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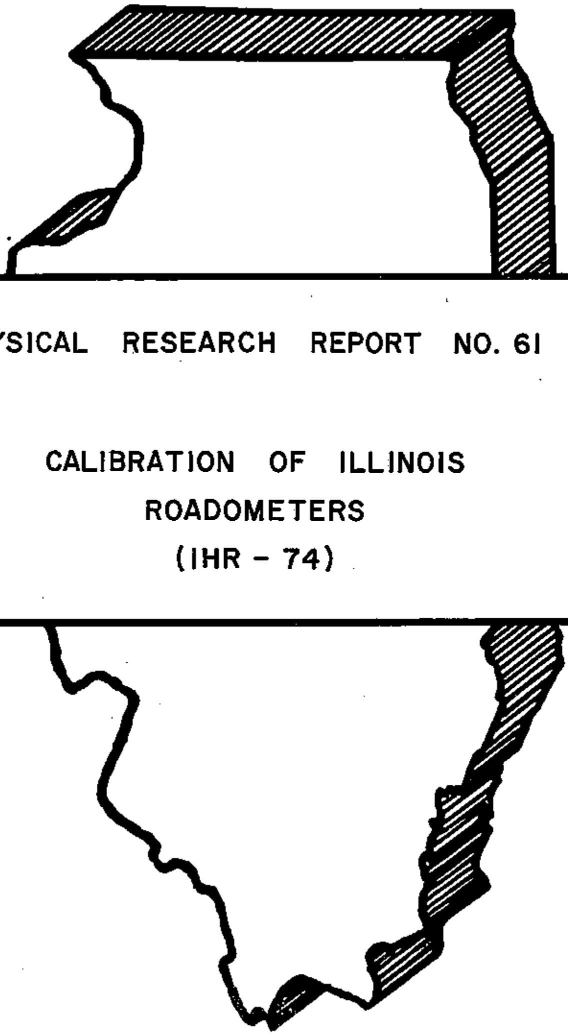

PHYSICAL RESEARCH REPORT NO. 61

CALIBRATION OF ILLINOIS ROADOMETERS

(IHR - 74)

SPRINGFIELD, ILLINOIS 62706 APRIL 1975

State of Illinois
DEPARTMENT OF TRANSPORTATION
Bureau of Materials and Physical Research

CALIBRATION OF ILLINOIS ROADOMETERS

By

J. E. LaCroix

Interim Report
IHR-74
Road Smoothness

A Research Project Conducted by
Illinois Department of Transportation
Springfield, Illinois 62706
in cooperation with
U. S. Department of Transportation
Federal Highway Administration

April 1975

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TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle

CALIBRATION OF ILLINOIS ROADOMETERS

5. Report Date

April 1975

6. Performing Organization Code

7. Author(s)

J. E. LaCroix

8. Performing Organization Report No.

Physical Research No. 61

9. Performing Organization Name and Address

Illinois Department of Transportation
Bureau of Materials and Physical Research
Springfield, Illinois 62706

10. Work Unit No.

11. Contract or Grant No.

IHR-74

12. Sponsoring Agency Name and Address

Illinois Department of Transportation
Bureau of Materials and Physical Research
Springfield, Illinois 62706

13. Type of Report and Period Covered

Interim (Phase III)

14. Sponsoring Agency Code

15. Supplementary Notes

Study Title: IHR-74 - Road Smoothness
This is conducted in cooperation with the U. S. Department of Transportation, Federal Highway Administration

16. Abstract

Several calibration procedures have been used in Illinois to determine the repeatability of roadometer measurements. The integrator was independently calibrated under static conditions. The roadometer was periodically calibrated by operating the instrument over a field calibration course. Until 1968, annual correlations were made between the roadometer and the CHLOE profilometer.

Although the use of these fundamental calibration and correlation concepts, indicated when changes in roadometer output had occurred, none of them were entirely satisfactory. To overcome limitations in the established calibration procedures, a new roadometer calibration concept was developed based upon frequency response analysis.

The roadometer is a viscously damped spring-mass system; therefore, it has the characteristics which would allow frequency response analysis. In this calibration, response curves were obtained by subjecting the roadometer to sinusoidal forces over a moderate range of frequencies. A standard curve was developed using the average of data from all tests.Data from periodic tests were compared to the standard curve and changes in roadometer output were observed; however, the changes could not be associated with specific components of the roadometer. Therefore, further consideration should be given to the development of equipment capable of analyzing all the major components in the system. On the basis of this study, frequency response analysis appears to be a potentially good method to determine whether the Roadometer response to a given input remains the same from time to time.

17. Key Words

Roughometers, Roughness, Calibrations, Frequency Curves, Frequency Response, Dynamic Response, Dynamic Characteristics.

18. Distribution Statement

19. Security Classif. (of this report)

Unclassified

20. Security Classif. (of this page)

Unclassified

21. No. of Pages

28

22. Price

Form DOT F 1700.7 (8-69)

SUMMARY

In Illinois, a roadometer patterned after the device first introduced by the Bureau of Public Roads has been used to measure pavement riding quality since 1959. The roadometer has proven to be dependable, easy to operate, and an economical device for measuring road smoothness. However, a major disadvantage of the roadometer is the lack of a direct means of calibration to assure that the response to a given set of pavement surface conditions is the same from one year to another.

Several procedures have been used in Illinois to determine the repeatability of roadometer measurements. The integrator-recording system was independently calibrated under static conditions using a reciprocating mechanism. The entire roadometer system was calibrated dynamically in the field by operating the roadometer over a one-mile calibration course. Until 1968, correlations between the roadometer and a CHLOE profilometer were made annually to compensate for any differences in roadometer output from time to time.

Although the use of these fundamental calibration and correlation concepts indicated when changes in the roadometer output had occurred, none of them were entirely satisfactory. Because of limitations in calibration equipment, the static calibrations of the integrator-recording system were conducted at lower frequencies and amplitudes than are normally encountered in the field. When changes occurred in roadometer output during field calibrations, it was impossible to determine whether the roadometer or the calibration pavement had changed. Correlations between the profilometer and the roadometer were statistically adequate, but the two instruments do not measure the same elements of pavement roughness, and their frequency response characteristics are different.

Because of limitations in the aforementioned calibration procedures, a new and more reliable calibration method was sought. Since the roadometer is basically a viscously damped, spring-mass system, it can be analyzed by frequency response methods. By subjecting the roadometer to sinusoidal forces over a moderate frequency range, frequency response curves can be generated and compared from time to time to indicate whether changes have occurred in roadometer behavior.

To induce the desired input, a simple vertically oscillating platform was constructed. The results of the platform tests indicate that the roadometer output closely follows that of a system having linear damping with one degree of freedom. Although the basic shape of the response curve did not change from one test to another, the position of the curve shifted very slightly.

Because of the shifts of the curve, a standard curve which would serve as a base level for comparison purposes was desirable. The standard curve was developed using an equation that best describes a system having the characteristics of the roadometer, and using test data representing the average roadometer output throughout the test period. Data from periodic tests were compared with the standard curve, and any changes in roadometer output were noted.

On the basis of this study, frequency response analysis appears to be a potentially good method to determine whether the roadometer response to a given input is the same from time to time. However, at the present time the components of the roadometer causing the changes cannot be isolated. The development of equipment capable of independently analyzing all the major components of the system would be the next step toward more complete confidence in roadometer results.

INTRODUCTION

In Illinois, a roadometer patterned after the device first introduced by the Bureau of Public Roads has been used to measure pavement riding quality since 1959. The roadometer consists of a single-wheel trailer which measures irregularities in the pavement surface as it is towed along the highway. Differential vertical movements of the wheel relative to the frame are transmitted by a wire cable to a double-acting ball-clutch integrator which converts the upward vertical motion to unidirectional rotary motion. This rotary motion is recorded as a measure of riding quality.

The BPR-type roadometer has proven to be dependable, easy to operate, and an economical device for measuring road smoothness; however, calibrations must be made at frequent intervals to insure that the field results are reliable. A major disadvantage with the roadometer is the lack of a direct means of calibration to assure that its response to a given pavement input remains the same from one year to another.

Several methods of calibrating the roadometer are available, although no one method by itself is entirely satisfactory. Accuracy of the integrator is very important in the successful operation of the roadometer. In Illinois, the operation of the integrator and recording package was checked periodically by making static calibrations using a reciprocating mechanism. Field calibrations are scheduled at weekly intervals to check the dynamic interaction of the entire system by operating the roadometer on a one-mile section of relatively new rigid pavement.

Until 1968, the Illinois roadometer was correlated annually with the CHLOE profilometer to measure any differences in roadometer output from one year to another. The output of the CHLOE profilometer was assumed to be equal to the output of the AASHO Profilometer with which the initial Illinois roadometer had been originally correlated.

Although the results obtained from these calibration and correlation procedures were statistically adequate, these methods of verifying the roadometer results were not entirely satisfactory. For example, fluctuations in the weekly average RI (Roughness Index) from field calibration measurements were common, but it was impossible to determine how much of the change in weekly average RI was due to the roadometer and how much was due to changes in the pavement being tested.

Because of the uncertainties, a new approach to roadometer calibration was needed to gain greater confidence in the calibration results and to assure that the response to a given set of pavement surface conditions is the same from year to year. A new calibration technique was developed based on the classical technique of frequency response analysis. A vertically oscillating platform was constructed to induce simple harmonic vibrations into the roadometer. The output from the platform tests was compared to a standard frequency response curve developed by assuming that the roadometer can be represented by a system having linear damping with one degree of freedom, such as the case of a mass suspended from a frame by a spring.

Platform testing of the roadometers has been conducted periodically since 1971. The results obtained from these tests have been promising; however, methods must be developed for checking the system's damping factor, the integrator performance at frequencies higher than resonance, and the dynamic effects of the test tire before this new approach to roadometer calibration will gain its full potential.

This report briefly describes past correlation with other roughness measuring devices and current calibration procedures, and introduces a new concept for roadometer calibration which has shown initial promise in determining the degree of repeatibility of the roadometer from one year to another. The work described in this report was conducted as Phase III of Illinois Research Project IHR-74, "Road Smoothness." The study was conducted in cooperation with FHWA since 1957.

CORRELATION OF ILLINOIS ROADOMETERS

In the early stages of roadometer development, the most difficult problem was the establishment of a working relationship between the results of roadometer measurements and highway user opinion of pavement riding quality. During the AASHO Road Test, a relationship was established between subjective ratings of any pavement's ability to serve the traveling public and measurements of surface irregularities made by a profilometer, which records variances in the longitudinal slope of pavements. Therefore, the first step in using the roadometer as a measurement of riding quality was a correlation with the AASHO profilometer. From this initial correlation, a mathematical expression of the relationship between highway user opinion and roadometer measurements, plus certain physical pavement features such as cracking, patching, and rutting, was established. The results of this correlation, plus early experience with the roadometer in Illinois, were reported in 1962 by Chastain and Burke (1). The success of this early correlation greatly enhanced the value of the roadometer in assessing the remaining useful life of pavements.

The original Illinois roadometer was correlated to the AASHO profilometer in 1960. Test data for this correlation were collected by operating the AASHO profilometer and the roadometer in both wheelpaths of ten rigid and eight flexible pavement sections. Analysis of the data consisted of least squares regression between the output of the roadometer and the profilometer. The correlation coefficients and the root mean square error were used to evaluate the resulting equations.

A summary of results is as follows:

For Flexible Pavement

$$\log(1+SV) = 2.04 \log CIR_{20}$$
$$r^2 = 0.84$$
$$\text{rmse} = 0.75$$

For Rigid Pavement

$$\log(1+SV) = 2.4 \log CIR_{20}$$
$$r^2 = 0.84$$
$$\text{rmse} = 0.75$$

where SV (Slope Variance) = output of AASHO profilometer
CIR_{20} = output of Illinois Roadometer at 20 mph

An analysis of road roughness measurements from different devices has indicated that slope variance (profilometer output) has the highest statistical correlation with the pavement serviceability ratings. However, the use of the roadometer for surface smoothness determinations is preferred in Illinois because the roadometer can operate at 20 mph while the profilometer is limited to about 3 to 5 mph, which can create a safety hazard in the traffic stream. Also, the complex electronic equipment of the profilometer is subject to frequent breakdown, which requires the services of a highly skilled electronic technician.

Because the output of the profilometer has a high correlation with the pavement serviceability ratings, and because the relationship between highway user opinion and roadometer measurements was initially formulated by a correlation between the roadometer and the profilometer, the periodic comparison of roadometer output with the output of a slope variance measuring device was desirable. However, at the conclusion of the AASHO Road Test project, the original AASHO profilometer was no longer available for correlation purposes. In 1962, a CHLOE profilometer, which was of the same type used at the Test Road, was made available to the State of Illinois by the Bureau of Public Roads. Until 1968, the roadometer was correlated annually with the CHLOE to determine any differences in the relationship between roadometer measurements and slope variance which may have occurred since the Roadometer 1 was correlated to the original profilometer.

Data for the annual correlation-calibration were collected from ten one-mile test sites, with surface conditions that ranged from smooth to very rough by Illinois standards. Roadometer measurements were made in each wheelpath at each site. CHLOE measurements were made on two 500-ft segments in each wheelpath at each test site because the control box in the CHLOE was capable of accepting data only for lengths up to 500 ft. Analysis consisted of least squares regression between the outputs of the roadometer and profilometer.

The use of the CHLOE as a reference was never entirely satisfactory because of frequent malfunctions in CHLOE's electronic system and because of the limited range of slope variance (equivalent to approximately 165 in./mi in terms of roughness) which CHLOE was capable of measuring.

In 1968, extensive rehabilitation of CHLOE was required if the instrument was to remain in service as a correlation device. A decision was made to discontinue using CHLOE for correlations because the limited benefits of its questionable output did not justify the high cost of performing the necessary repair work.

A second BPR-type roadometer was purchased from the Illinois Toll Highway Commission and, after extensive modification and calibration, was placed into regular service in 1961. Hereinafter, the original roadometer will be referred to as Roadometer 1 and the second roadometer as Roadometer 2. Although both roadometers are similar to the BPR device, there were some differences in the two machines. Initially, Roadometer 1 contained a more complex electrical recording system and traveled within an outrigger trailer, while Roadometer 2 was transported to the test sites within the tow vehicle.

In 1971, both roadometers were modified to make each system as nearly similar as possible. The recording system of Roadometer 1 was modified and simplified because no significant advantage resulted from operating the more complex auxiliary equipment. At the same time, an outrigger trailer was added to Roadometer 2, which eliminated the necessity of carrying the device in the tow vehicle.

The output of Roadometer 2 was generally higher than the output of Roadometer 1. To compensate for this difference, Roadometer 2 was correlated annually to Roadometer 1 before and after extensive winter maintenance, which included complete disassembly, replacement of worn parts and wiring, cleaning, and lubrication. Data from Roadometer 2 were correlated to and reported in terms of Roadometer 1 data because the AASHO performance equations were modified for use in Illinois by using data from Roadometer 1.

Both Illinois machines have always shown good reproducibility of results when properly maintained, and the correlations between roadometers have always been statistically adequate. For correlation purposes, seven one-mile lengths of pavement were used, which ranged up to 235 in./mi in roughness. With two exceptions, the same pavements have been used since 1968. Eight readings were taken on each pavement, four from the center of each lane, within about 40 minutes. The variation between individual readings generally increased as the pavement roughness increased. Each set of four readings ranged between 0 in./mi on the smoother sections to 16 in./mi on the rougher sections. Correlation coefficients averaged 0.995 and ranged between 0.980 and 0.999, and values for the standard error of estimate averaged 5.1 in./mi and ranged between 3.8 and 8.9 in./mi.

Although correlations between the roadometers have been statistically adequate, the use of one roadometer as a reference device for another is not a desirable situation. For greater accuracy in results, the roadometer should be compared to a standard to insure that the roadometer response to a given set of pavement surface conditions remains at the same base level from one year to another.

CURRENT CALIBRATION PROCEDURES

Frequent calibrations of the BPR-type roadometer are necessary to insure that the results remain at the same base level. In Illinois, the calibration procedures used include: (1) static calibrations which check only the integrator and electrical recording system, and (2) field tests on one-mile pavement sections to check the interaction of the entire system under actual operating conditions.

Static Calibrations

Static calibrations of the integrator and electrical counting system were generally scheduled for six-week intervals. Calibrations also were made immediately before and immediately after yearly maintenance or when equipment malfunction was suspected. The tests were made with a reciprocating mechanism capable of inducing frequencies up to two strokes per second and inducing a nominal amplitude up to 0.5 inches per stroke.

Integrator output deviated from input values by as much as ± 2 percent when the integrator and recording system were in proper repair. A major disadvantage of the static calibrations is the low frequencies which can be induced into the integrator.

While the frequency and amplitude at which the integrator is calibrated are limited to two strokes per second and 0.5 in./stroke, the frequencies and amplitudes which the roadometer is subjected to in the field far exceed this upper limit. Although the response of the integrator to induced displacements may be linear at lower frequencies, the inertia of the mechanical integrator system may cause the relationship between input and output to the nonlinear at higher frequencies.

Field Calibrations

Field calibrations are made periodically to check the roadometer under actual operating conditions. During the first four years of the study, the device was checked on an average of once per month. Since then, the time interval between calibrations has been reduced, and field calibrations are now made on the average of one per week during the test season. The time interval was shortened to increase the confidence in the results, i. e., malfunctions are detected sooner, thereby reducing costly retesting.

Calibration courses, consisting of measured, one-mile sections of two-lane pavement, were established in the Ottawa area for Roadometer 1 and the Springfield area for Roadometer 2. Over the years, four to seven courses have been available for use in both the Ottawa and Springfield areas. From time to time, new courses were selected and old courses were eliminated from use for various reasons, such as, but not limited to, (1) resurfacing, (2) excessive roughness, which caused equipment breakdowns, (3) tremendous increase in traffic volume, (4) travel time to and from the course was too great to be economical to continue use of the course, and (5) extensive rehabilitation in the form of deep patching. The courses available for calibration purposes generally ranged in roughness between "very smooth" and "unsatisfactory" by Illinois standards.

The calibration procedures have remained basically the same throughout the life of the study. Prior to taking any measurements, the tire pressure and damper fluid levels were checked, and a warmup of one to five miles was given the roadometer, depending upon the air temperature. This was done in an effort to condition the tire and to bring all components up to stabilized operating temperature before measurements were begun. Four measurements were made at 20 mph in each direction of travel on a single smooth PCC pavement. The average RI and range of RI from each set of four readings were determined and were compared with previous results. At less frequent intervals, generally when malfunctions were suspected, measurements were made on the other courses following the same procedures.

Prior to 1967, two measurements were made in each wheelpath; however, since 1967, four measurements were made in the center of each lane of pavement. Changing to the center of the lane from the wheelpaths provided several advantages. First, increasing the replicates gives a better indication of repeatability and possible malfunction of the roadometer. Second, the calibration takes less time because the crew does not have to change the position of the test trailer for wheelpaths. Finally, as time passed, it was noted that the center of the lane did not deteriorate at the same rate as did the wheelpaths, and it remains in a more relatively uniform condition than the wheelpaths.

Beginning in 1967, calibration data were compared using classical statistical quality control concepts as suggested by Grant (2). The average RI and the range of RI from each calibration were plotted and compared with three standard deviation control limits which were established for each lane of pavement. The initial control limits were established using classical procedures and data collected from 80 roadometer measurements made within three- to four-day periods. The 80 measurements, by the order in which the measurements were made, represent 20 subgroups of four readings per subgroup. Twenty subgroups were considered to be a statistically adequate base on which the control limits could be established.

The control limits were revised whenever at least 14 of 17 successive average RI points on the control charts fell outside the same control line (2). The sequence of 14 of 17 successive points was selected arbitrarily as a check because, generally, the bulk of the field work was completed in the 16-week period from the beginning of June until the end of September; therefore, the use of 17 successive points resulted in one review of the control limits per test season.

No fixed rules could be made regarding the course of action based upon the interpretation of the results plotted on the control charts. On the smooth PCC pavements, which have been used for calibration purposes since 1967, the average RI from each set of four measurements fell outside the upper limits on many occasions throughout each summer test season. The limits were very tight because the large sample (80 passes) was taken in a very short time interval (3 to 4 days). On the other hand, the range of RI within each set of four measurements on any one day averaged less than 3 in./mi and very seldom fell outside the upper control limit which never exceeded 5 in./mi. As a result, when only the average RI was "out of control," the roadometer was given a cursory field examination and, if no malfunctions were found, then it was assumed that the pavement had changed rather than the roadometer. Whenever both the average RI and the range of RI were "out of control," the roadometer was brought back to the office and given a thorough examination and, in most instances, detectable problems were discovered and repaired.

Variations in the average RI from week to week on the "smooth" course were generally less than 6 in./mi, and in several instances the variations in average RI from month to month tended to increase but no permanent increases or decreases were observed. Some variations appeared to be related to temperature and to moisture.

Although some roadometer malfunctions were detected using the field calibrations and quality control charts, this means of calibration was not considered to be satisfactory for verifying roadometer results. As previously indicated, an inherent problem with the weekly calibration pavement is that the RI values of the selected calibration pavements vary throughout the test season, and appear to vary with changes in temperature and moisture. Therefore, it is not possible to determine how much of the change in average RI is due to the roadometer and how much is due to the pavement being tested. Because of the inadequacies of each of the previously mentioned correlation-calibration techniques, it was desirable to develop a new calibration concept or device that will remain constant and can function as a standard.

NEW CALIBRATION CONCEPT

Many instruments that measure vibrations, such as accelerometers, vibrometers, and seismometers, are calibrated by evaluating their frequency response characteristics. In the calibration, frequency response curves are obtained by subjecting the instruments to sinusoidal forces over a large frequency range. The parameters of range, calibration factor, linearity, damping, and natural frequency, usually are evaluated. The instruments generally are represented as a mass suspended from the frame by a spring. Damping is provided either mechanically or electrically.

The new roadometer calibration concept is based on this classical technique of calibration by evaluation of frequency response characteristics. The roadometer has the design elements which would allow calibration by this method. It is a viscously damped spring-mass system which will respond to the irregularities in the pavement surface which are within the roadometer's range of sensitivity.

Figure 1 shows a schematic diagram of the roadometer system. In the Figure, the displacement of the roadometer wheel caused by irregularities in the pavement surface when the roadometer is being towed along the highway is represented by "δ." The symbol "Z" represents the relative vertical movement between the frame and the axle, which is the value that the integrator measures as roadometer output.

Roadometer response to forced vibration by harmonic excitation would describe the system's characteristics and would include the effects of springs, roadometer weight, dampers, integrator, tire, and other components of the roadometer. A simple, vertically oscillating platform was constructed to induce sinusoidal forces over a moderate frequency range. The platform will move up and down at controlled

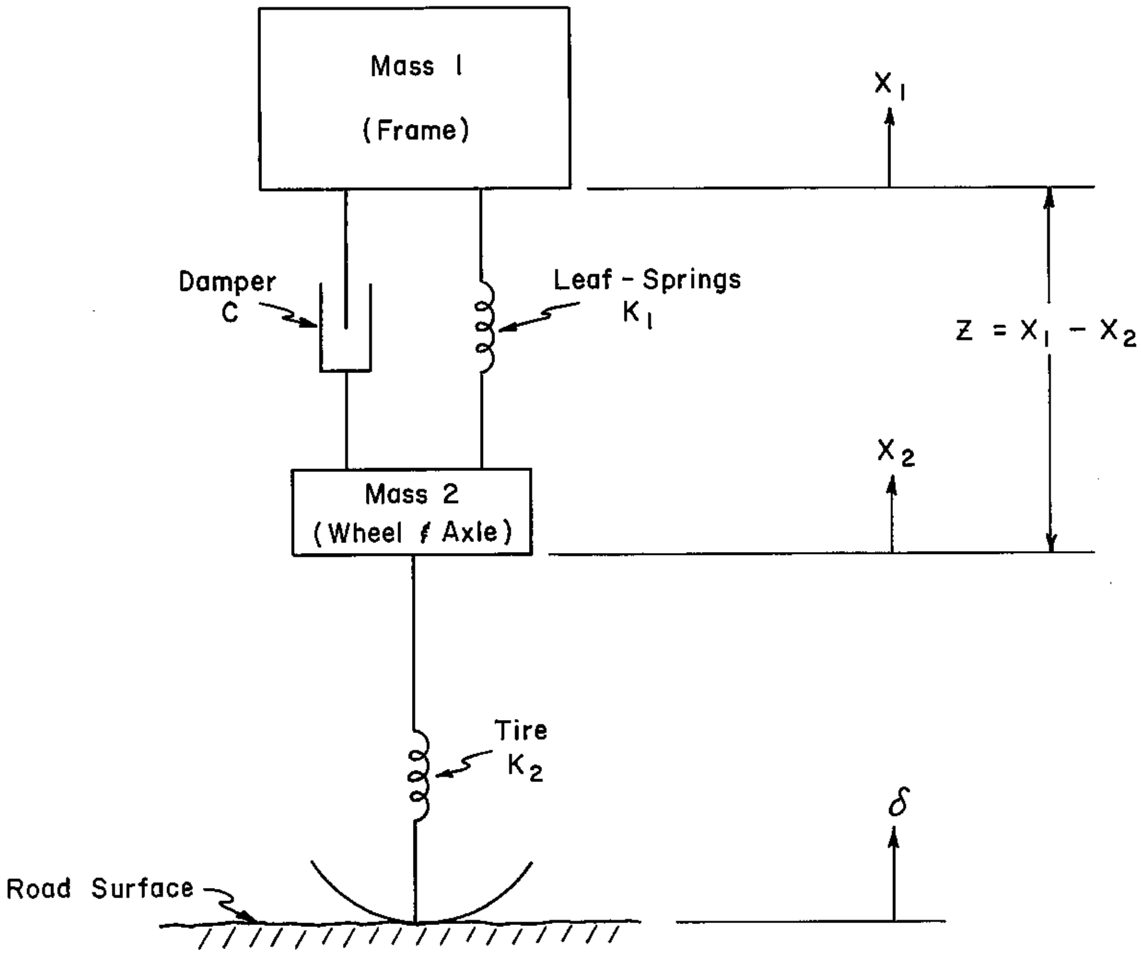

Figure 1. Schematic Diagram Of Basic Roadometer Elements

frequencies between 1 and 7.2 cps. The amplitude can be varied by switching cams; however, funds were limited and only one cam capable of 0.297 in. peak-to-peak excursions was installed. The platform is located in the garage floor at the Physical Research Laboratory, Ottawa, Illinois. The oscillating platform test equipment is shown in Figure 2.

Platform testing of Roadometer 1 was conducted on the average of once per week between August 13, 1971 and October 22, 1971, and annually since then. Frequency response curves were plotted and the results were compared.

A typical response curve is shown in Figure 3. Platform frequencies, in cycles per second, are coordinates along the horizontal axis, and amplitudes, which are the roadometer output divided by platform input (frequency times stroke), are coordinates along the vertical axis.

As can be seen in the Figure, the roadometer responds differently to the various input frequencies. Marked increases in amplitude (magnification) occur as the input frequencies increase between 1 and 2.3 cps. As the input frequency is increased from 2.3 to 7 cps, the amplitude decreases and levels off at about 1.3.

Comparisons of the frequency response curves, which were obtained throughout the test period, show that the shape of the response curve has not changed, but very slight changes have been observed in maximum amplitude and the frequency input at maximum amplitude. However, neither permanent increases nor permanent decreases have occurred in either maximum amplitude or frequency input at maximum amplitude. In order to compare platform calibration results from one period to another, a standard frequency response curve was desirable.

The test results show that the roadometer output closely follows that of a system having linear damping with one degree of freedom. Referring again to

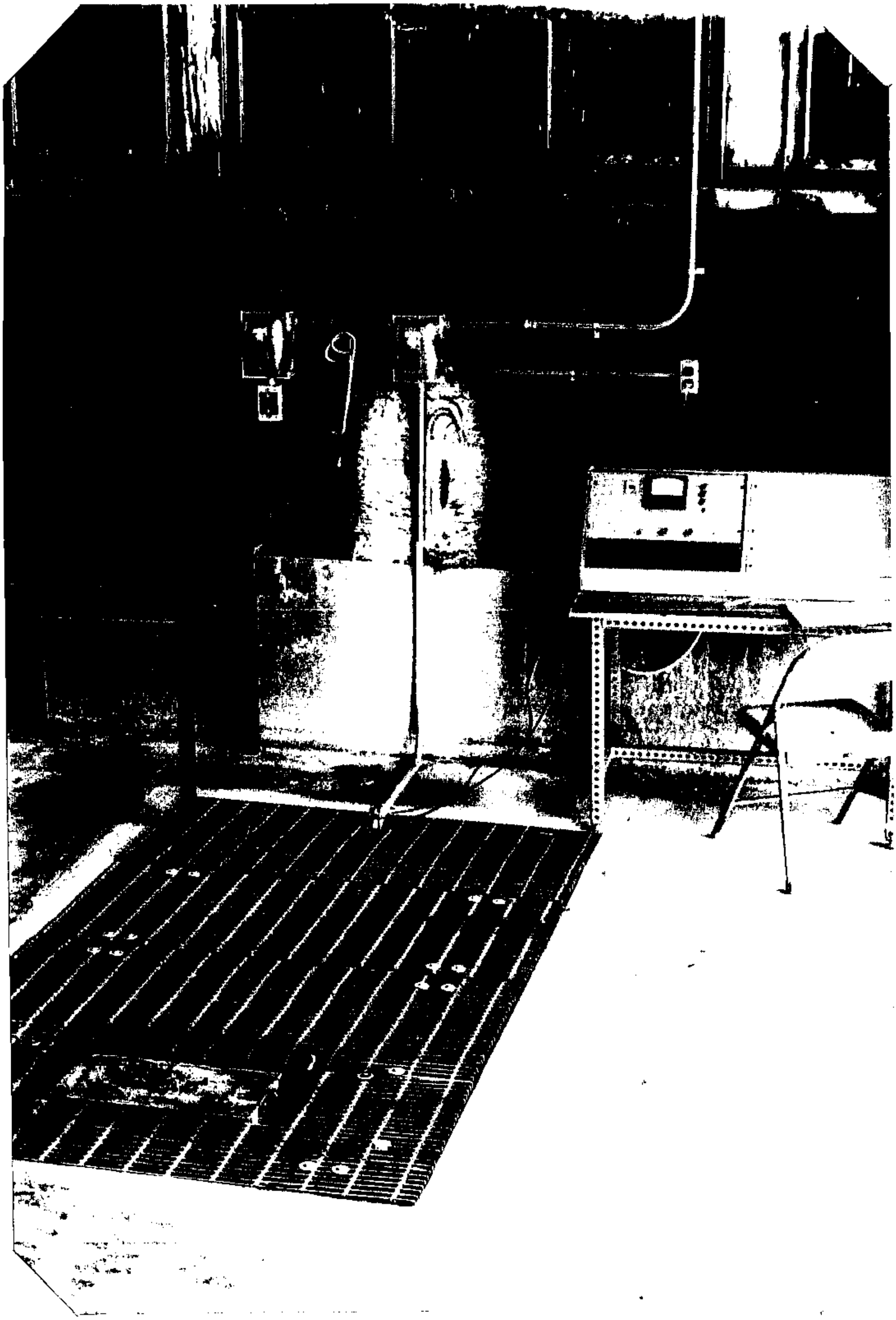

Figure 2. The Oscillating Platform Test Equipment

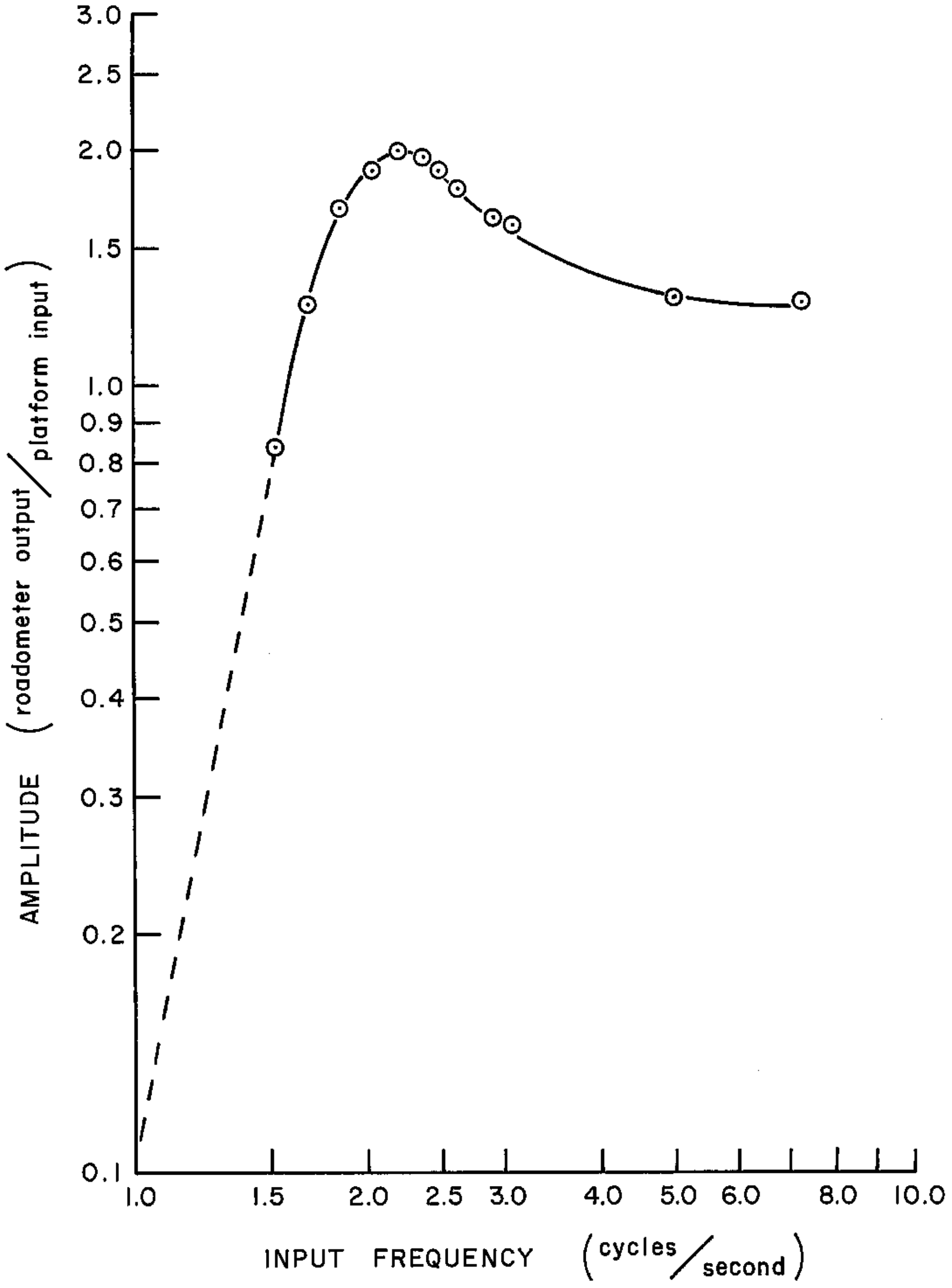

Figure 3. Platform Results For Roadometer I On 10-22-71

Figure 1, when the roadometer is being calibrated on the oscillating platform, δ represents the amplitude of the platform input into the roadometer spring-mass system. For purposes of developing a standard frequency response curve which would be comparable to the real output of the roadometer, the vertical movement of the wheel and axle, X_2, was assumed equal to δ. Since the motion induced into the system has a harmonic oscillation, $\delta = \delta_o \sin \omega t$ where δ_o is the amplitude of the induced motion. The differential equation for this system is:

$$M_1 \frac{d^2Z}{dt^2} + C \frac{dZ}{dt} + K_1 Z = \delta_o \omega^2 \sin \omega t$$

The solution to this equation, as presented in several textbooks on engineering mechanics (3 and 4), can be expressed as:

$$\left|\frac{Z}{\delta}\right| = \frac{\left(\frac{\omega}{\omega_n}\right)^2}{\sqrt{\left[1 - \left(\frac{\omega}{\omega_n}\right)^2\right]^2 + \left(2 \frac{c}{c_{cr}} \cdot \frac{\omega}{\omega_n}\right)^2}} \qquad (1)$$

where Z = the relative movement between the roadometer axle and the frame = roadometer output in inches per second.

δ = the movement induced into the roadometer by the oscillating platform = Input Frequency (cycles/sec) x stroke (in./cycle)

$\frac{Z}{\delta}$ = a dimensionless value termed the magnification factor

ω = the frequency of the induced oscillations

ω_n = the natural frequency of the mass of the wheel and axle

$\frac{\omega}{\omega_n}$ = the frequency ratio

C = viscous damping coefficient

$C_{cr} = 2M\omega_n$ = critical damping coefficient

$\frac{C}{C_{cr}}$ = damping factor

By plotting Equation 1 in the form $\frac{Z}{\delta}$ versus $\frac{\omega}{\omega_n}$, a unique frequency response curve results for each value of $\frac{C}{C_{cr}}$. From test data, values for $\frac{Z}{\delta}$ and ω are known. A relationship between $\frac{\omega}{\omega_n}$ and $\frac{C}{C_{cr}}$ at the point of maximum magnification factor can be established by setting the first derivative of Equation 1 equal to zero. This results in the equation:

$$(2) \qquad \frac{\omega}{\omega_n} = \sqrt{\frac{1}{1 - 2\left(\frac{c}{C_{cr}}\right)^2}}$$

By substituting Equation 2 into Equation 1, the following relationship results between the maximum magnification factor and the damping factor:

$$(2) \qquad \left|\frac{Z}{\delta}\right|_{max} = \frac{1}{2\left(\frac{c}{C_{cr}}\right)\sqrt{1 - \left(\frac{c}{C_{cr}}\right)^2}}$$

Thus, by knowing the maximum magnification factor from test data, the value of $\frac{C}{C_{cr}}$ for the frequency response curve can be found from Equation 3, and the frequency ratio at which $\left|\frac{Z}{\delta}\right|_{max}$ occurs can be found from Equation 2. With this information, the frequency response curve for the system can be plotted.

Based on the above relationships, each day's test data were analyzed by computer, and the data points plotted in the form of a frequency response curve. Although the basic shape of the response curve did not change from one test to another, very slight shifts of the curve occurred. Because of the shifts in the curve, a standard curve which would serve as a base level for comparison purposes was desirable.

A standard frequency response curve for Roadometer 1 was developed based on Equation 1 and on an average magnification factor obtained during the testing of Roadometer 1. Similar procedures were used to establish a standard frequency response curve for Roadometer 2.

Figure 4 contains a plot of the standard frequency response curve for Roadometer 1 and a plot of actual Roadometer 1 data points which were collected on October 22, 1971. As can be seen in the Figure, the actual field data closely

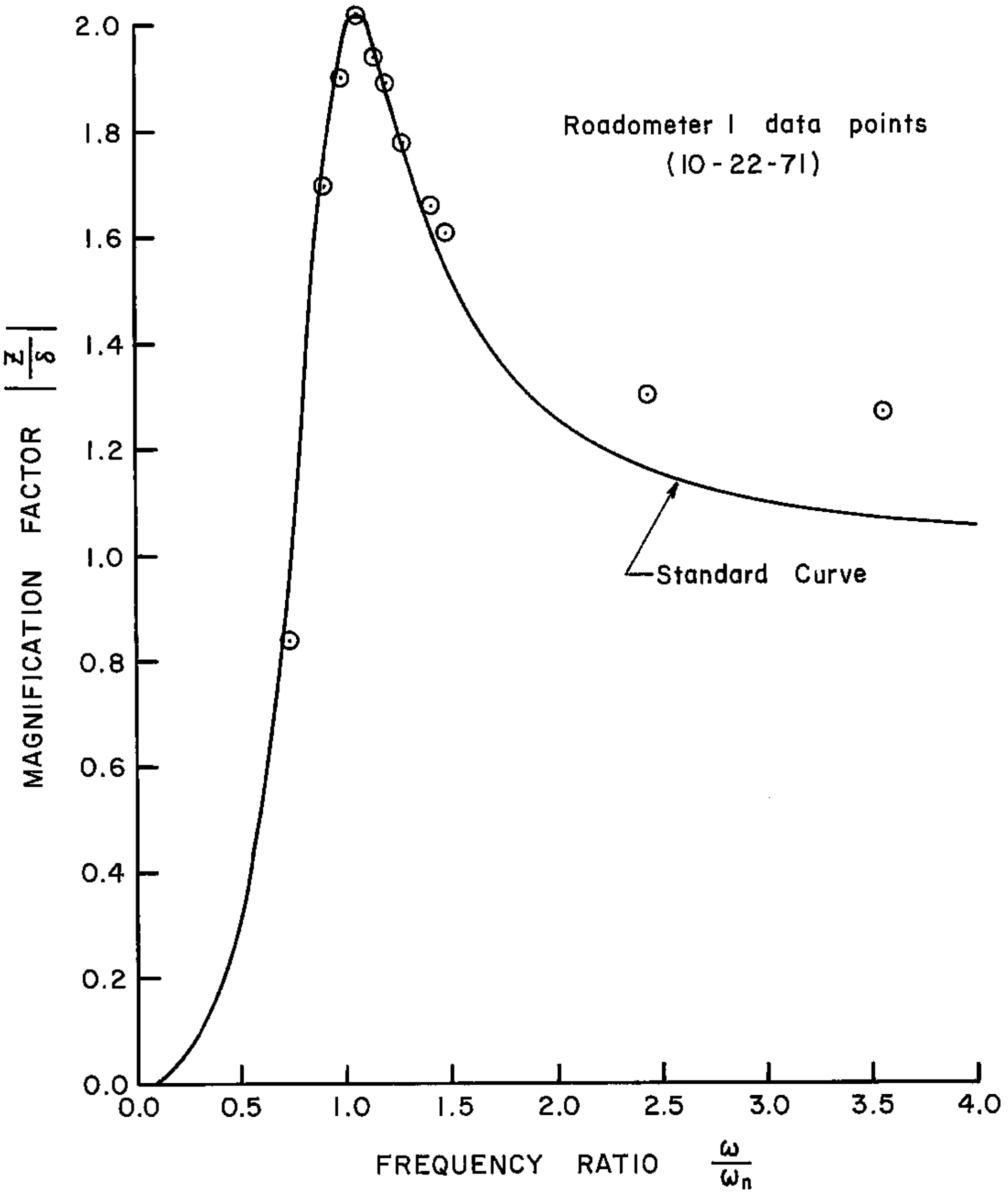

Figure 4. Actual Roadometer Data Points Compared To The Standard Frequency Response Curve

follow the theoretical line between frequency ratios of about 0.8 to approximately 1.3. From frequency ratios 1.3 to 4, the standard curve approaches a magnification factor of 1, but the actual roadometer output approaches 1.2 magnification factor.

The divergence of actual data points from the theoretical line is believed attributable to the integrator. Although the mechanical integrator presently in use reacts linearly within the frequency and amplitude range which can be analyzed with present calibration equipment (up to 2 strokes/sec and 0.5 in./stroke), it is believed that the integrator reacts nonlinearly at higher frequencies and amplitudes.

The fact that the actual roadometer output closely follows the theoretical line strongly suggests that the roadometer can be analyzed using classical methods, and that the roadometer output can be analyzed periodically to assure that the response to a given set of input conditions is the same. However, the full potential of this method of calibration has not been realized.

At the present time, actual data can be compared with the standard curve, but the effect of roadometer components cannot be isolated. Theoretically, the roadometer could be calibrated very accurately by isolating and modifying the effects of the various components. Experience has shown that the leaf springs and roadometer weight can easily be controlled; however, the dampers, integrator, and tire present a more difficult problem. Therefore, further consideration should be given to the standardization of roadometer parts; to the development and construction of test equipment capable of measuring the damping factor, the integrator output at higher frequencies and amplitudes, and the effects of the roadometer tire; and to expanding the input capabilities of the oscillating platform.

CONCLUSIONS

The various methods used to calibrate the roadometer all provide some indication of the realiability of roadometer data; however, they all have certain limitations.

While static calibration using a reciprocating mechanism has proven to be a satisfactory procedure for checking the operation of the integrator within the available calibration equipment limits, the input frequency and amplitudes are lower than those encountered during the operation of the roadometer. Although the deviation in integrator output has been shown to be ± 2 percent or less through the recommended test procedures, the accuracy at higher frequencies and amplitudes commonly encountered in the field has not been established.

Field calibrations accomplished by operating the roadometer over a selected section of pavement do not provide conclusive results. Although the calibration indicates that changes have taken place, uncertainties exist as to whether the roadometer or the pavement was the factor that changed.

Periodic correlation of the roadometer with the CHLOE profilometer was not entirely satisfactory because of frequent malfunctions of CHLOE's electronic recording system, and because of the limited range of slope variance which CHLOE was capable of measuring. Consequently, the use of CHLOE as a correlation device was discontinued in 1968.

The use of an oscillating platform as a calibration device has shown promise in determining the repeatability of roadometer response to a given input. The platform method includes the combined effect of the entire roadometer system on the output results under controlled conditions. On the basis of these results, the roadometer can be analyzed using frequency response analysis as is used to evaluate the response characteristics of such devices as the accelerometer, the vibrometer, and the seismometer. From the differential equation of motion most closely describing the action of the roadometer system, a standard frequency response curve can be obtained for each roadometer. A comparison of the roadometer-oscillating platform results with the standard curve indicates the deviation of roadometer response from one time to another.

Presently, a comparison of the platform calibration results with the standard theoretical curve can indicate that the roadometer is not operating correctly; however, the cause of any deviation from the standard curve cannot be pinpointed. This problem possibly can be alleviated in the future by the development of equipment capable of determining the individual effects of the major components of the roadometer system. Also, modification of the oscillating platform to increase its output capability would be helpful by expanding the range of frequency response which the platform is capable of inducing into the roadometer.

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