# Comparison of Four Different Methods for Measuring Deflections in Jointed Reinforced Concrete Pavements

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A total of 107 dynamic deflection tests on a jointed reinforced concrete pavement were conducted to compare the performance of four measuring instruments: the linear voltage displacement transducer (LVDT), the geophone, the falling weight deflectometer (FWD), and the Dynaflect. The deflections were measured at six joints of the test pavement in the southbound roadway on Route 23 in Chillicothe, Ohio. The deflections measured by LVDT and geophone were produced by the axle loads of a fully loaded two-axle truck. Thus, this test program allowed the comparison of not only the performance of the four types of instruments, but also the deflections caused by "real-life" truck loading with those caused by "artificial" FWD and Dynaflect test loadings. Furthermore, the deflection measurements at the joints due to truck load were compared at four different speeds: static (0 mph or 0 km/hr) and moving at 10, 35, and 50 mph (16, 56, and 80 km/hr). Another important aim of this test program was to determine whether the geophone measurements were reliable and how truck speeds affected them. It was found that the LVDT and geophone deflection measurements agreed well, provided that the truck speed was equal to or exceeded 35 mph (56 km/hr). Also, the static deflection test results closely agreed with those from the moving load tests. Furthermore, it was found that the normalized FWD test results yielded the highest deflections, approximately 13 percent higher than the deflections caused by the moving truck. On the other hand, the results from the normalized Dynaflect tests agreed well with the deflections caused by the moving truck.

In 1972 the Ohio Department of Transportation (ODOT) built a jointed reinforced concrete pavement test section 3,225 ft (983 m) long in the southbound roadway on Route 23 in Chillicothe, Ohio. The pavement slab is 9 in. (0.229 m) thick. Some portions of the slab were built on granular base 12 in. (0.305 m) thick; others on asphalt-treated base 4 in. (0.102 m) thick. This test section was studied from 1972 to 1980 (*1*–*3*), and again from 1989 to 1992 by researchers at the University of Cincinnati for joint behavior, such as horizontal movements and vertical joint deflections, and for various signs of deterioration. The pavement in Chillicothe is exceptionally suited for experimental studies because several key variables were incorporated into the pavement, namely, joint spacing, type of base, type of dowel bar, and configuration of the sawcut. Table 1 shows the joints that were tested in this program and the characteristic properties of the pavement segment straddling each joint.

In the early and mid-1970s joint deflections were measured under a fully loaded truck with a rear axle load of approximately 18 kips (80.06 kN) and moving at speeds of 10, 35, and 50 mph (16, 56, and 80 km/hr). When the pavement research was resumed in 1989, it was decided that the vertical joint deflections would again be measured under a moving truck so that the new results could be compared with the old ones. Also in this test program, the pavement was surveyed for longitudinal and transverse cracking, faulting of joints, and pavement and corner cracking. The most significant damage was transverse cracking. The pavement condition index (PCI) in 1991 ranged from a high of 80 to a low of 41. A weighted average PCI of 59 was obtained for the entire pavement.

Furthermore, in 1989 geophones were used as additional instruments for measuring vertical joint deflections. Also, in the fall of 1990, ODOT conducted falling weight deflectometer (FWD) and Dynaflect measurements at the same time and on the same joints as the truck tests.

In summary, the fundamental purpose of the test program was to compare joint deflections from truck tests with those from FWD and Dynaflect tests, and to compare geophone measurements with those from the linear voltage displacement transducer (LVDT). Specifically, the program aimed at answering the following questions:

- How do results from truck load tests relate to those from FWD and Dynaflect tests?
- How closely matched are the deflections measured by the various methods, and specifically, do geophone measurements agree with those from the LVDT?
- How do static deflections relate to the deflections under the moving truck load?
- Does truck speed affect the accuracy of geophone deflection measurements?

In this phase of the program, a total of six different joints were tested for vertical deflections. This paper presents a summary of the instrumentation, the calibration procedures, the test methods used, and the final results.

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**TABLE 1 Joint Designation and Test Pavement Information**

| Joint No. | Joint Spacing, m | Type of Base | Type of Dowel |
|---|---|---|---|
| 21 | 6.4 | Stabilized | Standard (Uncoated) |
| 29 | 12.2 | Stabilized | Standard (Uncoated) |
| 49 | 6.4 | Granular | Coated |
| 59 | 12.2 | Granular | Coated |
| 69 | 12.2 | Granular | Standard (Uncoated) |
| 89 | 6.4 | Granular | Standard |

## INSTRUMENTATION AND CALIBRATION

Four different deflection measuring instruments were used during this test program, namely LVDT, geophone, FWD, and Dynaflect.

### LVDT

The LVDT is a well-known and proven device used to measure relative displacements. Its drawback is that it requires a fixed reference point. The LVDT yields a voltage-time history directly proportional to the displacement-time history of its core-to-coil position. Table 2 gives the manufacturer's specifications for the LVDT used in these tests. Note that the only error listed by the manufacturer is that due to nonlinearity. For this transducer the error band is ±0.0025 in. (0.0635 mm). Because it is a bias error, the error band can be reduced by proper calibration techniques to yield an accuracy of ±0.0006 in. (0.0152 mm). Calibration of the LVDT was performed before each test to determine the appropriate calibration factor. The calibration curve for LVDT is shown in Figure 1.

### Geophone

The geophone is a device that measures an output voltage proportional to the velocity of the base of the unit. This response is frequency dependent, particularly at lower frequencies (less than 15 Hz). Care must be taken to properly calibrate the geophone and to appropriately process its response to obtain velocity versus time and, in this test series, to obtain the deflections-versus-time history of the pavement joint to which the base of the geophone was attached. One great advantage of the geophone is that it does not need a fixed reference point to make a measurement. However, the deflection must take place at a relatively high velocity; in addition, static deflection measurements cannot be made by a geophone. Table 3 gives the manufacturer's specifications for the geophone used in this project.

Thorough presentations on the characteristics of the geophone and its various uses can be found in papers by Nazarian (*4*), Nazarian and Bush (*5*), Nazarian and Alexander (*6*), and Graves and Drnevich (*7*).

To obtain the displacement-time history of the vertical deflection of a joint with a geophone, the frequency domain

**TABLE 2 LVDT Specifications**

| Model Number | 0242-0000 |
|---|---|
| Range (working) | ±0.250 |
| Maximum (usable) | ±0.375 |
| Input Volts, DC | 6.0 to 30.0 |
| Input Current | 8.3 ma @ 6V Input<br>to 52 ma @ 30V Input |
| Linearity % Full Scale Over Total Working Range | ±0.5 |
| Over Maximum Usable Range | ±1.0 |
| Internal Carrier Frequency (Hz), Nominal Greater Than | 3600 |
| % Ripple (rms) Nom. | 0.8 |
| Output Impedance (Ohms) | 5200 |
| Frequency Response 3 db Down | 115 Hz |
| Temperature Range | -65 °F to +250 °F |
| Resolution | Infinite |

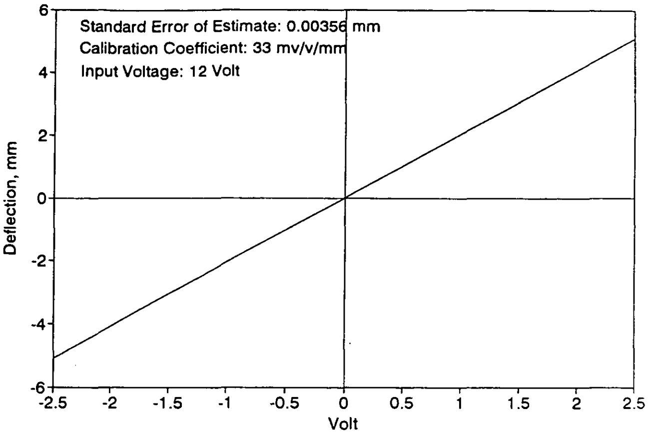


**FIGURE 1** Calibration curve for LVDT 4.

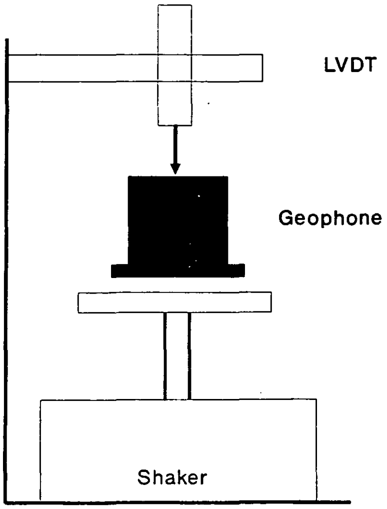


**FIGURE 2** Geophone calibration equipment.

solution, as described by Nazarian (*4*), was implemented. Specifically, before the geophone was used in the field, its frequency response function was determined through calibration. After the field measurements were taken, each velocity-time response was transformed to the frequency domain, using a fast Fourier transform. Next, this was divided by the frequency response function of the geophone to obtain the velocity spectrum. Division of the velocity spectrum by the angular frequency yielded the displacement spectrum. Finally, this signal was inverse Fourier transformed to obtain the displacement-time history of the deflected geophone (the same as the pavement joint to which it was attached).

The calibration of the geophone used in this project was performed at the Structural Dynamics Research Laboratory of the University of Cincinnati. The equipment for the calibration is shown schematically in Figure 2. The shaker, or exciter, was put in motion over a range of frequencies, and the output of the geophone and the LVDT was measured and recorded. The frequency response function of the geophone was obtained by coupling the geophone output voltage to the actual displacement measured by the LVDT. An HP35660 signal analyzer was used for this purpose.

Two HP35660 signal analyzers were used to gather the field data. The reduction of the data was performed on a 386-based personal computer (PC), using the MATLAB analysis software.

### FWD and Dynaflect

The FWD and the Dynaflect, both commercial road-testing devices, were provided by the Ohio Department of Transportation and operated by ODOT personnel. The falling weight

**TABLE 3** Geophone Specifications

| | |
|---|---|
| Model Number | L-10B |
| Standard Frequency Range, Hz | 4.5 - 10 |
| Frequency Tolerance | ±0.5 Hz |
| Standard Coil Resistance, Ohms | 138/215/374 |
| Resistance Tolerance, % | 5 5 6.5 |
| Maximum Distortion @ .7in/s @ 12 Hz or Resonance | 0.2% |
| Transduction Constant, V/in/s ±10% | 0.041*SQRT(Rc) |
| Open Circuit Damping, ±10% | 1.908/f |
| Coil Current Damping | 12.15 (Rc)/f(Rc+Rs) |
| Suspended Mass, Grams | 17.00 |
| Power Sensitivity, mW/in/s | 1.67 |
| Case-to-Coil Motion, in. p-p | 0.080 |
| Basic Unit Diameter, in. | 1.25 |
| Basic Unit Height, in. | 1.4 |
| Basic Unit Weight, oz. | 5.0 |

deflectometer device was a Dynatest model and was operated with a dynamic force output of between 14,968 and 15,826 lb (66.58 and 70.39 kN). The load was transmitted by a circular plate with a radius of 5.9 in. (0.150 m). The deflections were picked up by geophones.

The Dynaflect device was operated with the standard 1,000-lb (4.448-kN) peak-to-peak dynamic force range. The load was transmitted by two 16-in.-diameter (0.406-m) by 2-in.-wide (0.051-m) urethane-coated steel wheels. The deflections were sensed by geophones.

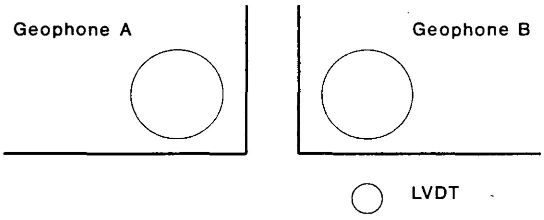
Both devices were calibrated each morning by their operators, using standard procedures, before leaving the ODOT garage.

## TEST PROCEDURE

A total of 107 dynamic tests, which included a moving fully loaded two-axle ODOT truck and the FWD and Dynaflect devices, were performed on southbound State Route Ross 23 in Chillicothe, Ohio, the site of an ODOT test pavement. The tests were conducted during the fall of 1990. A geophone and an LVDT were placed at the various joints of the pavement, as shown schematically in Figure 3 for a typical joint.

The required fixed reference point for the LVDT measurements was provided by driving a steel rod 10 ft (3.048 m) long and $1\frac{3}{8}$ in. (0.035 m) in diameter approximately 4 in. (0.102 m) away from the edge of the pavement in a 9-in.-deep (0.229-m) cutout hole, adjacent to each of the six joints tested. The tip of the rod was driven to be flush with the bottom of the 9-in.-thick (0.229-m) pavement slab. For each test sequence the coil assembly of the LVDT was attached to the side of the pavement at a point directly above the reference rod. The core of the LVDT was attached to the top of the reference rod. Deflection of the pavement at one side of the joint caused the coil assembly to move in relation to the fixed core. An output voltage proportional to the pavement movement was produced and recorded. Power to the LVDT was supplied by a 12-V battery.

a) Top View



b) Side View

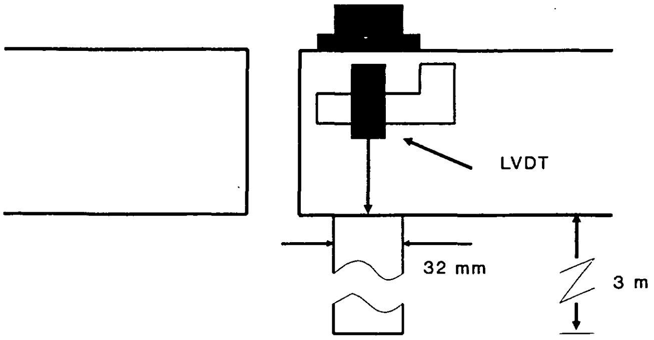


FIGURE 3 Placement of geophone and LVDT on pavement.

The geophone was glued to the top surface of the pavement, approximately 3 in. (0.076 m) from both the joint and the edge of the pavement. The sudden deflection of the pavement from truck loading caused the geophone to record the velocity changes, producing an output voltage directly proportional to this velocity. Both geophone and LVDT signals were recorded by HP35660 signal analyzers.

For each of the six joints, the tests began by placing the rear axle of the fully loaded two-axle truck, with front and real axle loads of 7,600 and 20,450 lb (33.80 and 90.96 kN), respectively, on the leave side of the instrumented joint to measure the static slab deflection. Afterward the truck was driven across the joint consecutively at speeds of 10, 35, and 50 mph (16, 56, and 80 km/hr), and the vertical deflection of the joint was again measured. Lines were placed on the pavement to guide the truck so as to maintain a constant 12-in. (0.305-m) distance from the pavement edge.

The data recorded were uncalibrated geophone and LVDT voltages. The LVDT voltage was converted to displacement by multiplying the data by a constant scale factor that was derived earlier during the calibration procedure. The geophone data were converted from a raw voltage (that was proportional to velocity) to a displacement, using

$$\mathrm{IFFT} = \mathrm{FFT(DATAFILE)} \cdot \mathrm{FRF} \cdot \mathrm{K1} \qquad (1)$$

where IFFT is the displacement function and FFT is the recorded voltage function from the data file. The frequency response function (FRF) was established previously for the geophone during the calibration procedure. K1 is a constant of the LVDT that was used in calibrating the geophone.

## RESULTS

The LVDT and geophone measurements were analyzed, digitized, and then plotted for each of the six joints and for each of the three truck speeds (two or three trials each). Because the values from the trials agreed well with each other, only the average value was reported in Table 4. Typically, for each test, the LVDT and geophone deflection-versus-time plots were printed on the same sheet, and to the same scale, for ease of comparison. Of course, for the static tests only LVDT data were taken. As an example, Figure 4 presents the LVDT (solid curve) and geophone (dashed curve) plots of deflections for Joint 59 caused by the fully loaded two-axle truck moving across the joint at a speed of 35 mph (56 km/hr). There are two peaks on each curve, the first caused by the passing of the front axle of the truck over the joint, and the second caused by the passing of its rear axle. The net deflection of the joint from either of the plots, and caused by either of the axles, can be obtained by reading the deflection at the peak point and adjusting this reading by the zero offset at the beginning of the plot.

**TABLE 4 Summary of Peak Deflection Measurements**

Date: October 31/November 1, 1990     Rear Truck Axle: 90.96kN

| Joint # | Static Load | LVDT | | | Geophone | | | FWD, Normalized | Dynaflect, Normalized | AM/PM | Pavement Surface Temperature, $^0$C |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 16 km/h | 56 km/h | 80 km/h | 16 km/h | 56 km/h | 80 km/h | | | | |
| 21 | 0.1016 | 0.0610 | 0.0584 | 0.0940 | 0.0356 | 0.0635 | 0.0737 | 0.0965 | 0.0762 | PM | 19 |
| 29 | --- | 0.1321 | 0.1118 | 0.1041 | 0.0686 | 0.0991 | 0.1016 | 0.1092 | 0.0864 | AM | 17 |
| 49 | --- | 0.0965 | 0.1092 | 0.1143 | 0.0406 | 0.1219 | 0.1067 | 0.1397 | 0.1219 | PM | 21 |
| 59 | 0.1422 | 0.1854 | 0.1778 | 0.1651 | 0.0813 | 0.1422 | 0.1549 | 0.1346 | 0.1219 | AM | 13 |
| 69 | 0.1321 | 0.0914 | 0.0991 | 0.0940 | 0.0584 | 0.1168 | 0.1245 | 0.1321 | 0.1168 | PM | 19 |
| 89 | 0.0991 | 0.0813 | 0.0914 | 0.0940 | 0.0533 | 0.1016 | 0.1143 | 0.1422 | 0.1270 | PM | 21 |
| Mean | 0.1067 | 0.1080 | 0.1080 | 0.1110 | 0.0564 | 0.1074 | 0.1125 | 0.1257 | 0.1085 | | |

Note: All tabulated deflections are net average deflections.
The range of temperature gradient during testing was from -0.04$^0$C/mm to -0.01$^0$C/mm, where the bottom of slab was permanently warmer than the top.

The FWD and Dynaflect measurements were processed by the on-board computers in the ODOT vans, and the printouts of the results were provided by ODOT to the researchers.

The composite of all results from the measurements taken during the fall of 1990 is presented in Table 4. Here, for each tested joint, the peak deflections from the LVDT and geophone measurements under the moving rear axle of the truck are tabulated, together with the normalized FWD and Dynaflect measurements. The FWD and Dynaflect measurements were normalized using one level of dynamic force for each (see the section on instrumentation and calibration) and linearity. In addition, the deflection of the same joints caused by the static application of the rear axle of the truck is also presented. Also shown are the pavement surface temperature and the time of day each test was conducted.

## ANALYSIS AND CONCLUSIONS

The results from the extensive investigation of the vertical deflections of six joints in the ODOT test pavement in Chillicothe, Ohio, are summarized in Table 4. After analyzing this table and other accumulated data, the following conclusions can be drawn:

- The overall means of the results from the static tests, the 10-, 35-, and 50-mph (16-, 56-, and 80-km/hr) LVDT tests,

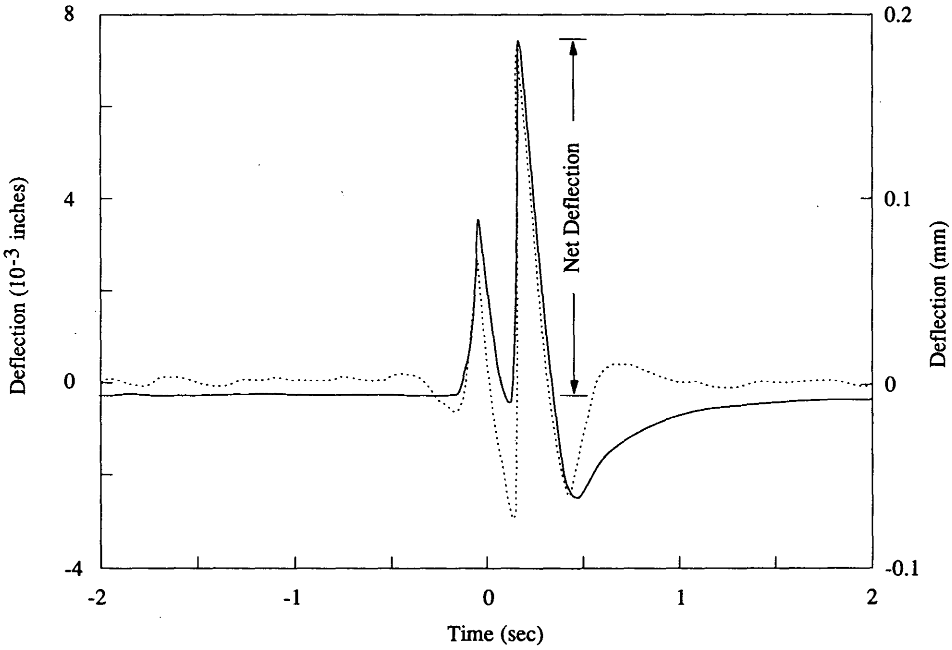


**FIGURE 4 LVDT and geophone plots of deflections for Joint 59.**

the 35- and 50-mph (56- and 80-km/hr) geophone tests, and the normalized Dynaflect test results all compared well.

- The joint-by-joint comparison of LVDT deflections with geophone deflections at 50 mph (80 km/hr) showed good agreement in three out of six cases. The spread of deviation was 2 to 32 percent. Also, for afternoon (p.m.) measurements, the LVDT deflections at 10 mph (16 km/hr) were all found to be smaller than at 50 mph (80 km/hr). Furthermore, all FWD deflections were slightly higher than the LVDT and geophone deflections at 50 mph (80 km/hr), except at Joint 59.
- Truck speed had relatively little effect on the deflection results from LVDT measurements in this test series. Specifically, the mean deflections increased from 0.0042 to 0.0044 in. (0.00011 to 0.00012 m) as the truck speed increased from zero (static test) to 50 mph (80 km/hr). However, at four out of the six joints tested, the joint deflections were found to be large at higher speeds. In general, increasing truck speed should result in increased joint deflections on concrete pavements, especially on older and rougher pavements, because of the dynamic interaction between the pavement and the truck tires, as shown by Gillespie et al. (*8*). The comparison of a large number of joint deflections on the same pavement from another phase of testing during four seasons of measurements by LVDT and at truck speeds of 10 and 50 mph (16 and 80 km/hr) showed generally larger deflections at the higher speed [see report by Minkarah et al. (*9*)].
- Truck speed had a pronounced effect on the results obtained from geophone measurements. Specifically, at a truck speed of 10 mph (16 km/hr), the overall mean deflections were only approximately 50 percent of the mean deflections from the 50-mph (80-km/hr) tests. Also, there was a small (4.5 percent) decrease in the mean deflections obtained from geophone measurements as the truck speed decreased from 50 to 35 mph (80 and 56 km/hr). The reason for this may have been the working mode of the geophone, which requires fast deflection of the pavement slab for accurate measurement. Namely, at lower speeds the low frequency of deflection vibrations would result in a nonlinear relationship between the velocity of deflection and the voltage output by the geophone.
- It appears from the limited data that the overall mean of the morning (a.m.) deflections of the joints was greater than the mean of the afternoon (p.m.) deflections. This may be explained by the upward curling of the slab corners during the morning hours, as shown by Poblete et al. (*10*). The curling results in reduced support and larger deflection under wheel loading.
- Both the normalized FWD and Dynaflect measurements gave reliable joint deflections for a variety of slab dimensions, base conditions, and types of dowels, even though the FWD deflection measurements were slightly higher than the "true deflections" (LVDT). However, all FWD tests were run only at one load level; therefore, more tests will be needed to justify the linear normalization used.
- From another phase of testing on this pavement, the mean of joint deflections on granular base was found to be greater than the mean of joint deflections on stabilized base [see report by Minkarah et al. (*9*)].
- Finally, more field testing will be needed to enlarge the data base and substantiate the findings of this test program.

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