A New Research Tool for Measuring Pavement Deflection

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•IN CONNECTION with current research being conducted for the Texas Highway Department and the U. S. Bureau of Public Roads, it became necessary in 1964 for the Texas Transportation Institute to measure deflections on several hundred flexible pavement sections on highways throughout Texas. Before initiating a program of that size, we decided to investigate a device recently developed by Lane-Wells Division of Dresser Industries, Inc., capable of recording the deflection of a road surface caused by the application of a relatively light oscillating load. If it could be shown that the deflection so induced correlated reasonably well with static deflection measured by conventional means, we felt that certain unique advantages of the device would warrant its use in our research.

This report describes the Lane-Wells measurement system, gives the results of the preliminary investigation, and presents data illustrating how the deflection basin is ›cted by variations in the structural design of the pavement. It also describes an ı...proved model of the system developed in 1965 by Lane-Wells as a result of their experience in this research.

Figure 1. Dynaflect halted for measuring roadway deflections; force generator is located in covered trailer; deflection pickups rest on pavement beneath trailer tongue.

1965 VERSION OF DEFLECTION MEASURING SYSTEM

General Description

The Lane-Wells Dynaflect, developed after completion of the 1964 measurements program on Texas highways, consists of a small two-wheel trailer containing a dynamic force generator and equipped with a set of motion-sensing devices (Fig. 1).

Deflections of the roadway, or other material beneath the trailer, caused by a cyclic downward force, are measured while the trailer is halted briefly at each test location. Deflections are read directly on the meter shown in Figure 2.

Dynamic Force Generator

The cyclic force is produced by a pair of counter-rotating unbalanced flywheels

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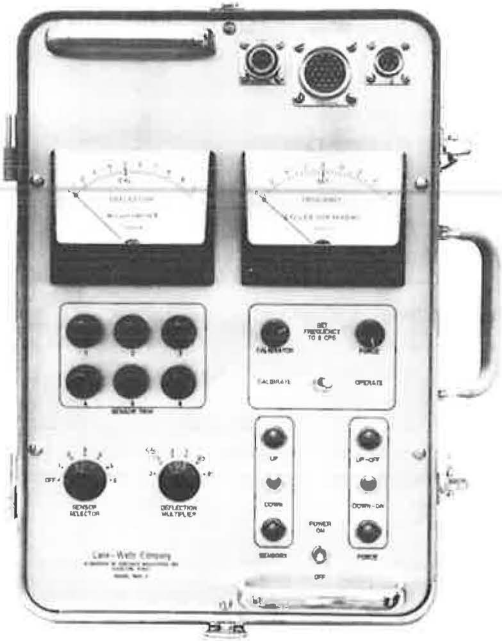

Figure 2. Control panel with frequency and deflection meters.

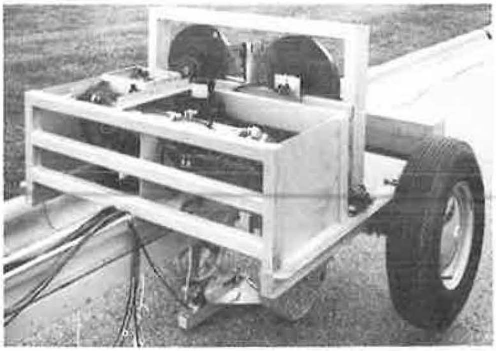

Figure 3. Trailer with hood removed; force generated by unbalanced flywheels at top of picture is transmitted to road through steel wheels at bottom.

(Fig. 3). Two eccentric rotating masses produce a vertical reaction force which is transmitted to the ground. The horizontal reactions cancel by virtue of the opposing rotations. The instantaneous force is proportional to the unbalanced mass and to its vertical acceleration. Accordingly, its value is given by the expression:

$$F = 4\pi^2 f^2 r \frac{W}{g} \sin (2 \pi f t)$$

where

F = force, in lb;
f = rotation rate, in cps;
r = radius of eccentric mass, in ft;
w = weight of eccentric weight, in lb;
g = acceleration of gravity, in ft/sec^2;
t = time, in sec.

In the present model, operating at 8 cps, the dynamic force varies in sine-wave fashion from 500 lb downward to 500 lb upward during each rotation, a total excursion of 1,000 lb. The entire force applied to the ground consists of the weight of the trailer,

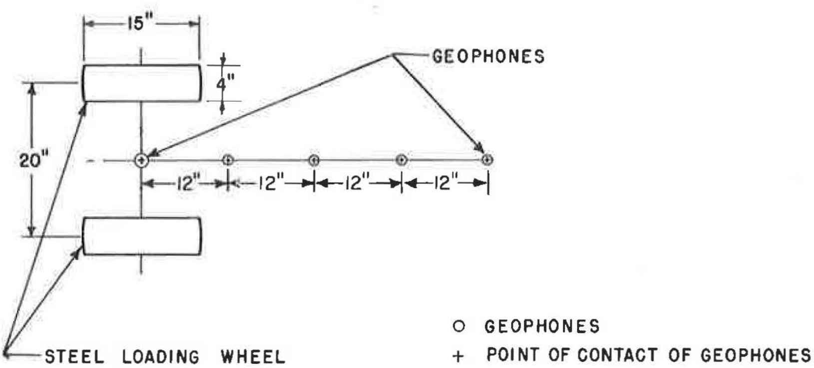

Figure 4. Typical arrangement of geophones used with the Dynaflect (plan view).

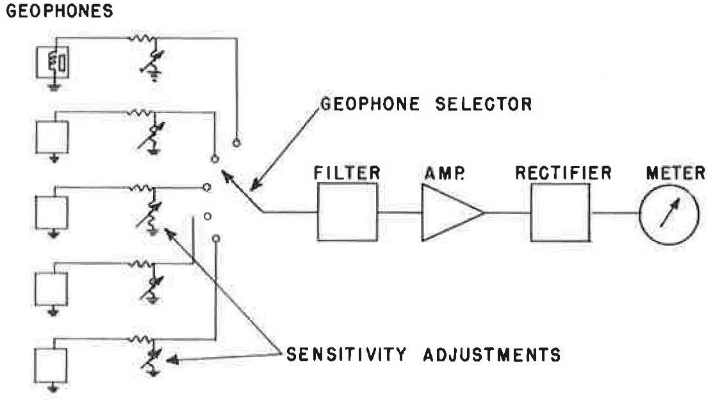

Figure 5. Motion sensing and measuring system.

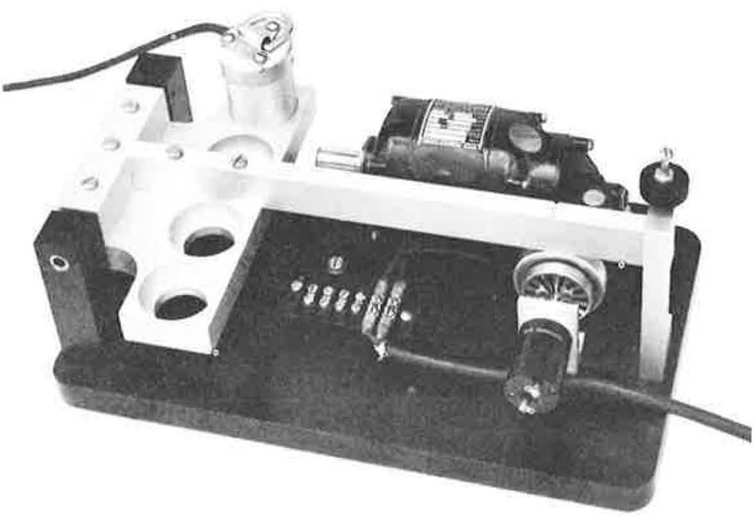

Figure 6. Device for calibrating geophones.

approximately 1,600 lb, together with the dynamic force which alternately adds to and subtracts from the static weight. Since the static weight amply exceeds the dynamic force, there is always a substantial downward component. Thus there is no tendency for the device to lose contact with the ground.

The cyclically varying force is applied to the ground through a pair of steel wheels, whereby the equipment can be moved readily from one measuring point to another.

The rotation rate of 8 cps has been chosen sufficiently low to provide good correlation with static deflection measurements, yet sufficiently high to render the apparatus simple and compact.

Deflection Measuring System

The material to which the dynamic force is applied deflects in synchronism with the force, not only directly beneath the wheels, but throughout a nearby region which constitutes the deflection basin. The amplitude of this induced cyclic vertical displacement is sensed by geophones (seismometers) which are lowered into contact with the

Figure 7. Dynaflect is controlled and deflections recorded inside towing vehicle.

surface at appropriate distances, between a few inches and several feet, away from the steel wheels (Fig. 4). Because these distances are all large in comparison with the area of contact between the wheels and the surface, variations of the contact area have negligible effect on the observed deflections.

The geophones respond to the 8-cps induced motion and produce electrical signals proportional to this motion. Since the displacements are cyclic, their measurement does not require a fixed reference point in the vicinity. For this reason, the dynamic method is immune to the errors encountered with other methods when their reference points lie within the deflection basin.

Each geophone consists of a coil, spring-suspended for vertical motion, within the field of a permanent magnet. When the magnet is subjected to cyclic vertical motion, the coil tends to remain stationary. Accordingly, the coil acquires a cyclic velocity with respect to the magnet and a voltage proportional to the instantaneous velocity is developed within the coil. At any single frequency of excitation, the magnitude of the geophone output voltage is precisely proportional to its motion.

The geophones are used, one at a time, to determine the deflection at each point in the array (Fig. 5). The electrical output signal from each geophone is filtered and amplified to produce a reading on a meter. The narrow-band filter limits the response of the system to the fundamental frequency component of the induced motion at 8 cps. Thus the meter readings represent only the displacements induced by the force generator and are unaffected by extraneous vibrations caused by moving traffic or other sources. Deflections up to a maximum of 30 thousandths of an inch and down to a minimum of 0.01 thousandth can be measured with the present apparatus.

Standardization of the deflection measuring system is accomplished by placing each geophone on a cam-adjusted platform which provides a smooth, repetitive, 0.005-in. vertical motion at 8 cps (Fig. 6). Individual sensitivity controls associated with each geophone are then adjusted to obtain the corresponding reading of 5 milli-in. on the deflection-indicating meter.

Operational Characteristics

A lift mechanism in the trailer moves the force generator in or out of contact with the ground. When lifted, the trailer is supported on rubber tires for travel at legal driving speeds. With the force generator in contact, the unit may be moved on its steel wheels from one measuring point to another at speeds below 10 mph. To enable such moves to be made rapidly, the geophones are raised and lowered by remote control (Fig. 7).

Setup and calibration requires less than 3 min. Measurement of the deflections at each location takes less than 1 min.

1964 VERSION OF DEFLECTION MEASURING SYSTEM

The deflections reported herein were made with a system (Fig. 8) that differed significantly from that described previously only in the following respects:

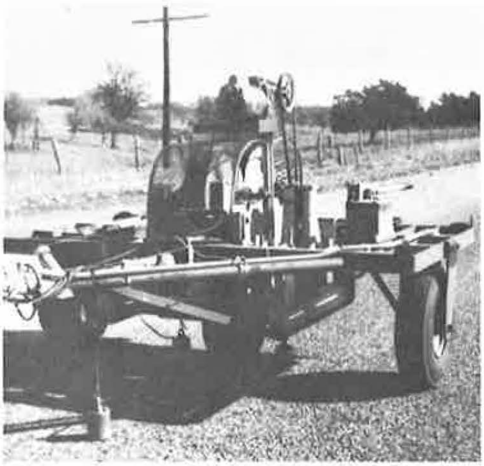

Figure 8. 1964 model of Dynaflect which was correlated with static deflections on Texas highways.

Figure 9. 1964 model in which force was transmitted to roadway through a single steel wheel.

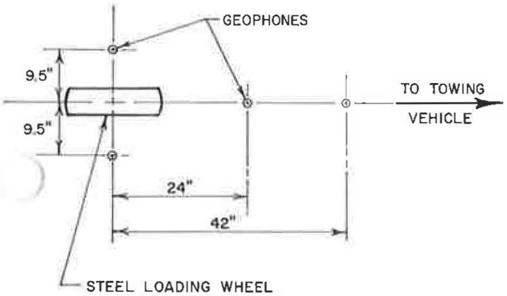

Figure 10. Arrangement of geophones in relation to point of load application used in correlation study and in routine measurements made in 1964; the average output of the two geophones at 9.5 in. from load was correlated with Benkelman beam deflections.

Figure 11. Three Benkelman beams sometimes used in 1964 correlation study: beam in background measured deflection at wheel load; two beams in foreground registered movement at the supports of distant beam.

1. The rotation rate in the 1964 model was 7. 1 cps (instead of 8 cps).

2. The dynamic force varied sinusoidally from 242 lb upward to 242 lb downward (instead of 500 lb upward and 500 lb downward).

3. The force (Fig. 9) was applied to the ground through a single steel wheel (instead of through two wheels).

4. The geophones were placed at distances of 9. 5, 24 and 42 in. from the load as shown in Figure 10 (instead of as shown in Fig. 4).

5. The readout device was a trace made by a pen on moving paper tape (instead of a direct reading meter).

INVESTIGATION OF 1964 SYSTEM

The investigation of the 1964 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 h a Benkelman beam. The procedure was as follows.

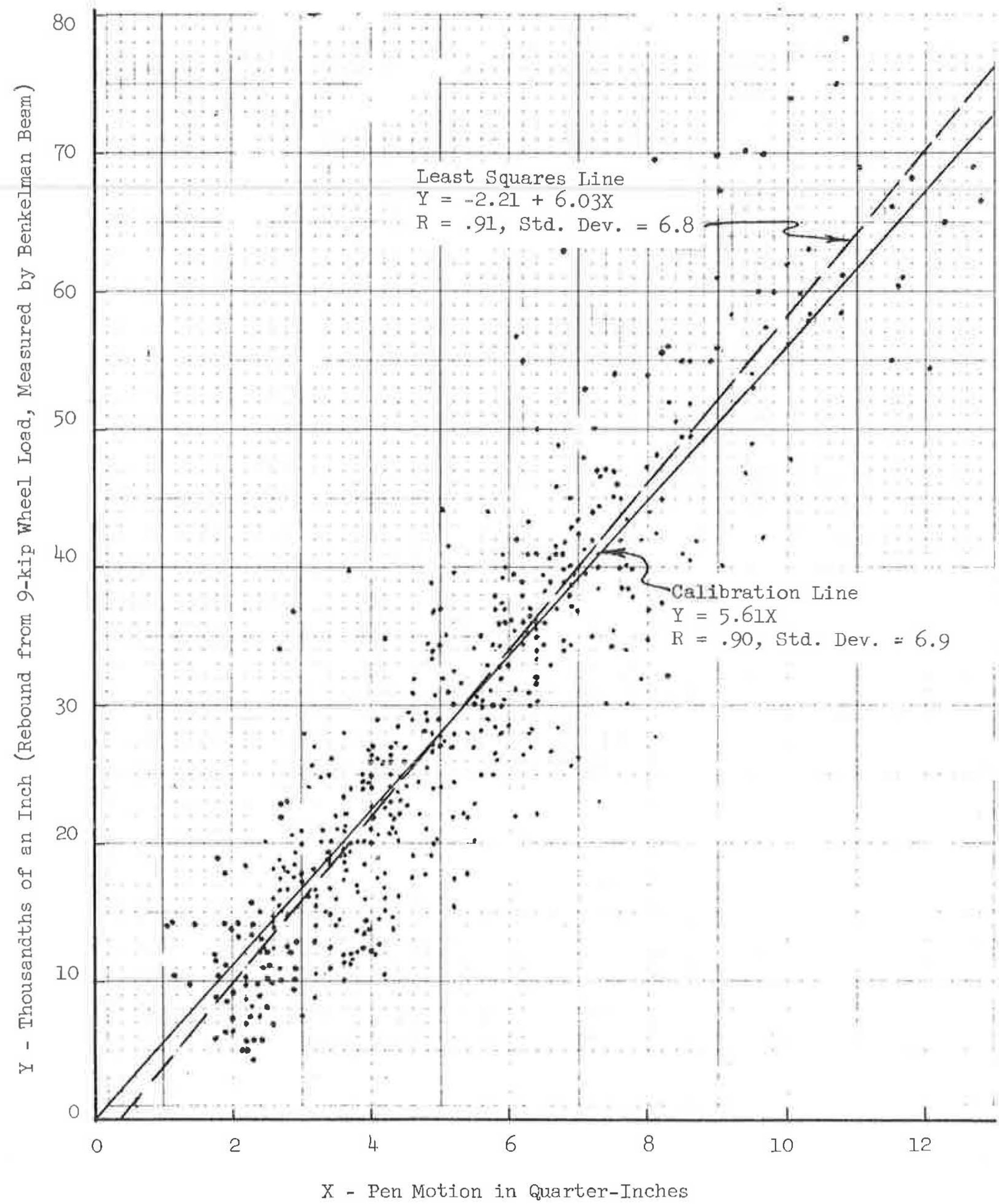

Figure 12. Calibration data for 1964 equipment: each of the 490 points represents a direct comparison between a reading taken at a point on a flexible pavement and a Benkelman beam measurement made at the same point (about 5 min later) of the rebound, following removal of a 9-kip wheel load.

A point in the outer wheelpath of a flexible pavement was tested with the dynamic deflection system. A keel 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 lb 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 wheels, and an initial reading of the dial was recorded. The truck was then driven ahead about 50 ft, and a second readin

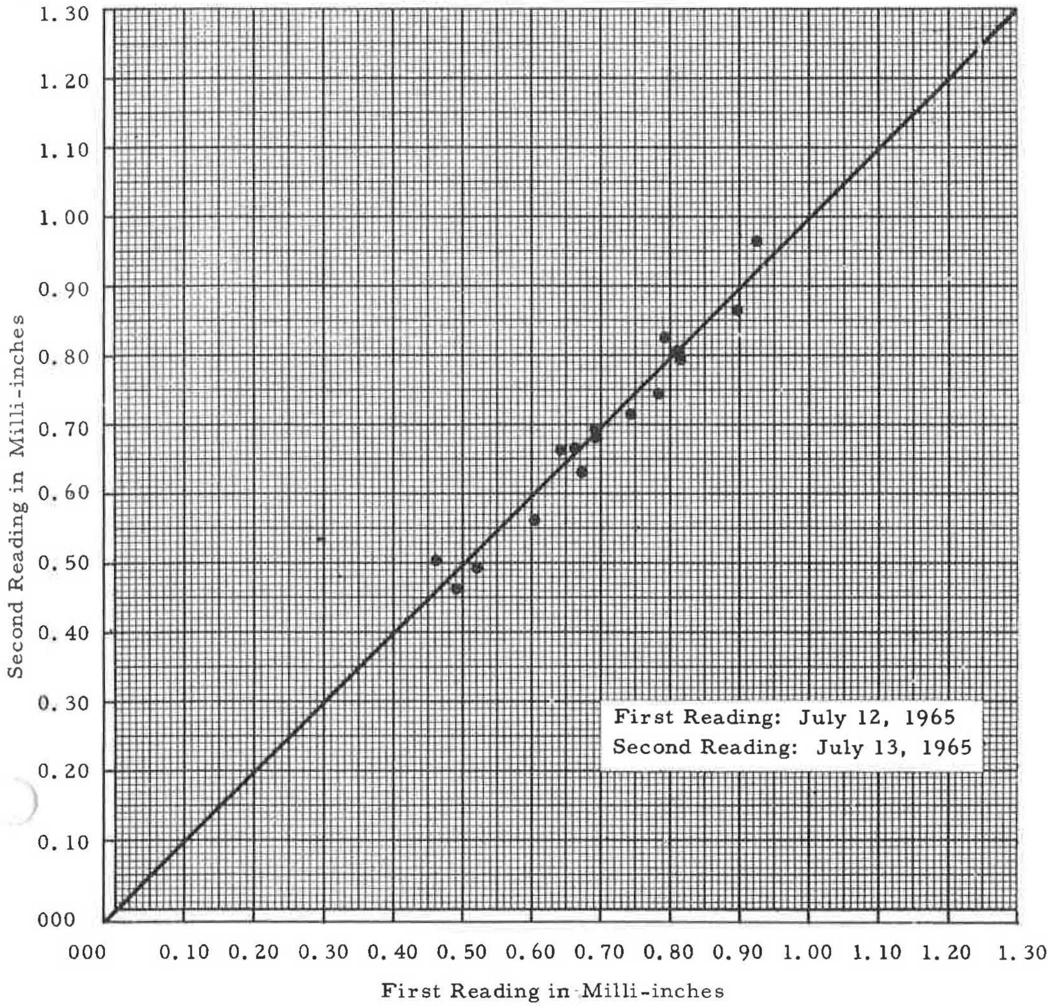

Figure 13. Repeatability of Dynaflect measurements.

of the dial was taken. From the two readings, the rebound deflection was calculated and recorded.

The truck was again placed on the mark and a second Benkelman beam rebound deflection was measured in the manner previously described. 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 (Fig. 11). Except in the case of exceptionally stiff (stabilized) pavements, however, the observed 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 and unreliable. As a result, the greater portion of the Benkelman data were not corrected for movement of the supports.

Comparison of the reading recorded by the dynamic deflection system with the Benkelman beam system was made at fourteen points in the outer wheelpath on each

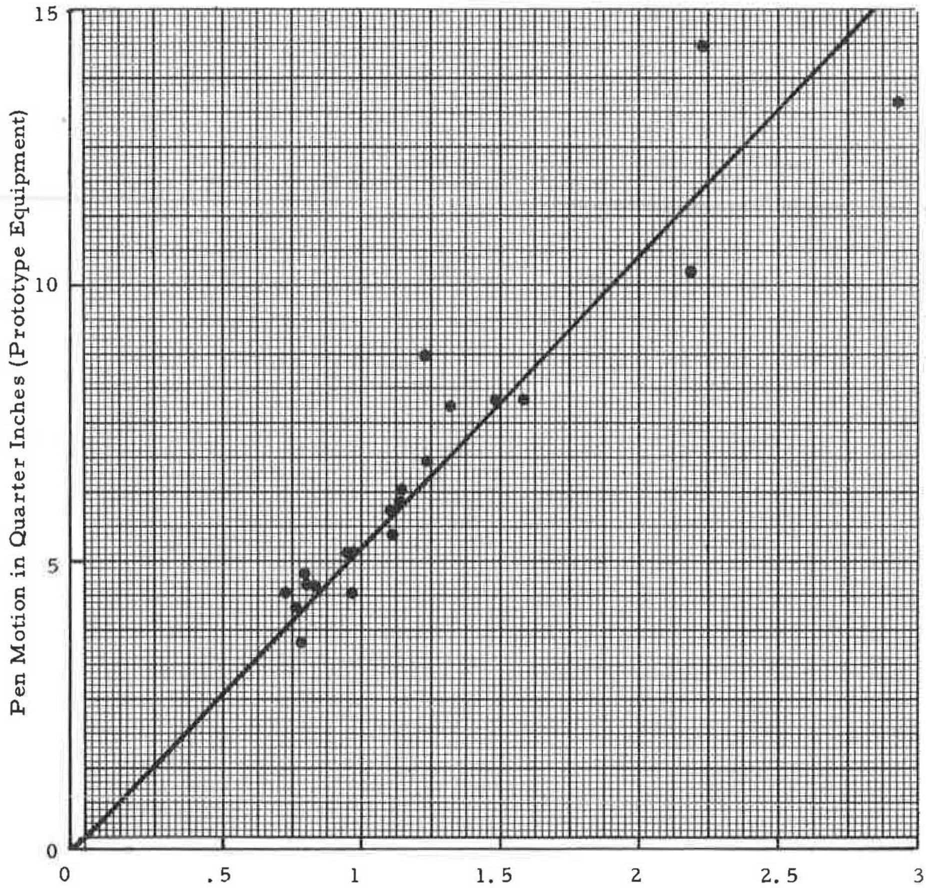

Figure 14. New model Dynaflect compared with prototype.

of thirty-five flexible pavement test sections, twelve of which were in Texas Highway Department District 12 (near Houston) and the remaining twenty-three in District 9 (near Waco).

Figure 12 shows readings of the Lane-Wells device representing the average of two geophones 9. 5 in. 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-lb wheel load.

There were 490 data points available for analysis. A least-squares regression yielded a correlation coefficient of 0. 91 between the two tests, and indicated that a Benkelman beam deflection could be predicted from a Lane-Wells test with a standard deviation of 0. 007 in. Figure 12 shows that the line fitted by minimizing the squared errors intercepted the Y (Benkelman beam deflection) axis at -0. 0022 in. 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

$$Y = 5.6X$$

where

Y = Benkelman beam deflection in thousandths of an inch, and
X = reading of dynamic deflection recording pen.

Although the least-squares line is perhaps slightly more accurate, the second line is more convenient for use in converting the dynamic deflection data (for the geophone located 9. 5 in. from the load) to estimates of deflections that would be caused by a 9,000-lb wheel load.

CORRELATION STUDY

Dynamic deflections measured at the same location on two successive days have been found to repeat within close limits. The results of one such comparison on flexible pavements are shown in Figure 13.

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, whereas the static deflections were not. A simple example of this source of scatter would be the case of the 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 in. from the load, whereas 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.

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

1. Although considerable scatter of the data is evident from Figure 12, the relatively high correlation coefficient was taken as good evidence that the 1964 Lane-Wells system responded to those properties of a flexible pavement structure that govern the deflection of the pavement under moving wheel loads.
2. The 1964 device appeared 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.
3. Based on the foregoing, the decision was made to use the instrument in our 1964 testing program involving several hundred flexible pavement sections.
4. While the correlation study was confined to the 1964 system, the authors are confident that the improved 1965 equipment would correlate as well, and possibly better, with static deflections, as the same design principles were used, and the distance from the load to the nearest geophone was reduced from 9.5 to about 2 in. (The conversion factor determined for the 1964 equipment for estimating 9,000-lb wheel load deflections, however, does not apply to the new equipment because the load configuration is different.) A comparison of the deflections measured by the two pieces of equipment at the same locations on flexible pavements is shown in Figure 14.

EXAMPLES OF MEASURED DEFLECTION BASINS

Existing Highways

Figure 15 shows the approximate range of the deflection determined in the 1964 program, during which 376 sections were tested, and illustrates the general shape of the deflection basins found on existing highways.

Each curve in Figure 15 represents an average of the deflection basins determined at fifteen locations in the outer wheelpath of a 2,500-ft test section. Design data for the five sections, including the Texas Highway Department's Triaxial Class for base, subbase (when present) and subgrade, are given in Table 1.

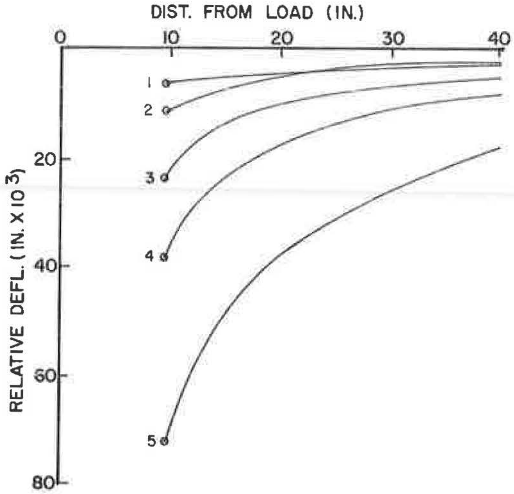

Figure 15. Typical deflection basins measured on Texas highways; circled points represent estimated static deflection under a 9,000-lb wheel load (see Table 1 for design data).

The deflection data for plotting the basins in Figure 15 were obtained by multiplying the output of the geophones (located at 9.5, 24, and 42 in. from the point of load application) by the calibration factor obtained in the correlation study previously described. Thus, the circled points plotted on the graph represent the estimated static deflection that would be caused by application of a 9,000-lb wheel load. It was felt that this method of presenting the data would be more meaningful than showing the actual deflections gaged by the oscillating load.

Special Sections

Figure 16 is similar to Figure 15 except that the data were obtained on newly constructed test sections before surfacing, and an additional geophone, placed at a distance of 5 in. from the load, was used. The four sections represented in the figure are a part of a statistically designed experimental facility recently constructed at Texas A & M University to provide a means for evaluating nondestructive pavement testing systems of all kinds. Sponsors of the facility are the Texas Highway Department, the U. S. Bureau of Public Roads, and the Highway Research Board in its role as administrator of the National Cooperative Highway Research Program.

The upper graph of Figure 16 shows the effect on the deflection basin of increasir. the proportion of cement-treated to untreated crushed limestone in a 16-in. structure resting on a clay subgrade. In the lower graph the deflection basin of a 24-in. layer

TABLE 1

DESIGN DATA OF HIGHWAY PAVEMENTS FOR WHICH DEFLECTION BASINS ARE SHOWN IN FIGURE 15

Curve No.	Layer No.	Material	Thickness (in.)	THD Class	Est. Static Defl. (in. × 10^3)	Test Section No.
1	1	Hot mix A. C.	7.0	—	6.5	521-4-2
	2	Cr. limestone	15.3	1.0		
	3	Clay	—			
			22.3			
2	1	Surf. treatment	0.5	—	11.8	244-2-1
	2	Iron ore gravel	9.0	1.0		
	3	Sandy loam	8.0	2.5		
	4	Sandy clay	—	3.5		
			17.5			
3	1	Hot mix A. C.	3.3	—	24.0	15-14-1
	2	Cr. limestone	15.4	2.0		
	3	Clay	—	5.2		
			18.7			
4	1	Cold mix A. C.	0.9	—	38.7	20-1-1
	2	Caliche	8.4	2.8		
	3	Plastic caliche	—	3.8		
			9.3			
5	1	Surf. treatment	0.8	—	72.1	220-7-1
	2	Caliche	3.5	2.0		
	3	Sandy clay	7.5	2.5		
	4	Clay	—	4.0		
			11.8			

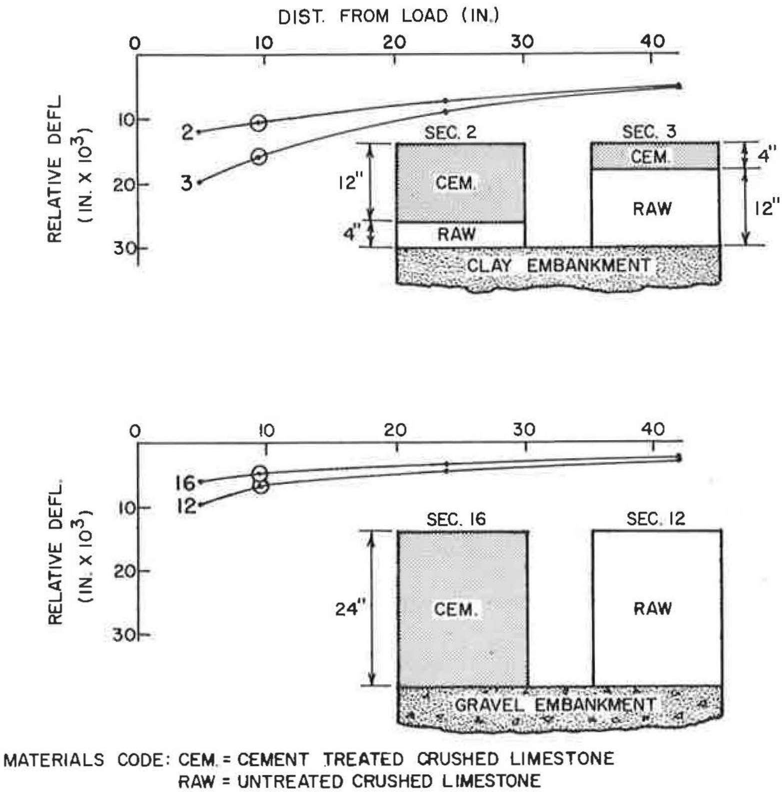

Figure 16. Deflection basins from four geophones on new sections before surfacing (designs correspond to curves); deflection scale refers to static deflection under a 9,000-lb wheel load as estimated from geophone located 9.5 in. from load (see circled points).

of cement-treated limestone on a gravel subgrade is compared with the somewhat deeper basin of an equal thickness of untreated limestone on the same subgrade.

At the present writing (August 1965) construction of the test facility mentioned previously is nearing completion. We expect later to make many other comparisons of the type described and to relate the size and shape of the deflection basin to the design of the test section. Such a relationship is expected to be useful in the interpretation of deflection data gathered on Texas highways.

CONCLUSIONS

Experience to date in the use of the dynamic deflection system described herein warrants the conclusion that it is rugged, reliable, simple and economical in operations, and capable of becoming a useful tool in pavement research concerned with the measurement of the relative stiffness of pavement structures.