AN ELECTRO-MECHANICAL SYSTEM FOR MEASURING THE DYNAMIC DEFLECTION OF A ROAD SURFACE CAUSED BY AN OSCILLATING LOAD

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1. INTRODUCTION

The 1963-64 plan of research for Research Project 2-8-62-32, "Application of the AASHO Road Test Results to Texas Conditions," required the investigation of a system developed by the Lane-Wells Division of Dresser Industries, Inc., for the purpose of recording the deflection of a road surface caused by application of an oscillating load. If the system proved satisfactory, Lane-Wells, working under contract with the Texas Transportation Institute, was to measure deflections on test sections included in the Phase III testing program of this research project.

This report describes the measurement system and then gives the results of the investigation.

Since the system is owned and operated by the Lane-Wells Division of Dresser Industries, Inc., the technical description given below was written (at the request of the Project Supervisor) by an employee of the firm, Mr. Gilbert Swift, who was directly involved in the development of the equipment and its use on this project. Quotation marks are used to separate Mr. Swift's remarks from the remainder of the report.

2. "LANE-WELLS DYNAMIC DEFLECTION DETERMINATION SYSTEM"*

"The Dynamic Deflection Determination (DDD) System consists of a

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*The Dynamic Deflection Determination System is proprietary with Lane-Wells Company and is covered by pending U. S. patent applications.

vehicle and trailer equipped with a dynamic force producing apparatus with appropriate deflection measuring and recording apparatus (Figures 1 and 2). The system is designed for use on roadways, bridges and other forms of construction which are accessible to the vehicle. It measures and records the deflection of the material beneath the trailer caused by application of an oscillatory force.

"The force is generated by a pair of counter rotating eccentric weights and is applied to the surface of the material through a slightly crowned steel wheel as shown in Figure 3. The periodic motion of the material is sensed by means of one or more geophones placed in contact with the material at suitable locations in the vicinity, and is recorded in the towing vehicle.

"The eccentric weights are customarily rotated at a constant speed of 425 rpm or 7.1 revolutions per second. The vertical force applied to the ground varies sinusoidally at 7.1 cycles per second from a minimum of 758 lbs. to a maximum of 1242 pounds.

"Two vertical motion sensing pickups (geophones) are customarily placed 9-1/2 inches from the force applying wheel; one at each side, in line with the axle (Figures 3 and 4). The outputs of these two pickups are added electrically to provide a reading representative of the average motion of the material at these two locations. The electrical response of the

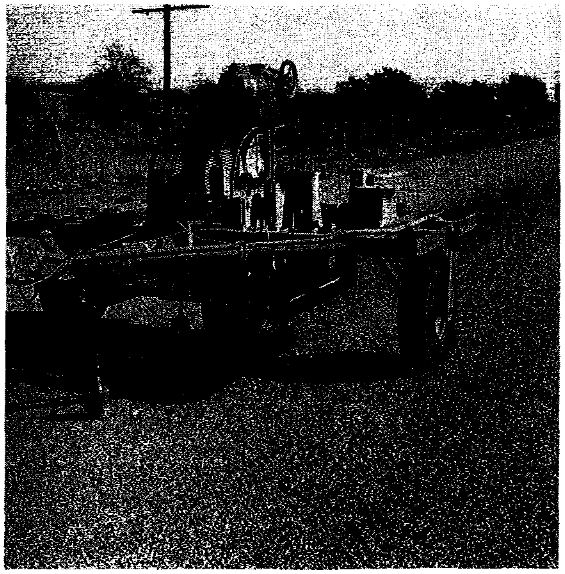


FIGURE 1: Trailer equipped with motor, eccentric weights and steel wheel through which oscillating load is applied.

FIGURE 2: Towing truck carries generator on bumper, recording equipment inside. The driver operates all equipment.

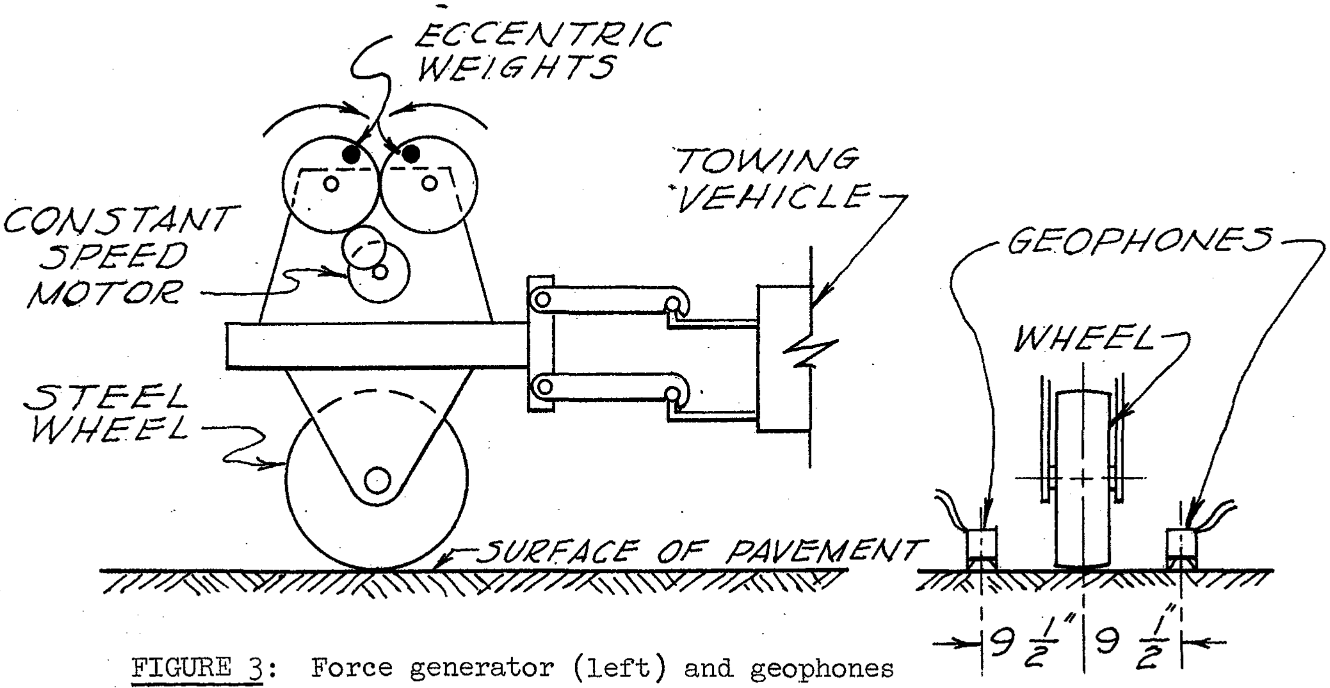


FIGURE 3: Force generator (left) and geophones for sensing ground motion 9.5 inches from point of load application.

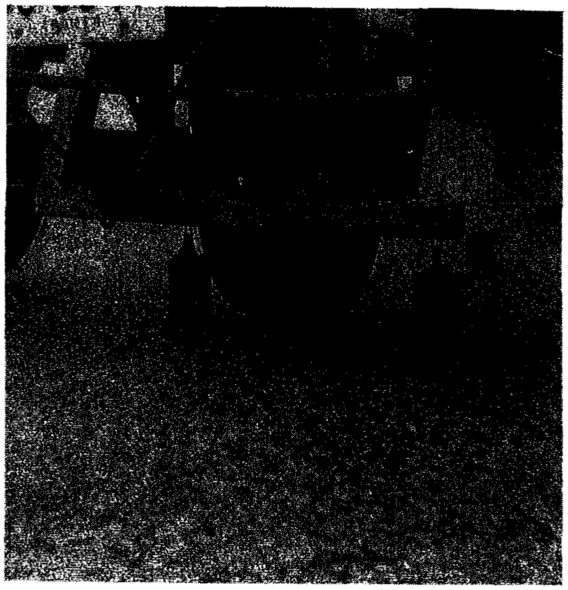


FIGURE 4: Close-up of force wheel and geophones.

amplifying and recording system is limited by narrow band filters to respond only to the fundamental frequency component of the motion, at 7.1 cycles/sec. As shown in Figure 5, the amplifier output is rectified, integrated over a period of one second and applied as direct current to a strip-chart recorder to provide a reading of the amplitude of the motion.

"As a consequence of using a sine-wave force, and of using narrow band filtering of the geophone output signals, the electrical input to the amplifier is an analog of the motion of the surface.

"Basically, a geophone consists of a coil suspended by a spring in the field of a magnet, as shown in Figure 6. When its case (and magnet) is subjected to vertical oscillatory motion the spring suspended coil tends to lag behind this motion. Accordingly, the coil acquires a velocity relative to the magnet. The output voltage of a geophone is precisely proportional to the instantaneous relative velocity between the magnet and the coil. For any single frequency of excitation this relative velocity bears a fixed linear relationship to the amplitude of the motion, and hence the electrical output of the geophone at this frequency provides a direct measure of the amplitude of the motion.

"Calibration of the entire motion sensing and recording portions of the system is achieved by placing the geophones on a cam-operated platform driven in synchronism with the eccentric weights (Figures 7 and 8). The response of the system is adjusted to a standard value with the geophones

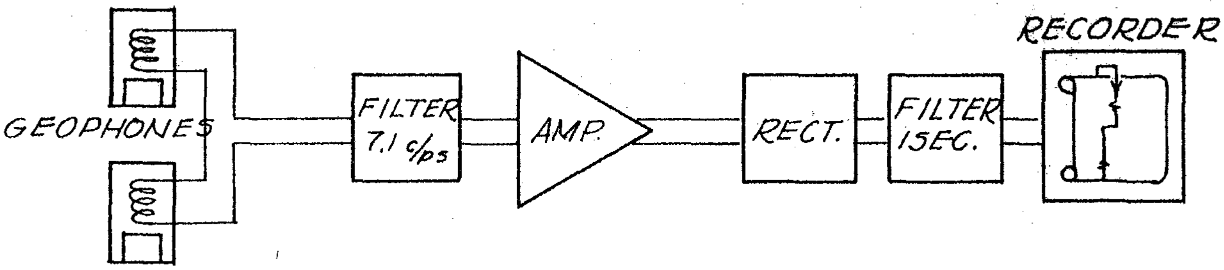


FIGURE 5: Motion Sensing and Recording Equipment.

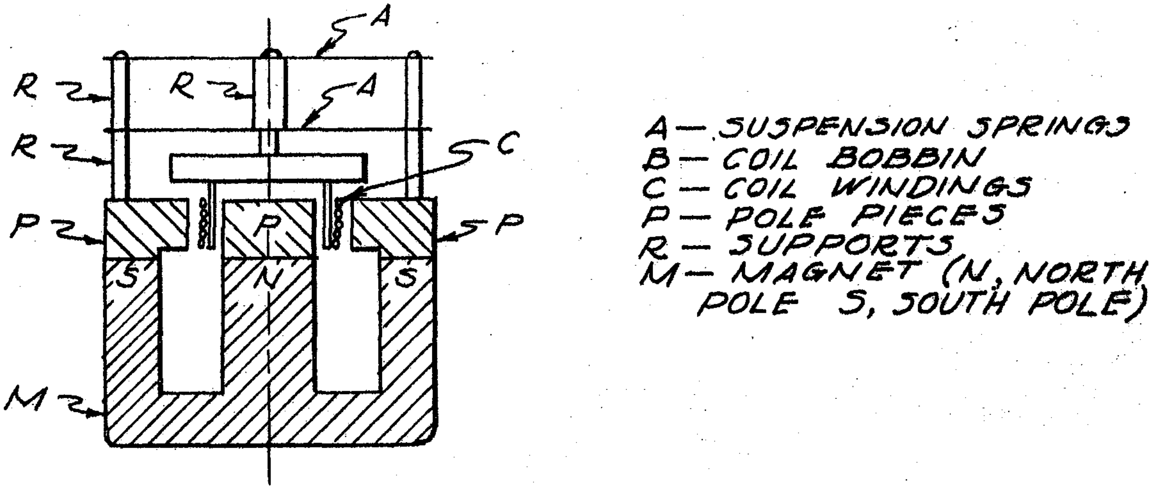


FIGURE 6: Typical Geophone.

FIGURE 7: Field calibration device driven through flexible shaft by same motor that drives eccentric weights on trailer.

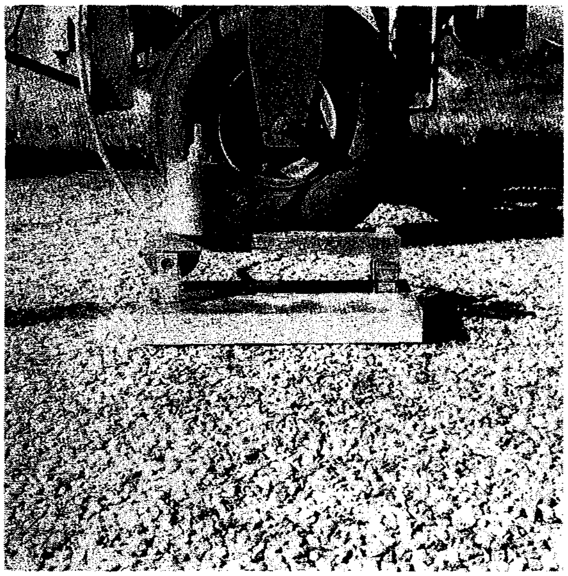


FIGURE 8: Close-up of calibration device. Cam at left imparts sinusoidal motion of known amplitude and standard operating frequency to geophone resting on lever pivoted at right.

in place on this platform whose motion is fixed at 0.01 inch by the eccentricity of its cam. All the observed responses obtained with the geophones on the ground can then be expressed in terms of the standard response and thereby related to actual deflections in fractions of an inch.

"The apparatus can be moved long distances at high speed by raising the force applying wheel and force generator, the weight of which is then supported by conventional vehicle tires. For shorter distances, only the geophones are picked up. The operator can raise and lower the geophones from within the vehicle and can thus stop, record a measurement and proceed to the next nearby location within less than one minute."

3. INVESTIGATION OF THE EQUIPMENT

The investigation of the equipment took the form of a correlation study of the output of the system with the rebound deflection of a 9,000 lb. wheel load as measured with a Benkelman Beam. The procedure was as follows:

A point in the outer wheel path of a flexible pavement was tested with the dynamic deflection system. A keep mark was made at the point where the oscillating load was applied. The instrument van and trailer were then driven ahead and a heavy truck, with a load of 18,000 pounds on the rear axle, was placed with the center of its outer dual wheel directly over the previously marked point. The probe of a Benkelman Beam was then placed on the mark between the outer dual wheels, and an initial reading of the dial was recorded. The truck was then driven ahead about fifty feet, and a second reading of the dial was taken. From the two readings the rebound deflection was calculated and recorded.

The truck was then again placed on the mark and a second Benkelman Beam rebound deflection was measured in the manner described above. The two deflections were averaged and recorded as the Benkelman Beam deflection at the point.

Some of the earlier Benkelman Beam data, when compared with the Lane-Wells measurements, indicated that the front support of the Benkelman Beam may have been within the deflection basin in a few cases. For this reason, a second beam was frequently used to check movement of the front support (sometimes at the rear support, also), and where movement was found the Benkelman Beam data were corrected accordingly (Figure 9). Except in the case of exceptionally stiff (stabilized) pavements, however, movements of the supports of the Benkelman Beam were small and the force of the wind acting on the instrument frequently made the reading of these motions difficult or impossible. As a result, the greater portion of the Benkelman Beam data was not corrected for movement of the supports.

Comparison of the reading recorded by the dynamic deflection system (corrected for non-linearity of pen motion as described below) with the Benkelman Beam system was made at fourteen points in the outer wheel path on each of thirty-five flexible pavement test sections, twelve of which were in District 12 and the remaining 23 in District 9.

As indicated earlier (Section 2) the ultimate output of the Lane-Wells

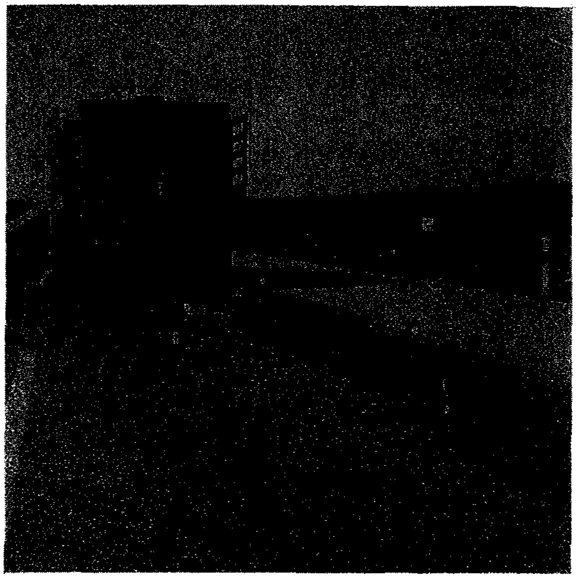


FIGURE 9: In correlation study three Benkelman Beams were sometimes used, one with probe between dual tires of truck in background, the others with probes at front and rear supports of the first.

device is a mark made by a pen on a moving paper chart. The chart is graduated into one-quarter inch wide bands normal to the direction of pen motion (Figure 10). The excursion of the pen is recorded manually in units and tenths of these one-quarter inch bands as indicated in Figure 10.

An experiment conducted by the Lane-Wells Company showed that the relation between pen motion and the amplitude of geophone output was curvilinear for pen excursions in the range from zero to 3.75 inches, and linear beyond that range. Data from the same experiment provided a means by which the actual pen excursions can be transformed to values that are linear with the geophone output -- and therefore with the amplitude of the pavement motion -- throughout the full range of pen motions. The relation between the actual and the transformed (or corrected) values is shown in Figure 11.

Figure 12 shows corrected chart readings of the Lane-Wells device representing the average output of 2 geophones 9.5 inches from the oscillating load, plotted against the rebound (measured by the Benkelman Beam) of the pavement surface at the same location after application and subsequent removal of a 9,000 pound wheel load.

There were 490 data points available for analysis. A least squares regression yielded a correlation coefficient of .91 between the two tests, and indicated that a Benkelman Beam deflection could be predicted from

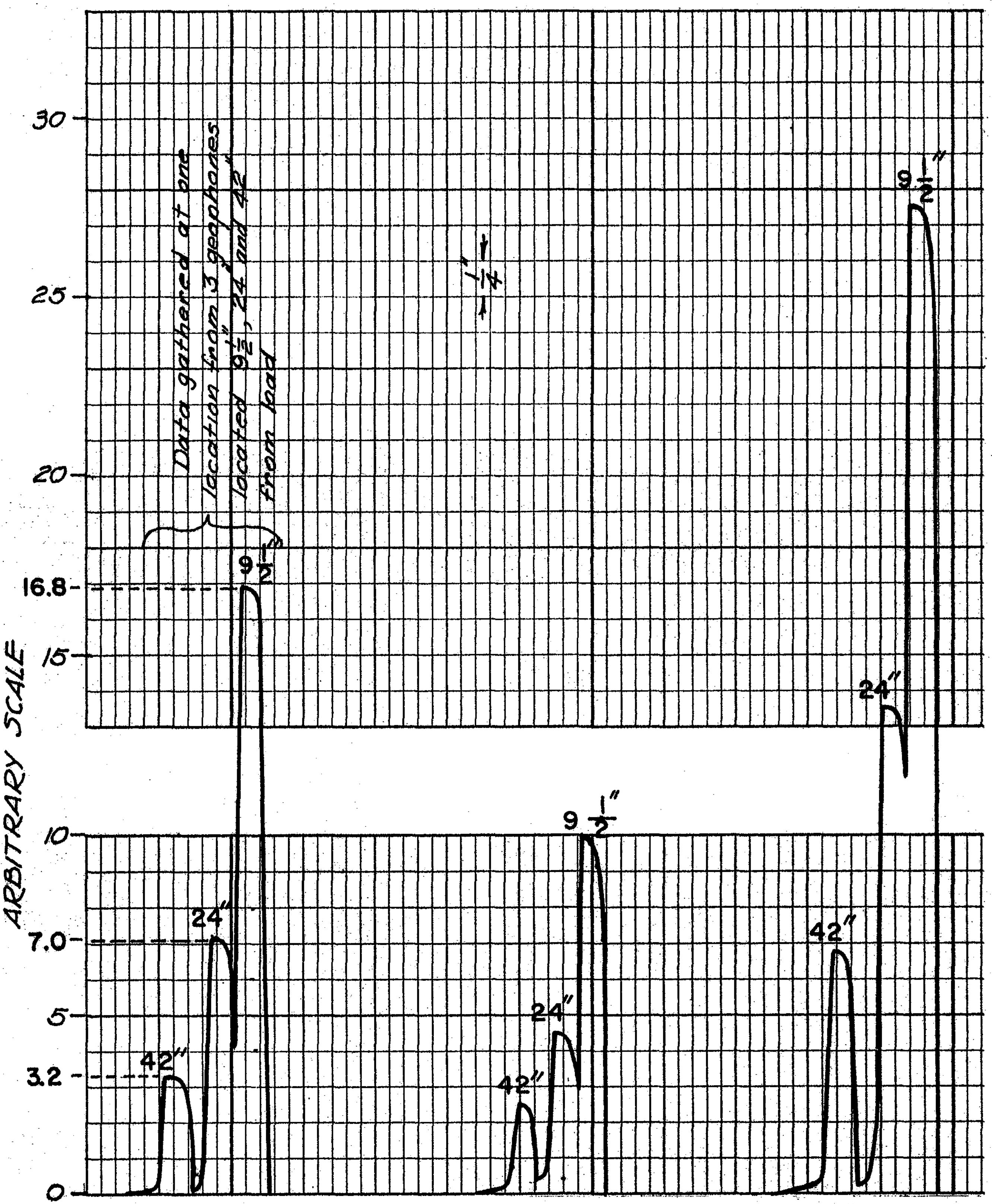
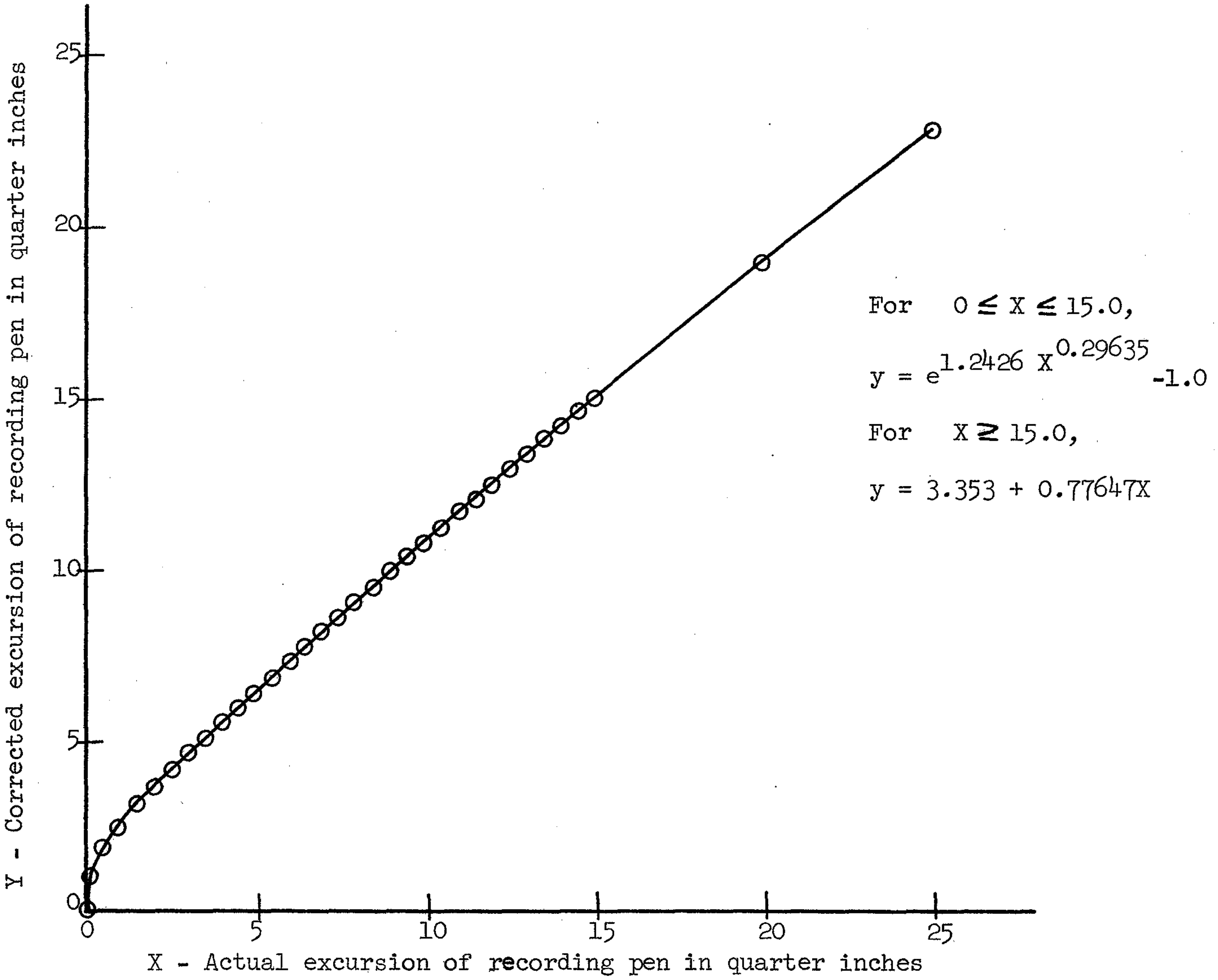


FIGURE 10: Samples of trace made by recording pen. (This chart was designed for another use requiring the blank space which serves no purpose here.)



For $0 \leqq X \leqq 15.0$,

$$y = e^{1.2426\, X^{0.29635}} - 1.0$$

For $X \geqq 15.0$,

$$y = 3.353 + 0.77647X$$

FIGURE 11: Graph of actual chart readings versus corrected values.

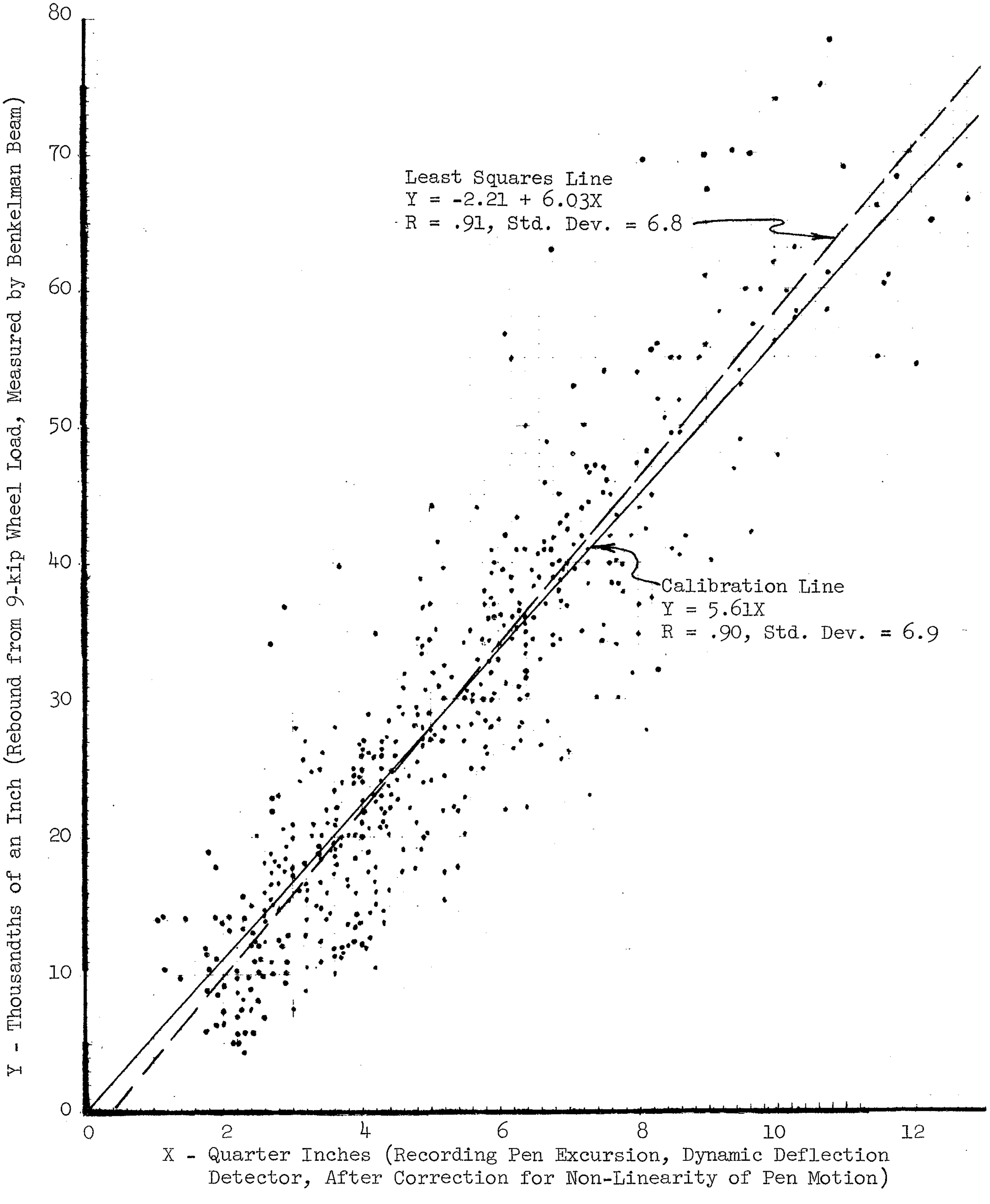


FIGURE 12: Dynamic Deflection Detector calibration data. Each of the 490 points represents a direct comparison between a Detector reading taken at a point on a flexible pavement, and a Benkelman Beam measurement made at the same point (about 5 minutes later) of the rebound following removal of a 9-kip wheel load.

a Lane-Wells test with a standard deviation of .007 inch. It will be noted from Figure 12 that the line fitted by minimizing the squared errors intercepted the Y (Benkelman Beam deflection) axis at -.0022 inch and had a slope of 6.03. A second line passing through the origin of the graph, and with a slope so chosen that the sum of the deviations of the data points from the line would be zero, has the equation

$$Y = 5.61X \tag{1}$$

where Y is the Benkelman Beam deflection in thousandths of an inch and X is the corrected reading of the dynamic deflection recording pen. While the least squares line is perhaps slightly more accurate, the second line is more convenient for use in converting dynamic deflection data to estimates of deflections that would be caused by a 9,000 pound wheel load.

Table 1 gives the design and <u>averaged</u> deflection data for each of the 35 test sections used in the correlation study. Individual Lane-Wells chart readings were corrected for non-linearity of pen motion before they were averaged. Analysis of the deflection data in the table indicated that a section average of 14 Benkelman Beam deflections could be predicted -- with a standard error of .005 inch -- from averaged Lane-Wells data by use of the equation:

$$\overline{Y} = 5.61\overline{X} \tag{2}$$

where $\overline{Y}$ is the section average Benkelman Beam deflection in thousandths

TEST SECTIONS INCLUDED IN CORRELATION STUDY

		SURFACING		BASE		SUBBASE		SUBGRADE		
Section	District	Type	Thick.	Triaxial Class	Thick.	Triaxial Class	Thick.	Triaxial Class	Average Benk. Beam Deflections	Average Corrected Chart Readings
15-7-2**	9	A.C.	4.0"	1.8	12.3"	3.5	7.7"	6.0	20.7	3.5
15-14-3	"	"	4.0	2.0	11.7	3.0	3.3	4.0	23.1	4.8
55-2-1	"	S.T.	1.2	2.0	5.6	3.0	5.0	4.8	21.0	3.9
209-2-1	"	"	9.5	2.0	9.4	3.5	9.2	5.5	31.8	6.2
209-3-1	"	A.C.	5.5	2.7	8.3	2.8	7.0	5.6	12.9	3.7
209-7-1	"	"	0.9	*	8.4	*	6.5		13.7	2.8
251-2-1	"	"	1.9	1.8	8.4	3.6	10.8	4.5	22.1	3.1
251-3-1	"	"	1.7	1.8	9.4	3.6	20.5	5.6	13.3	2.1
258-7-1	"	"	2.1	2.1	8.4	-	0	5.0	32.0	5.3
258-7-2	"	"	2.7	2.7	7.5	-	0	4.8	38.2	6.4
258-7-3	"	"	2.2	2.7	7.8	-	0	5.2	37.9	7.2
386-3-1	"	S.T.	0.5	1.8	8.4	2.8	2.0	5.5	38.4	6.1
386-3-2	"	"	0.5	1.8	8.8	2.8	2.7	4.8	26.8	4.5
386-4-1	"	"	0.5	2.5	5.2	-	0	4.8	46.8	8.4
386-4-2	"	"	0.5	2.5	6.9	-	0	5.2	46.8	7.4
398-5-1	"	"	0.5	2.7	7.1	-	0	4.9	25.1	3.0
519-3-1	"	"	0.5	1.8	9.3	-	0	4.3	29.2	4.9
590-2-1	"	"	0.5	2.1	9.6	2.8	8.6	5.6	36.8	7.0
833-4-1	"	A.C.	1.5	*	13.4	-	0	3.0	17.3	3.2
833-4-2	"	"	1.5	*	6.7	-	14.0	5.0	12.9	2.8
836-2-2	"	S.T.	0.5	L.Stab.	5.8	2.8	6.7	5.2	19.8	4.5
1665-1-1	"	"	0.5	1.8	4.9	-	0	5.6	45.3	8.8
2305-1-1	"	"	0.5	2.8	5.3	-	0	4.8	19.1	4.0
27-9-1	12	A.C.	2.7	L.Stab.	7.7	C.Stab.	5.3	5.3	15.2	4.3
111-1-1	"	"	1.5	C.Stab.	13.8	-	0	5.5	6.7	2.2
179-2-1	"	S.T.	1.8	3.0	9.7	4.0	8.0	4.5	54.0	8.7
389-5-1	"	A.C.	2.5	3.0	9.3	-	0	5.0	34.9	5.9
389-12-1	"	"	1.9	3.0	12.0	4.5	10.0	5.5	29.1	4.5
978-2-1	"	"	.9	C.Stab.	5.0	2.0	4.7	5.5	15.6	4.4
1005-1-1	"	AC over ST	1.0	3.0	6.8	3.2	3.8	4.3	34.4	5.9
1005-1-2	"	"	1.0	3.0	6.7	4.3	3.5	5.4	36.1	6.1
1607-2-1	"	S.T.	0.7	3.0	6.8	4.2	8.7	5.5	63.4	11.4
1685-3-1	"	"	0.5	3.0	7.3	-	0	4.3	26.4	4.3
1685-3-2	"	"	0.4	3.0	6.8	4.3	10.0	5.5	41.8	6.9
2105-1-1	"	"	0.8	3.0	7.2	3.5	9.0	5.0	31.8	6.8

* Triaxial class not available - ** 5-Layer section; layer not shown is 5.8-inch lime-stabilized subgrade

Abbreviations: A.C.= Asphaltic concrete. S.T.= Surface treatment. L.Stab.= Lime stabilized. C.Stab.= Cement stabilized.

of an inch and $\overline{X}$ is the average of the corresponding Lane-Wells corrected chart readings. The correlation coefficient was .93.

4. ROUTINE USE OF THE DYNAMIC DEFLECTION DETERMINATION SYSTEM

For routine use on flexible pavements the Lane-Wells instrument has been equipped with two additional geophones, so that deflections can be measured at three distances -- 9.5", 24" and 42" -- from the point of load application. From these measurements the general shape of the deflection basin can be estimated.

Only one man is required to operate the equipment and transport it between the sections. The operator transcribes the recorded data on Fortran sheets ready to be sent to the IBM key punch operator, and he mails the sheets daily to project headquarters. Here the data are punched in cards for further processing in the IBM 709 computer. Thus between fields and computer the data are hand written only once.

The three deflection measurements previously described are made at each of 15 locations in the outer wheel path of each 2500-ft. test section, for a total of 45 deflection determinations per section. The averaged elapsed time from arrival at the beginning point of a section to departure after completion of the last test is approximately 30 minutes.

In the first month of routine operation (February 11 through March 11, 1964) deflections were measured on 70 sections located in Districts 12, 13, 16, and 21, in an area extending along the Gulf Coast from Galveston to the southern tip of Texas. In this period -- which included 22 working days -- the operator travelled 2500 miles (exclusive of week-end trips to his Houston headquarters) and recorded 3150 deflections.

In the routine operations to date there has been only one hour of lost time chargeable to equipment maintenance.

5. DISCUSSION AND CONCLUSIONS

Some of the scatter of the data evident from Figure 12 may have resulted from the fact that the dynamic deflections were affected by the inertia of the pavement structure, while the static deflections were not. A simple example of this source of scatter would be the case of two pavement structures equal in all linear dimensions and mechanical properties except density. These two pavements would logically deflect equally under a static load but unequally under a dynamic load. Deflection data from two such pavements, if plotted on a diagram like Figure 12, would appear as two separate points on the same horizontal line.

Another source of scatter may have been the fact that dynamic deflections were measured at a point located 9.5 inches from the load, while static deflections were measured at the center of gravity of the load. Thus, two pavements exhibiting equal static deflections would yield different dynamic deflections if the two deflection basins differed in shape. As in the case discussed in the previous paragraph, deflection data from these two pavements would appear as two points on a horizontal line in Figure 12. (A later model of the Lane-Wells device will be equipped with an additional geophone capable of sensing the motion of the rigid load wheel so that deflections at the point of load application can be measured.)

Regardless of the reasons for the scatter of the data, the following conclusions are drawn from this study:

1. While considerable scatter of the data is evident from Figure 12, the relatively high correlation coefficient is taken as good evidence that the Lane-Wells Dynamic Deflection Detection System responds to those properties of a flexible pavement structure that govern the deflection of the pavement under heavy wheel loads. For this reason, and in accordance with the research plan outlined in the 1963-64 Proposal, the instrument is being used in the Phase III testing program of this project.

2. The device appears to be rugged, rapid, reliable and more economical to operate than other systems known to the writers, especially in cases where the objective is to determine the shape of the deflection basin.