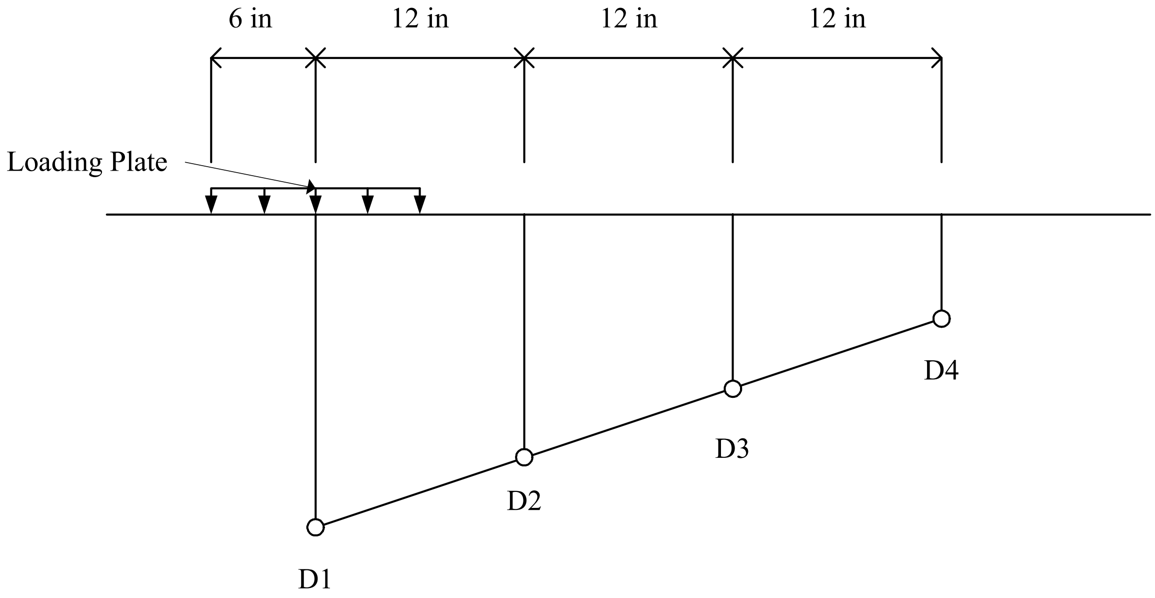
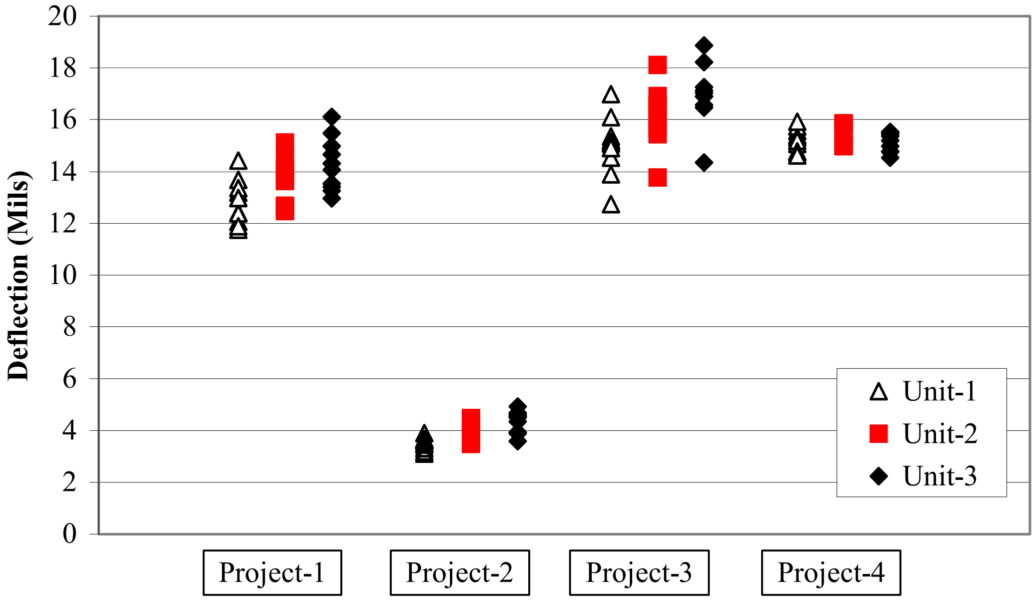


FIGURE 2 Schematic Illustration of the AREA Basin Shape Factor

Sensor-1



Sensor-6

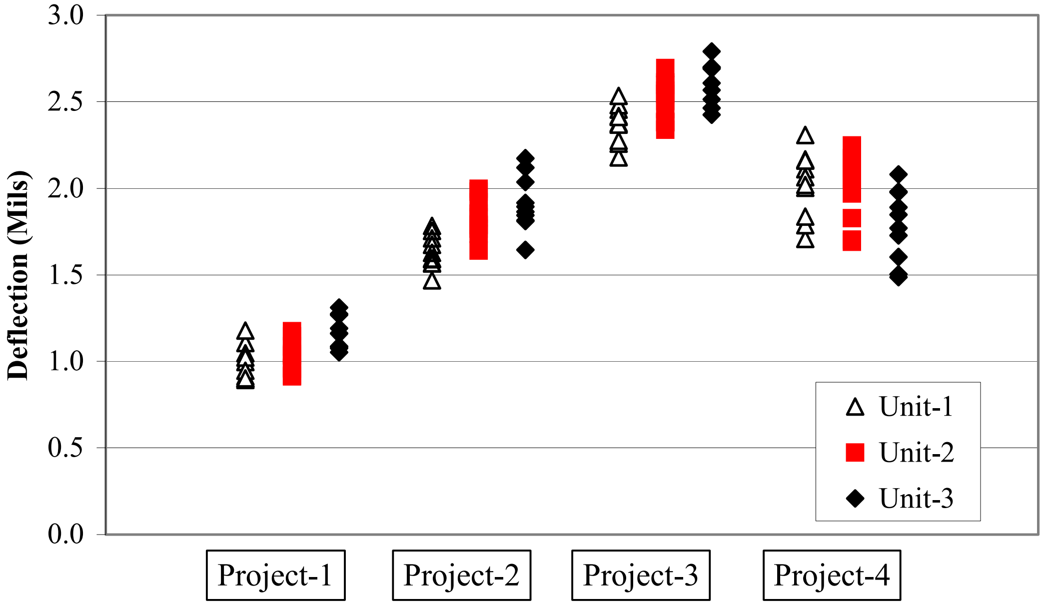


FIGURE 3 Illustrative Comparison of Respective Deflection Measurements as Determined Using Sensors 1 and 6 (Random Sequence Testing).

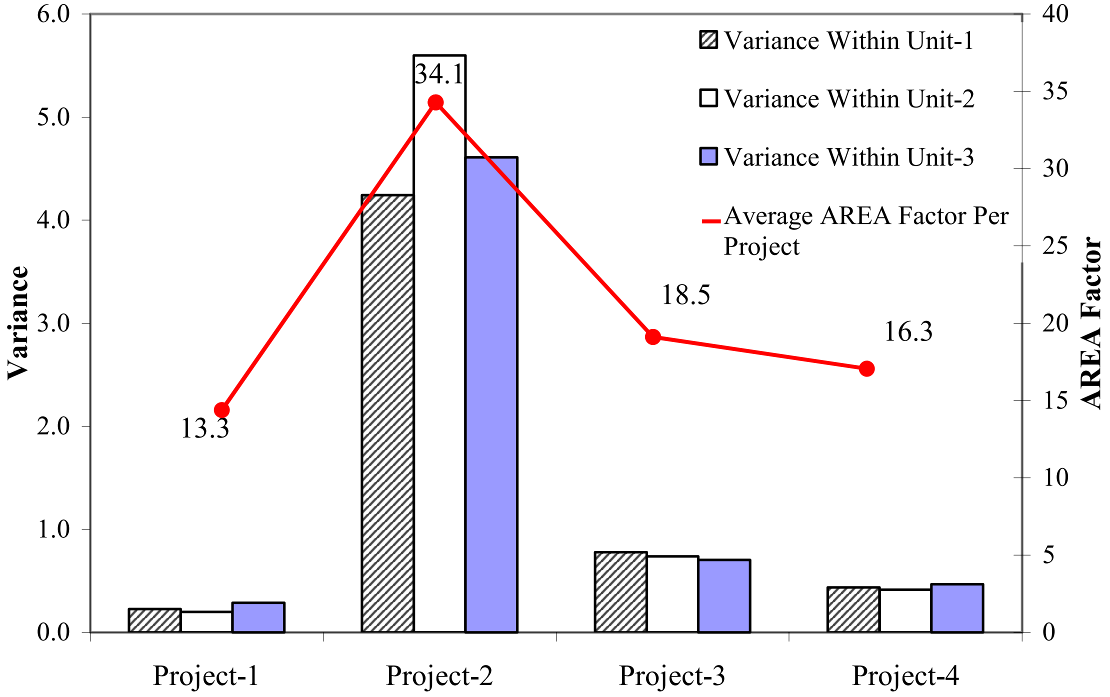


FIGURE 4 Illustrative Comparison of Respective Variance and Average AREA Factor Values.

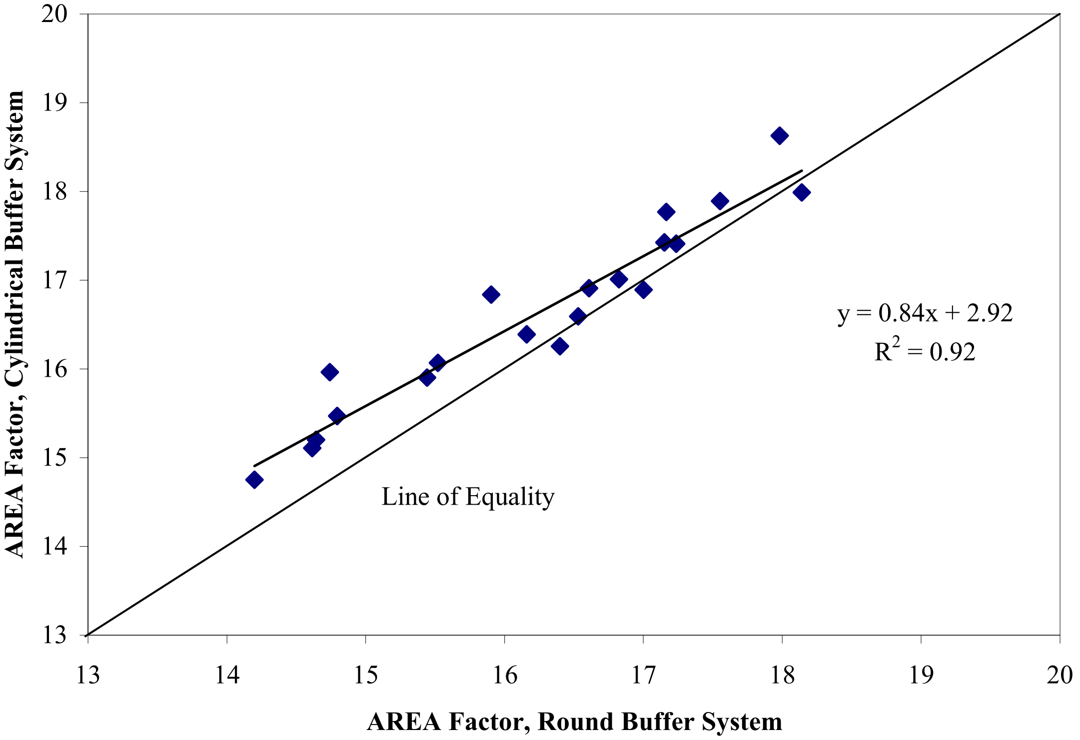


FIGURE 5 Comparison of Respective AREA Factors as Determined Using Round and Cylindrical Buffer Systems.

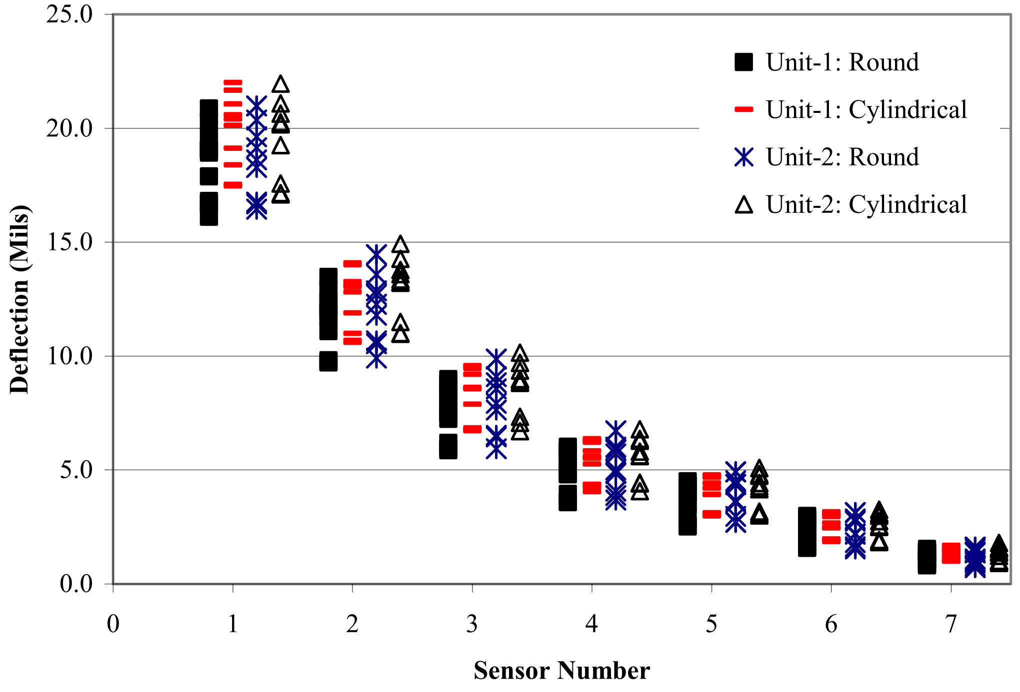


FIGURE 6 Comparison of Respective Deflections as Measured With Round and Cylindrical Buffer Systems.